Key Documents of the Biomedical Aspects of Deep-Sea Diving

SELECTED FROM THE WORLD'S LITERATURE
1608–1982

Volume V

SATURATION DIVING

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SATURATION DIVING

R. W. Hamilton

Without doubt Haldane, and probably Paul Bert before him, were aware of both the mechanics and the advantages of saturation diving. Behnke mentioned it seriously in a 1942 paper with regard to tunnel work (Behnke, 1942), but it remained for George Bond and his colleagues to grasp the idea and run with it. The *Genesis* series of experiments at New London involved at first a variety of animal exposures to determine that it was the oxygen in air that made it toxic in long exposures at pressure, and that normoxic helium mixtures were well tolerated (Workman, Bond, and Mazzone, 1962). The next step in *Genesis* was to "try it with people." The team worked up to a 200 fsw exposure with 3% oxygen and 97% helium, *Genesis E,* which proved successful (Bond, 1964).

The first to take these ideas to sea was E. A. Link, who built a small aluminum submersible decompression chamber for this purpose. Link's Man-in-Sea operation enabled a single diver, Robert Sténuit, to remain at 200 fsw for 24 h in the Mediterranean during September 1962. Link described his program in a *National Geographic* article (1963), and the diver himself gave his own account (Sténuit, 1966). When Cousteau heard of Bond's work, he waited "a discrete interval" (which he said was about 45 minutes) and went to work to place his divers at shallower depths, also in the Mediterranean. Like Link, he chose the *National Geographic* as his medium for publication (Cousteau, 1964). There does not seem to be a detailed scientific account of either operation in English before the one by Aquadro and Chouteau in the 3rd Symposium, which I do not consider a seminal document, but Fructus and Chouteau described Conshelf I (Fructus and Chouteau, 1963), as did Chouteau in the 1969 edition of Bennett and Elliott.

The U.S. Navy's underwater habitat program was known as Sealab I, with George Bond as principal investigator. A formal documentation of this project was authored by O'Neal et al. (1965), but it contains very little medical/physiologic information.

Another somewhat obscure document which is worth including is the writeup of Sealab II prepared by Hock, Bond, and Mazzone (1966).

The experiences mentioned above all refer to seafloor habitats, but commercial development of saturation diving, as well as military application, were to involve instead the "commuter" diving concept, whereby the divers live on deck in a Deck Decompression Chamber and are taken to and from the worksite in a sealed diving bell (transfer capsule). The first use of this technique was in the Smith Mountain Dam job (Krasberg, 1967). The concept that excursions offer a decompression advantage over an equivalent surface dive was shown by Larsen and Mazzone in a report in the 3rd Symposium.

The Navy's experience in saturation diving outdistanced its medical documentation, and it was necessary for two diving doctors to publish a "wildcat" guide to get the word out (Cook and Van Dyke, 1971).

Two additional documents meet the requirements as "key documents" because of their topic and timing.

The first is a report on the first well-documented study of exposure to a deep saturation environment, a 650 fsw laboratory dive conducted in 1965 (Hamilton et al. 1966).

The second is the basic work in the use of air excursions from nitrogen-based saturation habitats. This project established the NOAA OPS diving concept, which is only now finding its way into extensive commercial use (Hamilton et al. 1973).

SATURATION DIVING

R. W. Hamilton

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The Medical Clinics of North America
July, 1942.

EFFECTS OF HIGH PRESSURES; PREVENTION AND TREATMENT OF COMPRESSED AIR ILLNESS*

ALBERT R. BEHNKE, Jr., M.D.†

THE fundamental studies of Paul Bert,[1] Heller, Mager, and von Schrötter,[2] and Boycott, Damant, and Haldane,[3] as well as the vast body of experience derived from tunneling operations particularly in New York State, have given us a survey of the methods underlying the prevention and treatment of compressed air illness.

During the past ten years systematic research has been conducted at the Harvard School of Public Health and at the Experimental Diving Unit, Navy Yard, Washington, D.C., leading to (*a*) the development of a highly effective method of treating compressed air illness utilizing oxygen, (*b*) the employment of helium to make possible deep-sea diving in excess of 400 feet, (*c*) a better knowledge of decompression based upon quantitative studies, and upon long exposures in compressed air, and (*d*) a specific method for testing personnel with reference to susceptibility to compressed air illness.

Recently a great deal of attention has been paid to traumatic injury of the ear as a result of pressure variation, and to lesions in bones and joints looked upon by some authors as a specific complication of compressed air illness.

Mention must be made also of the identical symptoms associated with caisson disease that have been elicited during rapid ascent in aircraft and in numerous rapid decompressions to simulated altitudes of and above 30,000 feet in the low pressure chamber.

If a better perspective is to be obtained of the principles underlying the prevention and treatment of compressed air illness, consideration should be given to recent studies in the

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* The contents of this paper are not to be regarded as an official expression of the Navy Department.

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low pressure chamber which have shed new light on perennial problems.

PHYSIOLOGIC EFFECTS OF PRESSURE

Primary Pressure Phenomena

Pressure *per se* in the range that concerns us is apparently without physiologic effect provided that equalization of pressure is effected without trauma in sinal and aural spaces. A pressure of 240 pounds per square inch can be applied to the body of a diver, or the pressure can be decreased to 2 pounds per square inch in the case of the aviator without demonstrable injury.

If, on the other hand, the openings of air spaces in the ear and sinuses are occluded, then slight pressure variations in the range of 1 to 2 pounds (50 to 100 mm. Hg) per square inch elicit painful response and induce congestion, edema, and hemorrhage in the affected tissues. The cause of the occluded orifices is almost invariably related to chronic or acute infection of the nasopharynx. In the field of aviation the term *aero-otitis media* has been applied by Armstrong and Heim[4] to the traumatic changes which are also typical of the injury produced in caissons.

Temporary impairment of hearing is associated with the trauma, but a rapid spontaneous resolution of all symptoms takes place over a period of several days. The evidence at hand indicates that *pressure trauma* does not cause deafness. Moreover, the complications of suppurative otitis media and pansinusitis are rare in my experience if individuals stay out of water. The pressure trauma, however, appears to create a favorable condition for the growth of pathogenic organisms. Immediate exemption of individuals harboring infection of the nasopharynx from further pressure exposure has undoubtedly kept our complications minimal.

Requarth[5] observed that suppuration in the middle ear occurred in twelve out of 400 caisson workers complaining of pressure trauma and with the exception of a small percentage of men infection was present in the respiratory tract. Helium inhalation was of some value in alleviating symptoms but the evidence is not conclusive.

Divers with occluded eustachian tubes show about the same resistance to pressure increase irrespective of whether the atmosphere is air or a helium-oxygen mixture. It is not likely that helium penetrates the occluded tube faster than nitrogen, but possibly there is a more rapid diffusion of helium into the blocked space by way of the circulating blood.

Effects of Increased Partial Pressure of Gases

The more important physiologic phenomena incident to changes in pressure are related to the property possessed by gases of diffusing into the body when the atmospheric pressure is increased, and to the difficulty in their removal when the pressure is subsequently lowered.

Nitrogen Absorption and Elimination Curve.—The manner in which atmospheric nitrogen diffuses into or out of the body by means of the circulating blood is indicated by the graph shown in Fig. 175. The values represented on the graph were obtained by rendering the body free of dissolved nitrogen during the inhalation of oxygen. From nine to twelve hours are required for complete desaturation as far as can be determined by measurements but considerable variability is to be expected on the basis of variation in fat content of different individuals.

The substances in the body absorbing nitrogen are the fluids and the fat, in the ratio of 1 to 5. Hemoglobin also absorbs a small quantity of nitrogen. Since bone marrow contains about 90 per cent lipid substance and the spinal cord about 27 per cent, the nitrogen uptake by these tissues is of great importance.

Exercise increases the rate of gas elimination. However, the value of exercise is chiefly during the first thirty minutes when the inert gas is diffusing from body fluids. Exercise probably does not greatly influence the elimination of inert gas from the fat depots of the body.

At each atmosphere of increased pressure the absorption of nitrogen will follow the curve (Fig. 175), and the quantity absorbed will be a simple multiple of pressure corrected for the time of exposure.

Physiologic Reactions Associated with the Inhalation and Absorption of Nitrogen.—Beginning at a pressure of 4 atmospheres nitrogen acts as a *narcotic substance* to depress neuromuscular activity. At a pressure in excess of 10 atmospheres, consciousness may be lost. This remarkable property of nitrogen is consistent with the Meyer-Overton hypothesis relating narcotic action to solubility in lipid substances of the central nervous system.

The *substitution of helium* for nitrogen abolishes or renders negligible the narcotic effects of pressure, and an individual breathing a helium-oxygen mixture feels nearly as well at a pressure of 16 atmospheres as he does breathing air at normal barometric pressure.

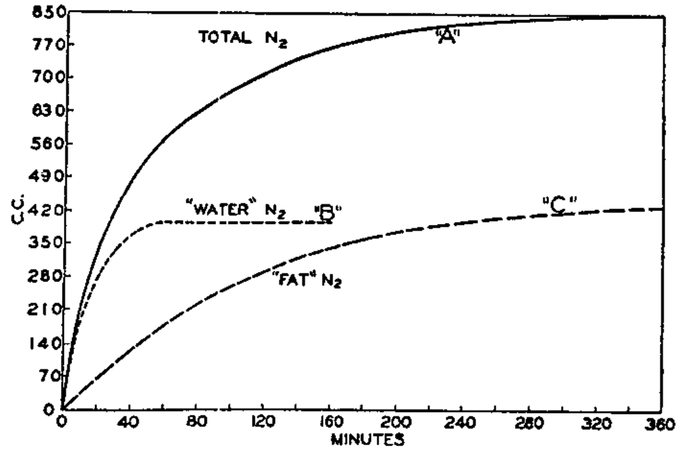

Fig. 175.—Solid line shows nitrogen elimination from a young lean man weighing about 60 kilograms. The nitrogen in the body is soluble in fat and fluids. The elimination or absorption of this nitrogen with changes in barometric pressure is represented by the hypothetical, broken-line curves on the graph. (Am. J. Physiol., *114:* 138, 1935.)

Resistance to the inhalation of compressed air is increased roughly in proportion to the square root of the density. In the diving suit or pressure chamber up to 10 atmospheres the increased resistance is scarcely perceptible to the healthy individual. However, if respiratory appliances are worn, the increased weight of the air may prove to be a limiting factor in their use.

By contrast, *inhalation of oxygen* is effortless in the low pressure chamber at simulated altitudes of 30,000 feet. The absence also of the nitrogen pressure effect and the ease with which any symptoms of aeroembolism may be treated make activity in the low pressure chamber a matter of ease compared with the impediments encountered in high pressure atmospheres.

Increased humidity accompanying the introduction of air under pressure is due to the concomitant rise in temperature, since the capacity of air to hold moisture is a function of temperature and not of pressure. High temperature combined with the high humidity have brought about debilitating fatigue during prolonged exposure in compressed air.

Reactions Associated with High Pressure of Oxygen

The increased partial pressure of oxygen in compressed air is capable of producing pulmonary damage. F. J. C. Smith and his associates[6] found that at a pressure of 4 atmospheres, partial pressure of oxygen equivalent to 83.6 per cent of one atmosphere, adult rats developed active hyperemia and acute edema of the lungs with a mortality of 13 per cent in three days. In the lower animals there is no question as to the toxic effects of oxygen pressure of about 70 per cent of one atmosphere. *Prolonged residence in compressed air then is limited to a pressure of about 3 atmospheres absolute.*

In the Navy an important advance in the field of diving has been the employment of oxygen for the prevention and treatment of compressed air illness. During rescue and salvage operations connected with the *U.S.S. Squalus* disaster, the administration of oxygen constituted a life-saving measure. It is important, therefore, to know man's tolerance to the inhalation of pure oxygen.

Tolerance to Inhalation of Pure Oxygen.—At *sea-level pressure* the period of time that pure oxygen can be safely breathed is a matter of controversy. Although the tolerance of the anoxemic patient may be greater than that of the healthy individual, we find that healthy men frequently do not tolerate the inhalation of pure oxygen continuously for periods in excess of seven hours. In recent tests the time has been extended to seventeen hours but there are some individuals who are sensitive to oxygen and one man developed manifestations of allergy. Irritability is a common symptom. It should be pointed out that periods of intermission when air is breathed, or a decrease in the percentage of inhaled oxygen greatly extends the tolerance time.

At a *pressure of 3 atmospheres* pure oxygen can be inhaled for a period of three hours. Symptoms indicative of pulmonary irritation do not arise but during the fourth hour of inhalation there may occur a rise in blood pressure, increase in pulse rate, and a contraction of the visual fields. *Pallor* may be extreme. Periodic waves of *nausea* constitute the most common subjective manifestation of oxygen toxicity. In diving operations, therefore, the working pressure for oxygen is limited to two and one half atmospheres.

At a *pressure of 4 atmospheres* oxygen usually can be safely breathed by men *at rest* for a period of thirty to forty-five minutes. In excess of this period convulsive seizures or syncope may occur. While the nervous manifestations of oxygen toxicity are alarming, apparently complete recovery follows when air is again inhaled.

If pure oxygen is inhaled during *exercise* at 3 atmospheres pressure, the tolerance time is greatly reduced. Pedalling a bicycle at a rate sufficient to increase normal oxygen consumption three-fold limited the inhalation of oxygen to a period of about twenty minutes. This exercise test is valuable in determining the oxygen tolerance of a given individual. It also provides a clue as to the nature of oxygen poisoning.

Fortunately these limits defining man's tolerance for oxygen permit this gas to form an essential part in the prevention and treatment of compressed air illness.

The Effect of Carbon Dioxide

Carbon dioxide enhances the toxicity of oxygen and the narcotic effect of nitrogen. In the diver's helmet the percentage of carbon dioxide must be reduced to a minimum. It was undoubtedly an increased percentage of carbon dioxide in the diving helmet that rendered operation in compressed air impracticable in connection with the salvage of the *U.S.S. Squalus.*[7]

In combination with high oxygen pressures, carbon dioxide has been responsible for loss of consciousness on several occasions followed by a maniacal type of reaction during the recovery of consciousness in the recompression chamber. On one occasion similar symptoms could be attributed to the effect of carbon dioxide itself.

With respect to work in compressed air a higher incidence of "bends" has been associated with a rise in the carbon dioxide level. At atmospheric pressure a percentage of 1.5 is well tolerated by slightly active individuals for periods of forty-eight hours. Higher percentages invariably cause headache. At higher pressures the percentage must be correspondingly reduced so that the partial pressure does not exceed 1.5 per cent of 1 atmosphere. In the diver's helmet the attempt is made to reduce the partial pressure of carbon dioxide to a value equivalent to 0.1 or 0.2 per cent of one atmosphere.

The Value of Helium

A notable advance in deep-sea diving making possible the salvage of the *U.S.S. Squalus* at a depth of 240 feet was the introduction of helium as a substitute for nitrogen in the diver's gas supply. Essentially practical diving operations have been increased from the physiologist's point of view from a depth of 150 feet to a depth of 500 feet.

The advantage of using helium is derived from its properties which (*a*) render negligible the narcotic effect of nitrogen, and (*b*) reduce solubility in fat compared with nitrogen in ratio of 1 to 4.5. The importance of this second property will be discussed in a subsequent paragraph.

COMPRESSED AIR ILLNESS

The Problem.—Rapid decompression after sufficient exposure in compressed air may give rise to the formation in the blood stream of bubbles composed chiefly of nitrogen together with small quantities of water vapor, carbon dioxide, and some oxygen. These emboli deprive tissue of normal blood supply to elicit characteristic symptoms of pain, asphyxia, and occasionally paralysis. The symptoms occur either singly or in combination and indicate that the areas for bubble formation and accumulation are veins, right chambers of the heart, pulmonary vascular bed, spinal cord, and the bones, especially bone marrow. Treatment aims at the removal of the emboli in the shortest possible time in order to minimize injury particularly with reference to the spinal cord and right ventricle.

Etiology, Symptomatology

Until further proof is adduced there is no reason to accept any other explanation for the cause of compressed air illness than Paul Bert's classic observation embracing the theory of nitrogen embolism.

IN ANIMALS.—Swindle[8] describes agglutination of the erythrocytes incident to rapid decompression. End[9] confirms this observation in lower animals. In anesthetized dogs rapidly decompressed from high pressure atmospheres, one observes that gas bubbles move through arteries and veins. As the number and size of the bubbles increase, blood flow slows down and ceases entirely.

Embolic interference with blood flow elicits a pathognomonic triad of symptoms consisting of *rapid respiration, fall in blood pressure,* and *decrease in pulse rate.* These symptoms are primarily attributed to asphyxia arising from massive pulmonary embolism.[10] This conclusion is substantiated by analyses of oxygen content of blood showing a marked reduction in the percentage saturation of both arterial and venous hemoglobin (Table 1[11]).

The most remarkable finding, however, was the occurrence of *hemoconcentration* shown by increased oxygen capacity of blood (Table 1). In some tests it amounted to as much as 30 per cent. The cause of hemoconcentration was thought to be due to a loss of fluid through capillaries damaged by asphyxia and possibly an increased mobilization of red blood cells from the spleen. Essentially a condition of shock supervenes. The blood, moreover, was difficult to withdraw because of the tendency to clot. In histologic sections of the lungs, cell packing in blood vessels was prominent. Agglutination was not observed.

It must be borne in mind that complete recovery follows the proper treatment of compressed air illness provided that paralysis does not develop. This fact is *a priori* evidence that agglutination and appreciable parenchymal damage from intra- or inter-cellular cavitation do not take place. In rapid decompression simulating ascent to high altitudes, bubbles have been demonstrated in cerebrospinal fluid and in joint spaces. It is not considered likely that such extravascular accumulation of gas plays an etiologic role under the conditions in which men, in contrast with lower animals, are decompressed from high pressure atmospheres.

TABLE 1

ANALYSIS OF OXYGEN CONTENT OF BLOOD FROM ANESTHETIZED DOGS RAPIDLY DECOMPRESSED FROM HIGH PRESSURE ATMOSPHERES*

Exposure	Period	Volume Per Cent Oxygen Content		Arterial Venous Difference	Oxygen Capacity	Per Cent O_2 Saturation		Pressure CO_2 Arterial Blood
		Arterial	Venous			Arterial	Venous	
9†	Control	15.9	10.1	5.8	17.7	90	57	45
	Following decompression	5.4	0.5	4.9	22.4	24	2	59
	Recompression	17.9	7.9	10.0	20.3	88	39	
	Following recompression	5.9	2.3	3.6	22.8	26	10	
10‡	Control	20.6	17.0	3.6	22.8	90	75	
	Following decompression	14.6	7.7	6.9	26.1	56	30	
	Recompression	31.7§	20.0	11.7	27.3	100	64	
	Following recompression	26.9	7.3	19.6	29.8	90	24	

* Data from Behnke *et al.*, Am. J. Phys., *114*: 526, 1936.
† Air inhaled during two-hour recompression period.
‡ Oxygen inhaled during two-hour recompression period.
§ 4.4 volumes per cent oxygen in physical solution.

Apart from asphyxia and its complications, *paralysis* usually in the form of spastic paraplegia of the hind extremities was observed in dogs. Foot drop, paresis of hind limbs, and genito-urinary disturbances were occasionally manifest. That the spinal cord rather than the brain is primarily involved, is evident from the older studies.

IN MAN.—From these controlled experimental data one gains a better understanding of the symptomatology in man. *Asphyxia* or "chokes" is usually manifest by shallow, rapid respiration, dyspnea, and cyanosis, or by a pale, ashen gray appearance. Visual disturbances of an asphyxial nature are not infrequent.

We have noted that an early sign indicative of bubbles in the pulmonary vascular bed is a sensation of *substernal distress*, especially during deep inspiration, which elicits the cough reflex. In this condition habitual smokers are unable to tolerate the inhalation of tobacco.

The incidence of *paralysis*, while at present rare compared with the old reports, is the most serious complication of compressed air illness. The manifestations in man are similar to those observed in dogs, and indicate ischemic involvement and necrosis particularly of the thoracolumbar segments.

Residual injury pointing to involvement of the spinal cord is seen among the older sponge fishermen of Florida who have not had access to proper recompression treatment.

Demonstrable *injury of the cerebrum* in contrast with the spinal cord, and apart from asphyxial damage, is rare. Ménière's syndrome was described not infrequently in the older reports and is thought to be due to embolic deprivation of blood supply to the inner ear. It is certain that pressure trauma does not cause the entity.*

The most common manifestation of compressed air illness is a *dull, aching type of pain*, shifting in character, and frequently felt in the joints, or deeply in muscles and bones. Pain or pains of this nature are referred to as *bends*, a term established by usage to denote a well recognized clinical entity.

A most likely location giving rise to bends is bone, particularly the marrow with its high absorption coefficient for nitrogen. Furthermore, the sluggish, sinusoidal type of circulation in the marrow and the natural obstructions to the exit of bubbles possible only through the dichotomous branches of a vein traversing the rigid-walled cortex serve to make the bones a trap for gas bubbles disseminated from the general circulation or forming in situ in the marrow spaces. From

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* It should be pointed out here that there is an urgent need for a study of the histologic changes produced in the central nervous system as a result of rapid decompression.

the point of view of body economy the bones constitute the weak organ that renders man unsuited for long exposures in compressed air.

That bubbles are present in the marrow is inferred from the intensified pain experienced by some patients during early recompression. This type of pain is believed to arise from a difference in pressure or an actual squeeze of bone marrow tissue during the too rapid compression of bubbles to allow the body fluids to replace the suddenly diminished gas volume within the bone cortex.

Recent reports of characteristic lesions in bone appearing in caisson workers support the view that the symptoms giving rise to bends originate in part certainly from *ischemic changes in bone*. Kahlstrom, Burton, and Phemister,[12] Coley and Moore,[13] and Rendlich and Harrington[14] describe lesions in diaphyses and epiphyses of long bones complicated by joint involvement and attributed to aseptic necrosis of bone or interference with nutrition occurring secondary to the interruption of blood supply by liberated nitrogen gas.

However, the etiologic relationship between the presence of these lesions and embolic injury must be corroborated by additional findings and animal experiments before final conclusions can be drawn. In divers suffering repeatedly from experimental bends, Lieut. Walter Welham, (M.C.), U. S. Navy, and the writer found no characteristic lesions in a roentgenologic study at different periods following injury.

Some factor such as multiple, repeated injury, concomitant infection, or anomalous blood supply must operate in conjunction with embolism to produce the described changes. The analogy that may be drawn to the relationship between the ingestion of alcohol and cirrhosis of the liver suggests that an integrative analysis is required to evaluate the findings.

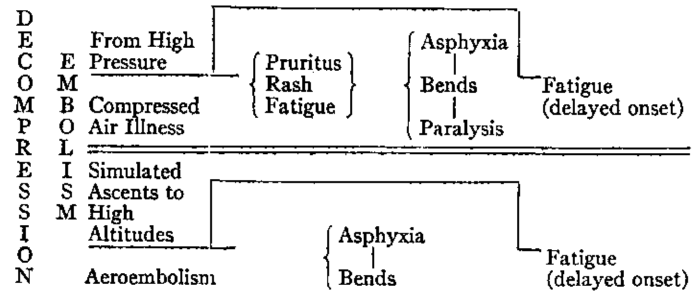
That interference of gas emboli with the blood supply to muscles may also form part of the picture of bends appears probable from the effects of too rapid decompression in a helium atmosphere. The decreased solubility of helium in fat renders the incidence of bone lesions less likely than the incidence of these lesions following air decompression.

Fatigue is a symptom of especial interest which may be prodromal or subsequent to bends. In experimental borderline decompressions, fatigue is frequently the first sign of excessive bubble formation. In association with bends, fatigue may take the form of an exhausting malaise combined with chills, fever, and sweating.

Minor symptoms as *skin rash* and *pruritus* occur with regularity if the skin is chilled during decompression.

It is important to bear in mind that the *onset of symptoms* may be delayed as long as twelve hours following decompression and that sudden collapse may occur without warning in an apparently well individual three or four hours following decompression. The failure to consider these probabilities has led to inexcusable errors.

The following diagram may clarify the symptomatology of decompression embolism:



Our deep-sea divers have experienced symptoms during simulated ascents to high altitudes identical with the bends characteristic of compressed air illness.

Diagnostic Considerations

Since intravascular bubbles have access to every part of the body, one must be aware of the protean nature of compressed air illness. The diagnostic rule is to regard every unexplained symptom following work in compressed air as caused by bubble formation. Serious errors have been made by not applying recompression at least as a diagnostic procedure.

On the other hand, patients have developed appendicitis during decompression, and a fracture of the neck of the femur was said to have been overlooked in a patient treated for compressed air illness.

Principles Underlying the Prevention of Compressed Air Illness

The prevention of compressed air illness depends upon the *elimination of nitrogen* absorbed during exposure to increased barometric pressure without excessive bubble formation in the blood stream.

From Fig. 175 it is observed that about 75 per cent of the total body nitrogen is eliminated at a comparatively rapid rate and hence does not usually contribute to the formation of bends. There appears to be, however, a relatively small amount of gas in the fatty bone marrow that requires many hours for proper elimination.

At a depth of 90 feet, for example, 10.5 hours of air decompression were required following a nine-hour exposure (probable saturation). On the other hand, a two-hour exposure (75 per cent saturation) at the same depth required only fifty-nine minutes for decompression (Table 2). Nine and one-half hours were therefore required for the dissipation of the remaining excess gas amounting to but 25 per cent of the total present in body tissues.

From our point of view the body may be compared with a mixture of water and fatty material contained in a beaker. Of the fat an important fraction is surrounded by bone representing marrow and spinal cord substance. This bone-contained fat may be considered as lying in the bottom of the beaker.

If the contents of the beaker are now exposed to a high nitrogen pressure for a short period of time and then quickly returned to atmospheric pressure, diffusion of nitrogen will take place from the water into the surrounding air and also into the unsaturated water and fat. Following short exposures the partially saturated fat appears to act as a buffer against bubble evolution. By contrast, after long exposures the large reservoir of nitrogen in the saturated fat constitutes the predisposing cause to embolism. The nitrogen within the bone, moreover, will require many hours for removal.

With reference to the matter of *tolerance for abrupt re-*

ductions in pressure, the body may be exposed to a compression of 4 atmospheres for a period of twenty-seven minutes followed by a rapid decompression to the normal level in two minutes. A period of ninety minutes, however, at the same pressure and followed by the same period of decompression would prove fatal.

The nitrogen absorbed in the early part of decompression and presumably dissolved in the body fluids is therefore readily eliminated by any method of decompression. In the rapid drop from 4 to 1 atmosphere, a degree of supersaturation appears to be tolerated by the body approaching a ratio of 4 to 1. By contrast, when the body is saturated at a pressure of 4 atmospheres, requiring a saturation period of nine to twelve hours, a ratio indicative of supersaturation of only 1.2 to 1 will not hold throughout the whole period of decompression.

TABLE 2

CHAMBER DECOMPRESSION FOLLOWING PROLONGED EXPOSURE IN COMPRESSED AIR

Simulated Depth (Feet)	Exposure Time (Hours)	Decompression Time (Minutes)	Remarks
30	12	1	No symptoms
38	5	1.5	No symptoms
38	7	1.5	No symptoms
38	9	1.5	Bends 3 hrs. following decompression
38	9	1.5	No symptoms. *Oxygen* 6 hrs. at surface
38	12	1.5	Bends 2.5 hrs. following decompression
38	12	1.5	No symptoms. *Oxygen* 6 hrs. at surface
60	6	69 (Air)	No symptoms
60	12	237 (Air)	Bends 10.5 hrs. following decompression
60	12	311 (Air)	No symptoms
Diver C. 60	12	79 (O_2)	Oxygen 2.2 hrs. at surface. No symptoms
Diver C. 60	12	79 (O_2)	Oxygen 4.3 hrs. at surface, bends 5 hrs. following decompression
Diver S. 90	2	59 (Air)	No symptoms
90	6	310 (Air)	No symptoms
90	9	458 (Air)	Bends 2 hrs. following decompression
Diver S. 90	9	583 (Air)	Bends 1 hr. following decompression
90	9	638 (Air)	No symptoms

Furthermore, during rapid decompression in the low pressure chamber, apparently ratios between the pressure of gas in the body and the ambient pressure of 3 to 1 or even 4 to 1 exist, *i.e.*, 1 atmosphere to 0.33 atmosphere or to 0.25 atmosphere.

On the basis of these facts the degree to which the body appears to hold gas in a state of supersaturation is *relative* and depends not only upon the degree of saturation but also upon the pressure level.

TABLE 3

PRESSURE SHIFTS AND INTERVALS OF WORK FOR EACH TWENTY-FOUR-HOUR PERIOD
(New York State Tables)

Pressure		Hours			
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
Minimum Number of Pounds	Maximum Number of Pounds	Maximum Total	Maximum First Shift in Compressed Air	Minimum Rest Interval in Open Air	Maximum Second Shift in Compressed Air
Normal	18	8	4	½	4
18	26	6	3	1	3
26	33	4	2	2	2
33	38	3	1½	3	1½
38	43	2	1	4	1
43	48	1½	¾	5	¾
48	50	1	½	6	½

Application of Physiologic Principles.—The important consideration is not mastery of a method of computing the decompression table on the basis of a ratio but rather the acquisition of an understanding of the *basic* physiologic principles of which one of the most important is the realization of the difficulty in getting excess nitrogen out of fatty tissue, especially the bone marrow.

From the point of view of field practice this difficulty has been overcome by progressively limiting *the time of exposure* in compressed air as the working pressure is increased. The New York State tables (Table 3) represent the culmination of this type of experience.

If it is desirable to increase working time at higher pressures three methods resting on a sound physiologic basis are available: (1) keep workers in a compressed air atmosphere for prolonged periods of time followed by slow decompression, (2) employ helium-oxygen mixtures in place of air, (3) employ oxygen during decompression.

1. *Prolonged exposures* in compressed air for periods of at least seven days at pressures of 30 pounds gauge have been made repeatedly. From the point of view of physiologic response and work output, the attempt to decompress men twice daily is not only potentially dangerous but highly uneconomical.

At a pressure of 50 pounds gauge, for example, the working time is under present conditions necessarily limited to about forty-five minutes. This time could be extended for a period of hours depending upon the capacity of individuals for work, were not the danger of bubble formation imminent following even long periods of decompression.

It would appear advisable therefore to keep men at work on a job continually under pressure. Following a work shift at maximum pressure, the pressure could be lowered rapidly to between 20 and 30 pounds and maintained at this level during the rest and sleep period. The final decompression prior to emergence into a normal atmosphere would be uniform over a period of eight to twenty-four hours.

2. *Value of Helium-Oxygen Mixtures.*—Since the objection to long exposures lies in the difficulty of eliminating the gas dissolved in fatty substance, the employment of helium with its low solubility coefficient in fat would appear to be ideal.

In diving tests, following short exposures in the compressed helium-oxygen or air atmosphere, the body fluids are well saturated with either gas and no particular advantage in decompression accrues from the use of helium (Table 4). Following long exposures, decompression time may be reduced as much as 75 per cent. Part of the reduction in decompression time is brought about by the inhalation of oxygen at the lower decompression stops, but the important factor is the lessened uptake of helium by fat.

In altitude test runs oxygen inhalation for a period of five hours is required under certain conditions to prevent aeroembolism. If the body nitrogen be removed and helium substituted, the time for oxygen inhalation can be reduced to at least ninety minutes or a reduction of 70 per cent.

Whether or not the employment of helium is practical in caisson work depends upon the development of a method of economical administration.

In deep-sea diving exposures are usually short and the advantage derived from helium is that it renders unimportant the narcotic effect of nitrogen as demonstrated in the *U.S.S. Squalus* salvage operations.

TABLE 4

COMPARISON OF TOTAL DECOMPRESSION TIME FOLLOWING EXPOSURE IN COMPRESSED AIR AND EXPOSURE IN A HELIUM-OXYGEN ATMOSPHERE

Depth (Feet)	Exposure (Minutes)	Decompression (Minutes)	
		Air	Helium-Oxygen
90	100	50	75
90	180	...	77
90	360	....	79
90	540	638	79
150	80	141	121
150	180	...	126
150	360	...	128
200	65	217	154
200	90	...	164

3. *Value of Oxygen.*—Essentially oxygen inhalation permits the elimination of an inert gas at a maximum pressure head as shown by the graph (Fig. 175), and at a pressure level sufficiently high to prevent injury from massive bubble evolution.

During the past three years the Navy has used oxygen routinely in helium-oxygen diving during the latter part of the decompression period beginning at the 60-foot level.

In air diving the British have had a great deal of experience with oxygen inhalation and the reader is referred to the book, "Deep Diving and Submarine Operations," by Robert H. Davis.[15] A reduction in decompression time of about 40 per cent is effected by the employment of oxygen according to British experience.

Following prolonged exposures in compressed air at comparatively shallow pressure-depths we have had the opportunity to test the value of oxygen and some of the data are recorded in Table 2. Under the conditions of these tests the long exposures in hot compressed atmospheres brought on fatigue which seemed to render variable the susceptibility of men to bends.

In one test the inhalation of oxygen for a period of seventy-nine minutes in the compressed atmosphere was adequate for decompression. In another similar test the same individual developed bends. Finally the oxygen decompression period had to be increased to one hundred and sixty-one minutes for the saturation exposure of twelve hours at a simulated depth of 60 feet. However, the corresponding decompression period in air was three hundred and eleven minutes.

The data in Table 2 demonstrate the value of oxygen inhalation following decompression at the surface level. Thus, the depth could be increased from 33 to 38 feet provided that oxygen was inhaled following abrupt decompression to the surface.

The conclusions drawn from these tests is that a considerable reduction in decompression time is brought about by oxygen. On the other hand, the occurrence of bends following a period of oxygen inhalation of ninety minutes during the initial stage of decompression demonstrates again the difficulty in getting rid of the comparatively small residual fraction of nitrogen in slowly desaturating tissue (bone marrow).

Oxygen inhalation undoubtedly serves its best purpose in preventing the serious symptoms of compressed air illness and its chief value lies in clearing the blood stream and body fluids of the excess nitrogen.

Further Principles Underlying the Prevention of Compressed Air Illness.--The value of exercise in promoting a more rapid elimination of nitrogen during the early part of decompression, and the danger inherent in the accumulation of carbon dioxide in the compressed atmosphere, have been discussed in previous paragraphs.

Danger of Too Rapid Ascent to the First Stop.—The tendency in diving is to bring men too rapidly to the first stop which usually is at one half the depth compared with the original level. This procedure leads to the initiation of the bubble state in the early part of decompression when the pressure head of gas in the tissues is highest.

Symptoms indicative of embolism have appeared during helium-oxygen diving at depths of 180 and 90 feet on two occasions following too rapid ascent from depths in excess of 300 feet. At present for helium-oxygen diving the rate of ascent is limited to 25 feet per minute and an arbitrary period of seven minutes is taken at the first stop in order to permit the blood to transport to the lungs the large amounts of helium diffusing into the blood stream.

It has been possible to show by actual measurements that too rapid decompression in the early stages leads to an accumulation of gas probably in bubble form so that equal quantities of gas are eliminated during each of the first two thirty-minute periods; if the blood stream is not overloaded, about two and one-half times more gas is given off during the first thirty-minute period compared with that eliminated during the second period (Fig. 175).

In air diving the reduction in rate of ascent to the first stop from 50 to 25 feet per minute greatly reduced the incidence of embolism manifested by the occurrence of pruritus and rash.

Selection of Personnel.—A routine physical examination may not be adequate to determine those individuals who are qualified for work in compressed air. We therefore employ specific *pressure tests* for the selection of fitted men.

With reference to patency of auditory tubes and presumably freedom from infection of the upper portion of the respiratory tract, the immediate application of a pressure of five pounds in the chamber will serve to select the qualified men. The assumption is made that the men have previously been instructed in the matter of "clearing their ears." Inspection of the tympanic membrane following the application of pressure reveals the degree of ability to accommodate to excess pressure. Two tests with an interval of several days intervening should be accorded an applicant who is otherwise in good physical condition.

With reference to susceptibility to bends, it follows from a consideration of the physiologic data that the elimination of excess nitrogen without the development of manifest air embolism depends upon effective blood flow through tissues and the absence of excess fat. The desirable type of man is therefore young and lean. Yet among such individuals the variation in susceptibility to compressed air illness makes necessary a specific *decompression test for the selection of deep-sea divers.*

This test consists in reducing the pressure from 1 atmosphere to 0.25 atmosphere during a period of seven minutes. Oxygen is inhaled at the start of pressure reduction. The duration of stay in the rarefied atmosphere is for a period of one hour. Under these conditions susceptible men develop bends while those men who are comparatively immune remain free from symptoms.

Too much stress cannot be laid on the necessity for the *maintenance of good physical condition* by men who work in compressed air. Empirical data indicate that any condition tending to impair cardiovascular tone renders men susceptible to the development of decompression embolism. Indulgence in alcohol should be specifically interdicted. Fatigue, infection, hot atmospheres, and excess carbon dioxide in the air are all factors associated with increased incidence of bends. Our deep-sea divers, therefore, maintain a system of training similar to that followed by the athlete.

Summary of Principles.—The following principles underlie the prevention of compressed air illness:

1. Limitation of time of exposure in compressed air or the employment of helium-oxygen mixtures for saturation exposures.
2. Reduced rate of ascent in the early stages of decompression.
3. Slow decompression following long exposures and the inhalation of oxygen at the lower decompression levels.

4. Careful selection and the maintenance of personnel in good physical condition.

Treatment of Compressed Air Illness

The prime requirement in treatment is the *rapid restoration of normal blood supply by compression and absorption of the obstructing gas emboli.* Behnke and Shaw[9] formulated a procedure of recompression utilizing oxygen, based on laboratory experiments (see Table 1) and later Yarbrough and Behnke[16] applied the principles to field practice.

In repeated treatments administered by this method incident to experimental diving and in submarine salvage operations, no significant change in procedure from that outlined in the original papers has been made. It has proved to be satisfactory.

Recompression.—Essentially the basis of treatment is prompt recompression and the inhalation of oxygen. Figure 176 serves as a guide in the recompression procedure. It is emphasized that the condition of the patient governs the detailed mode of therapy rather than rigid adherence to a system of tables.

Perhaps there is no therapeutic procedure more effective than recompression as applied to the asphyxiated, pulseless, cyanotic patient whose blood stream is filled with multiple gas emboli. Even patients presenting incipient lesions of the spinal cord have made complete recovery under immediate and prolonged recompression.

In the mild cases of compressed air illness characterized by bends, the minimum pressure applied in recompression is 45 pounds per square inch (gauge) equivalent to a diving depth of 100 feet. Relief of symptoms may occur at greatly reduced pressures but the additional compression reduces the size of the bubble 75 per cent compared with surface volume, and ensures against the initiation of lesions in the spinal cord.

For the serious cases characterized by asphyxia, probable involvement of the nervous system, or both conditions, recompression is limited to a pressure of 75 pounds gauge equivalent to a depth of 165 feet. At this pressure the surface size of the bubble has been reduced 83 per cent; higher pressures can do little to improve circulation and would unduly delay the pressure at which oxygen could be breathed.

The next stage is the *maintenance of the maximum pressure* for a period of thirty minutes. Usually this period of time is sufficient to ensure apparently complete recovery but should paralysis be present or suspected, or if the patient remains unconscious, the maximum pressure is maintained for an additional ninety minutes (Fig. 176, C).

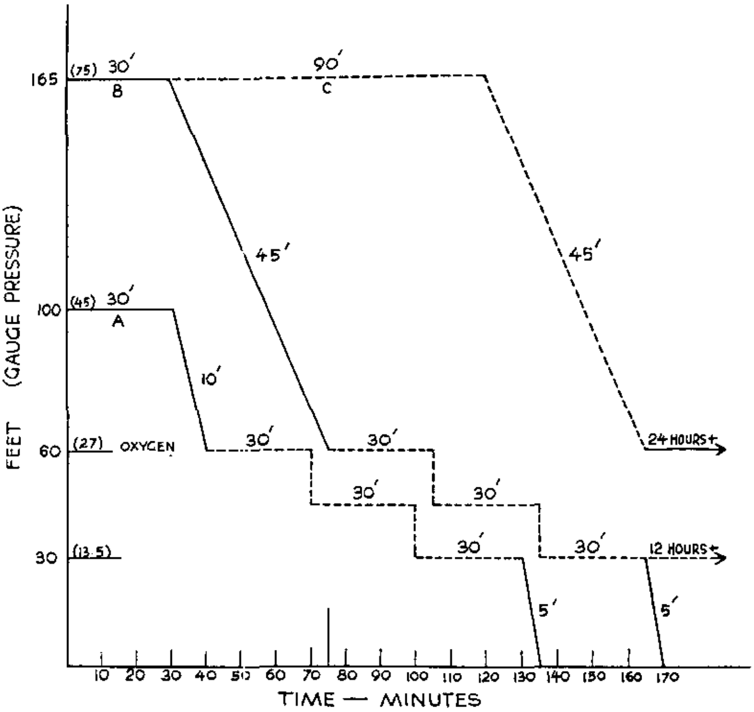


Fig. 176.—Guide for treatment of compressed air illness (after Behnke and Shaw, Yarbrough and Behnke).

A—For "bends."

B—For "bends"—asphyxia.

C—For asphyxia/paralysis.

At maximum pressure patient inhales air, or helium-oxygen of about (70:30 ratio) mixture.

At 60-foot level or below, patient inhales oxygen for ninety-minute period. Attendant inhales oxygen for thirty-minute period.

For prolonged recompression at or below 60 feet, air is inhaled.

At the maximum pressure, *air*, or if available, a mixture of *helium-oxygen* (about 70:30 ratio) is inhaled. At the end of the thirty-minute period the pressure is decreased uniformly for forty-five minutes until the 60-foot level (27 pounds gauge) is reached (Fig. 176, B). If a pressure of 45 pounds has been used (Fig. 176, A), a period of ten minutes is sufficient for decompression to the 60-foot level.

Oxygen inhalation is begun at the 60-foot level and continued for a period of ninety minutes until the 30-foot level is attained. If the patient exhibits an idiosyncrasy for oxygen, the usual symptom being *nausea*, oxygen inhalation is postponed until the 45- or 30-foot levels are attained. Air or the helium-oxygen mixture is inhaled for the period of time at the 60- or 50-foot levels that would otherwise have been devoted to the inhalation of oxygen.

It is unlikely that intolerance for oxygen will exist at the 45- or 30-foot levels and a period of ninety minutes for oxygen inhalation should be feasible for all patients prior to the termination of decompression.

Decompression* is then terminated from the 30-foot level by a uniform drop to the normal atmosphere over a period of five minutes.

For mild cases of compressed air illness this type of treatment usually affords permanent relief. Should symptoms recur in more seriously injured patients, recompression is again effected to a level between 30 and 60 feet for a period of twelve to twenty-four hours followed by a gradual return from the 30-foot level to the normal atmosphere during a period of four hours.

This practice of prolonged immersion in compressed air colloquially termed "the overnight soak" has proved to be the conclusive method of terminating treatment. The patient is permitted to sleep and the bubbles have adequate time for absorption. Should there be any question of involvement of the central nervous system, the prolonged immersion treatment is routinely put into effect.

For the moribund patient, the pressure level following the

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* For the *attendant* a thirty-minute period of oxygen inhalation should ensure adequate decompression.

two-hour treatment at a depth equivalent to 165 feet, is decreased to 60 feet during a period of forty-five minutes. Oxygen is then administered for ninety minutes, and *air inhalation is continued for a period of twenty-four hours or longer.* There should be no hesitancy in continuing treatment at the 60-foot level for a period of days. The increased partial pressure of oxygen at this level is also an effective therapeutic measure in treating the incipient or manifest pulmonary edema, anticipated as a complication of extensive embolism of the pulmonary bed (see Fig. 176, C).

Adjuncts in treatment are the judicious injection of glucose and saline solutions, or plasma in the severely injured patients in order to counteract the effect of hemoconcentration. The use of adrenalin and the application of warmth are additional measures if the shock syndrome is present.

The position of the patient's body should be recumbent since the site of bubble accumulation is influenced by gravity.

Errors in treatment have been:

1. Failure to apply the pressure test in doubtful cases, "It can't be compressed air illness."
2. Delayed recompression. The potential patient avoids the doctor.
3. Failure to keep the moribund patient at the 60-foot level.
4. Failure to keep the "treated" patient near the recompression chamber for a twenty-four-hour period.

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New Developments in High Pressure Living

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With the almost daily extension of man's capabilities in the areas of outer and inner space alike, environmental medical problems are of paramount importance, and, since any manned probes, whether extraplanetary or in the ocean depths, require the use of a closed ecological system, our professional attention is directed to the physiological problems of man in a synthetic environment. It is axiomatic that whenever man is removed from so-called natural life of sea-level, temperate-zone conditions, most of the physical elements of his surroundings must be modified, controlled, or synthesized, if the individual can be expected to function adequately, and without physiological decrement. In net, the probability of man's successful existence in a closed ecology, whether it be the earth, the modern industrial plant, outer space, or in submarine life, may be expressed as the sum of adaptation processes plus human ability to synthesize a total environment.

The techniques of environmental synthesis have origin in antiquity, and a fantastic range of sophistication. From the discovery of fire and the use of animal skins for thermal protection, mankind has progressed to the total environmental control of the space capsule and the nuclear-powered submarine. In all cases, however, the aim has been to achieve and maintain homeostasis; and to this end, we are concerned primarily with the problems of thermal control, metabolic balance, and provision of acceptable respiratory gases. Of these three problem areas, it would seem that the most important is that of atmospheric selection and composition. Hence, a major effort of our Laboratory has been directed at the determination of optimum

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respirable atmospheres for man, through a broad spectrum of tolerable pressure exposures, ranging from deep-sea diving to space capsule habitation. The experimental work to be described in this paper has to do with the former aspect, since exposure to high ambient atmospheric pressures is a daily fact of life in the Submarine Service. The title of this particular experiment is *Genesis I*.

The purpose of *Genesis I* is expansion of man's ability to utilize the products of the marine biosphere which makes up nearly three quarters of our earth. Within this salt-water environment is found much of the edible protein requirement of our generation; the mineral, archeological, and meteorologic discoveries of years to come; the possibility of fresh water recovery; a new generation of antibiotics for human use; and, finally, a new area for fundamental research. The reaches of space are a challenge to man's intellectual grasp; but knowledge of the ocean's environment, products, and impact on civilization deserves serious and urgent attention of the world's scientists, if human survival is to be guaranteed.

Man's desire for personal conquest of all reaches of the sea has been an enduring dream, extending backward past the span of documented history. Since the early 14th century, laborious and hazardous steps have been recorded of human effort to return as a free-ranging, effective agent to the ocean depths from which we once emerged to become dry-land inhabitants. With considerable ingenuity, the capacity of man's undersea existence and function has been advanced through development of diving bells, submarines, deep-sea diving gear, self-contained underwater breathing apparatus (SCUBA), and lately, with unpressurized vehicles capable of reaching the ocean bottom at its greatest known depths.

Despite these technological developments, the capability of prolonged, free-ranging existence in the ocean's depths remains, at this time, beyond man's reach. Encapsulated in pressureproof submersibles, we are presently able to range for appreciable distances, both vertical and horizontal, beneath the seas. From within these vessels, immediate and remote observations can be made, and samples of the environment secured with prosthetic devices. Yet, this does not suffice. In order to absorb and utilize every facet of the undersea environment, it may be necessary that the investigator have complete freedom of movement, and an ability to coexist under conditions identical with those of the marine biosphere under scrutiny.

An approach to this freedom may be attained through use of conventional deep-sea diving equipment, or with SCUBA equipment. Operational limitations of these devices, however, are stringent. Utilizing the older "hard-hat" diving suit, the diver is not only tied by an umbilical gasline to the surface, but hopelessly limited to a tiny circumference of search and observation. With use of SCUBA gear, considerably greater individual range is permitted; yet the availability of self-transported gas is a limiting factor, quite serious at depths beyond 15 fathoms. More importantly, in either case, the individual is subjected to immutable laws of physics, which would seem to limit not only the duration of undersea exposure, but also the depths to which man, as a free agent, may be effective.

About six years ago, personnel of the Naval Medical Research Laboratory began to explore new approaches to the old problem of inner-space exploitation. The reasons for this interest are apparent, from civilian and military point of view alike. For military purposes, the capability of undetected underwater existence and construction might add a new and potent string to the bow. On the other hand, this research, if successful, would certainly enhance civilian scientific utilization of oceanic resources. At the time, it seemed a worthwhile goal; and it was pursued with enthusiasm.

At first, it appeared that two major problems were involved: the choice of respirable gas mixture at any depth; and the ultimate question of decompression. Initially, it was necessary to provide a gas mixture which would minimize both narcosis and breathing resistance; next, the problem of decompression after *total* body saturation required resolution. Since the final operational application would involve exposure of man to gas pressures of up to 20 atmospheres for infinite periods of time, a great deal of basic experimental work required attention.

As a beginning, it was desirable to reconfirm the probability that compressed air would not be a satisfactory breathing medium for man under these conditions. Although this likelihood had been pointed up by the work of Drinker and his associates some three decades past, the earlier experiments were repeated, with some extensions. Shortly, it could be demonstrated that compressed air, breathed at an equivalent sea depth of 200 ft, was lethal for selected Wistar strain rat populations after 35 hours of continuous exposure. Examining the hypothesis that the increased partial pressure of oxygen caused death in this instance, equivalent groups of animals were exposed to an atmosphere in which the partial pressure of oxygen was held at 160 mm Hg, with nitrogen gas making up the pressure differential to seven atmospheres. In this experiment, all but one of 16 animals survived a 14-day exposure, but specific and irreversible lung lesions were found in the case of all survivors. These lesions were generally attributed to the density of the breathing mixture, although consideration was given also to the narcotic effect of nitrogen at this depth, insofar as it might alter normal respiratory patterns.

A final check was made on the lethal effect of elevated oxygen partial pressures. Another matching rat group was exposed, under similar conditions of temperature and humidity, to an atmosphere of 100% oxygen, at a pressure of approximately 22 lb per square inch absolute (psia). This exposure yielded an oxygen partial pressure of about 1,120 mm Hg, equal to that of the initial experiment at 200 ft (103 psia), which had previously resulted in 100% mortality after 35 hours. In this experiment, with reduced gas density and with the element of nitrogen narcosis excluded from the design, 100% mortality was again reached after 35 hours of exposure. Data from these experiments evidenced the predictable lethality of oxygen with respect to animal subjects.

Considering that the specific deadly effect of high pO_2 had been demonstrated, and could be controlled, the next effort was to reduce the density of the inert gas component. If nitrogen proved too heavy, the obvious lighter inert gas of utility was helium.

In the United States Navy, helium and oxygen mixtures had been used for divers' breathing sources for some decades, covering thousands of hours of intermittent human exposure. Nevertheless, many competent physiologists were convinced that atmospheric nitrogen was essential to mammalian existence. It was necessary to complete a number of experiments in which nitrogen was absent from the respirable atmosphere, to settle this point at an animal level. Following the neglected example of Barach; with sophistication of design parameters and a larger number of animal subjects, a sizable colony of rats was exposed to an atmosphere of 80% helium and 20% oxygen for a period of 16 days, with no adverse physiological effects, immediate or delayed. Thus, a long series of helium-oxygen exposures were commenced.

At first, adhering to original design parameters, and with careful control of environment, rats were exposed to the extreme depth of 200 ft, utilizing an atmosphere of 3% oxygen, 97% helium. All exposures were continuous for a 14-day period; and the protocol of extensive biochemical, physiological, and histopathological examination of all subject animals was maintained rigidly. Subsequently, animal experiments were extended under high pressure to encompass four more species, including goats and squirrel monkeys. After two additional years of successful experimentation, it could be reported that all animals exposed to a selected mixture of helium, oxygen, and lesser quantities of inert gases not only survived a 14-day exposure at a simulated depth of 200 ft.

but could be safely returned to sea level with no physiological damage. Decompression problems and treatment of decompression accidents involved in such an exposure were clarified in a separate series of experiments. After more than four years, the animal exposures were concluded.

In 1962, the Secretary of the Navy granted permission for utilization of human subjects in extension of this project. Shortly thereafter, following a cautious plan, the first set of volunteers was exposed to an essentially nitrogen-free atmosphere, for a total exposure of 144 hours. In this significant experiment, the average composition of the ambient atmosphere was 21.6% O_2, 4.0% N_2, and 74.4% He. Three human volunteers were selected for the exposure. Choice was determined by age, environmental chamber experience, and available physiological information. As in the case of our animal experiments, all parameters of blood chemistries and morphologies were carefully evaluated; in addition, EKG, EEG, metabolic values, and a multitude of psychophysiologic test values were obtained.

In this experiment, all major goals were achieved, and the human subjects completed the exposure with no measurable physiological decrement. Incomplete analysis of the test results, however, indicate a clear-cut stress response, a potential bacteriological problem, and a formidable problem of body temperature control. In addition, there was a persuasive suggestion that the inert gases of man's respirable atmosphere may exert a specific physiological effect on the exposed individual.

Intriguing evidence indicated that the sum total of the effects of a synthetic atmosphere might be advantageous to the human organism. In short, based on early findings, it seemed possible that fresh, sea-level air might not necessarily be the best of all possible atmospheres for human existence.

From data yielded by this experiment, it was possible to proceed to the next phase, requiring human exposure at 100 ft of simulated sea-water depth for a period in excess of six days. This experiment, accomplished in the chamber complexes at the Navy Experimental Diving Unit, involved use of a respirable atmosphere of 7% O_2, 86% He, and 7% N_2. As in the previous phase, a wide range of physiological and psychological values was recorded daily for all subjects. In addition, because of the unusual configuration of the pressure complex, the subjects were able to perform several hours of underwater work at this pressure daily, to simulate conditions of open sea habitation. Critical evaluation of the data from this exposure, when completed, indicated that although no physiological decrement was apparent in the course of the experiment, there were definite problems with respect to body temperature control and vocal communications. The accelerated thermal conductive properties of helium required maintenance of an ambient temperature of 88 F for subjective comfort; and the unique physical properties of the gas combined to distort the human voice, under pressure, beyond ordinary recognition.

Attuned to these problem areas, a final human laboratory exposure was made in August, 1963. Again, three Navy volunteers were utilized, two of whom were veterans of previous experiments. In this exposure, accomplished at the Naval Medical Research Laboratory, the subjects were compressed to an equivalent seawater depth of 200 ft, for a period of approximately 300 hours, with subsequent decompression amounting to 28 hours. The gas provided for this exposure was approximately: 3.5% O_2; 4.5% N_2; 92% He.

In this final experiment, both physiological and psychological test parameters were expanded and sophisticated. In all, approximately 100 items of psychophysiological data were acquired daily from each subject. Repetitive and cumulative matériel failures complicated the operation, and provided a very realistic stress situation with respect to experimenters and subjects alike; nevertheless, the entire run was successfully accomplished, without decompression sequelae. All biochemical, hematological, and other physiological values of subjects remained within normal limits, with exception of the conventional stress indicators, which reflected clearly initial exposure to the hazardous experimental situation, and to subsequent potentially fatal materiel casualties.

The persistent problems of thermal protection and voice communication, however, were definitely intensified in the course of this exposure. In order to maintain a "shirt-sleeve" environment, at 80% relative humidity, an ambient temperature of 91 F was required. Communication, even among the subjects in the chamber, was quite difficult; with outside observers, it was nearly impossible. Bacteriologic studies of fecal and oral samples failed to reveal development of any pathogenic strains, and no significant shifts of bacterial balance were found in any of the subjects during the 12-day exposure. Metabolic studies showed no evidence of alteration in the respiratory quotients of the subjects as a group, and caloric intake was equivalent to that obtained in the base line studies.

This last operation signalled the end of purely laboratory procedures in connection with Project *Genesis I*. As a result of some six years of animal and human studies involving closed ecological systems, elevated pressures, and synthetic atmospheres, the stage has been set for operational application of the work. It would now appear that we can safely station men at any point on the submerged continental shelf, with a reasonable expectancy of useful performance for prolonged periods of time.

It is of interest that a quite fundamental ecological problem has evolved from this sophisticated experiment. Although it is possible, quite accurately, to anticipate the problems of pulmonary function, body biochemistries, and psychomotor reaction under such rigorous and exotic conditions, the basic requirements of body temperature control and voice communications remain unfulfilled. It would seem that, having solved the more esoteric problems of human existence in a closed system, we are still doing poorly in the more primitive areas of animal comfort and basic communication.

What, if any, are the applications of this work to the present problems of occupational medicine? This is best answered with the statement that man, from his first day of life, is destined to exist in a closed ecological system. The atmospheres and other fundamental environmental factors of our world have, within fairly narrow limits, been unchanged for eons of time. To this system, man has successfully adapted over a reasonably long period of time, although environmental contamination may alter this picture in the near future. Today, man is seeking to move and remain in areas which are either above or below his natural milieu; for such activity, a synthetic environment is required. The immediate and certain medical challenge of our era is to provide such an environment for venturesome mankind.

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SEALAB I AND SEALAB II CHRONICLES

These Chronicles represent an unedited rendition of the daily reflections of the Principal Investigator of the Sealab I and II Operations. In retrospect, some of the opinions and judgments herein expressed should perhaps have been modified to spare the sensibilities of some individuals concerned; yet, these were the daily records as I saw them, 24 hours at a time, and I do not elect to change the record of my impressions. Indeed, it is possible that the frank nature of this narrative may contribute to improvement of future undersea operations.

In the course of any underwater venture similar to Sealab I and Sealab II, three written reports should be prepared for each operation. In the first place, it is necessary to prepare a situation report, or SITREP, which is a dispatch of a few words to Washington authorities, outlining all project success and omitting or minimizing unhappy events. Secondly, the daily log of the operation is maintained. This log is a greatly expanded version of the daily SITREP, with a small amount of personal commentary by the watchstander.

The Chronicles, however, are of different caliber and texture. Here, the Principal Investigator records each hour of the day his own personal evaluation of the total scenario. It is a biased account, twisted to meet the needs of the author; but since this same author is the man under the gun, it deserves some credence. For this reason, the Chronicles of Sealab I and Sealab II are presented without abridgement.

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MEDICAL WATCH STANDERS GUIDE FOR SATURATION DIVING

R.B. Cook
C. Van Dyke

1971

Action:
Medical Officers and Technicians

Purpose:
Guidance

Background:
Operational Need for Concise Compilation of Saturation Diving Information

Submitted:
Robert B. Cook, LCDR, M.C., USNR
Craig Van Dyke, LT, M.C., USNR

Approved:
George L. Miller, CAPT, M.C., USN

MEDICAL SATURATION WATCH STANDERS GUIDE

PART I Generally Accepted Statistics

(Since saturation diving is still experimental, the following figures should be changed to keep up with new developments. These figures were obtained from actual operational performance during MK1 D.D.S. Op. Tech. Eval., 1970.)

A. Compression Phase

1. Rate

a. 5 ft/min. or 300 ft/hr. is used frequently especially if the dive is less than 600 ft. and/or shallow and relatively long stops are considered (i.e., 180 ft, 300 ft, etc.)

b. 2 ft/min. for 20 min., then 40 min. rest (i.e., 40 ft/hr.) This is the more conservative rate to avoid compression problems.

2. Gas

a. Air to 14 ft.

b. Helium to depth maintaining pO_2 = 0.3 A. with oxygen.

B. Oxygen Levels

1. Chamber pO_2 generally 0.3 - 0.35 A. However under treatment conditions pO_2 may go up to 0.6 A. without causing alarm.

2. PTC pO_2 generally 0.4 - 0.6 A. (min. 0.3A.)

3. Open circuit pO_2 (i.e., band mask) generally 1.2 - 1.3 A.; range from 0.3 - 1.6 A.

4. Supply to Semi-closed UBA generally 1.2 - 1.3 A.; range 0.6 - 1.6 A.

5. Optimum bag pO_2 about 1.0 A.; range 0.8 - 1.2 A.

a. Generally accepted lower level 0.4 A. with a usual operational cutoff at 0.6 A. (i.e., dive usually terminated if pO_2 falls below 0.6 A.)

b. Level used to cal. sat. excursion tables, 0.4 A.

c. Min. bag level for saturation mode 0.21 A. (theoretical)

d. Min. bag level for surface supply HeO_2 (68/32) = 25%

6. Treatment levels for pO_2 1.7 - 2.8 A.

7. Emergency gas levels 0.21 - 1.6 A.

C. Carbon Dioxide

1. Chamber CO_2 will be less than 1.0% surface equivalent (recommended less than 0.5%)

2. PTC CO_2 will be less than 1.0% surface equivalent (less than 2.0% on recent protocols)

D. Carbon Monoxide will be less than 20 PPM (suggested less than 10 PPM)

E. Humidity will be 30 - 75%.

F. Decompression rate: first 30 ft = 10 ft/hr*
up to 200 ft = 6 ft/hr
200 - 100 ft = 5 ft/hr
100 - 50 ft = 4 ft/hr
50 - 0 ft = 3 ft/hr
rest periods 1400 - 1600; 2400 - 0600

*The initial 10 ft/hr rate is used only if no upward or downward excursions have been made in the previous 24 hours.

G. PTC decompression upwards limited to 20 feet, and divers don't rise above the PTC.

PART II Treatment of Decompression Sickness Occurring During Saturation Diving or Following a Saturation Dive

A. It is generally felt that compression to depth of relief is important in saturation diving, particularly with the first hit. Compression rate is probably not too important except under emergency conditions when the patient is rapidly deteriorating. Hence a rate of 5 ft/min. is used for the first 300 ft. An even slower rate can be started at that point. The important thing is to keep compression problems from clouding the clinical situation. If the patient's status dictates a faster rate (i.e., 10 ft/min up to about 25 ft/min) can be used. One must remember that at these faster rates there will be neuro-muscular changes in the patient. Besides, the chamber will be heated significantly.

The basis of the treatment is breathing a mixture of HeO_2 with a high partial pressure of O_2 (1.7 - 2.8 A., it should not go above 3 A.). The patient and the tender are compressed to the depth of relief. They breathe the high pO_2 mixture following one of three schedules:

1. Breathe 25 min high pO_2; 5 min chamber gas; 25 min high pO_2; 5 min chamber gas, etc. until 2 high pO_2 intervals have been accomplished after relief. Ascent is made at 1 ft/min to either the initial chamber depth or to a stop, whichever is deeper. The first stop is calculated by finding that depth where the partial pressure of the inert gas in the chamber with the chamber pO_2 is the same as the partial pressure of the inert gas at the treatment depth, i.e.:

Depth of stop = depth (treatment) – 33 (pO_{2_T} in A. – pO_{2_C} in A.)

pO_{2_T} = treatment oxygen level in atmospheres
pO_{2_C} = chamber pO_2 (generally 0.3A.)

Ascent from this stop is accomplished at the appropriate saturation decompression rate. The high pO_2 mixture and chamber gas alternate breathing can commence at the outset of compression and should be continued through the decompression phase. The high pO_2 exposure probably should be limited to four hours because of possible pulmonary changes, although alternating the high pO_2 with chamber gas is used to try to minimize this problem. If O_2 toxicity occurs, the high pO_2 mixture is not used.

Often it has been found that compression of 60 ft from chamber depth has been adequate to treat simple decompression sickness. Ascent can be made at 1 ft/min.

The tender breathes the same mixtures as the patient.

2. The Workman Method. Breathe 30 min high pO_2; 30 min chamber gas; 30 min high pO_2; 30 min chamber gas, etc., once the depth of relief has been reached. The first stop is calculated by manipulation of the depth figures. Subtract the original depth+ 30 from the treatment depth and divide this figure by 10. Multiply the dividend by 4. The result of this manipulation is added to the original depth to give a new figure which can be designated D_1. But there is still more to come! Subtract this D_1 from the treatment depth and divide by 10. This dividend is then added to D_1 to give D_2, or the depth of the first stop. Ascent is made at 1 ft/min to D_2 and the alternation of high pO_2 and chamber gas is maintained. At D_2 the appropriate saturation decompression rate resumes with the subject and the tender breathing the chamber gas.

3. After reaching treatment depth, the patient breathes high pO_2 gas for at least two intervals. On completion of the high pO_2 breathing, the chamber recommences decompression either by rising 30 feet and starting the appropriate saturation decompression rate, or by starting the appropriate saturation rate directly from the treatment depth. This is the most conservative and hence safest schedule.

NOTES

B. If the hit occurs at a depth less than 60 ft, one can try the subject on pure O_2 to 60 ft compressing with helium (empirically, however, it has been seen that compression of $\geq$ 60 ft from the depth of the hit is necessary for treatment). Therefore, if relief is not obtained in 20 min at 60 ft, then a suitable HeO_2 mixture must be used and the patient compressed to the depth of relief or to a depth which is at least 60 ft below the level where the hit occurred. At that point the previous equation for the first stop or the Workman Method of calculation should be used. If relief is obtained within 20 min on pure O_2 at 60 ft, then the following protocol can be used: 20 min O_2; 10 min chamber gas; 20 min O_2; 10 min chamber gas. Then ascend on pure O_2 at 1 ft/min to 5 ft below the starting depth where the hit occurred. At this depth the appropriate saturation decompression rate takes over.

If the hit is at a depth less than 60 ft one can also think of using table no. 6, although the use of air is potentially hazardous as gas diffusion characteristics may potentiate the problem.

C. Air Treatment – Although it is not recommended, air treatment has been used successfully in the treatment of decompression sickness occurring during saturation diving on HeO_2. Since air is the breathing medium, it is useful to compress only to 300 ft or less. Its advantages are that the tender and the patient do not have to wear masks, and that it can be used for treating gas embolic phenomena when table no. 4 would be inadequate.

The patient is compressed to the depth of relief. Once at the depth of relief, the patient and tender are kept at depth for 1/2 to 1 hour. The decompression schedule is based on the empirically derived rule that the controlling tissues of the body can safely tolerate an absolute pressure drop of the ratio 1.3 to 1 over a 5 hour interval. This means that each succeeding shallower decompression stop is computed by dividing the diver's absolute depth in feet by 1.3. This is in absolute feet, and to obtain actual feet 33 must be subtracted. The diver is decompressed to the new stop at a continuous rate over the 5 hour period.

In the event the symptoms reoccur during the decompression, recompression is carried out to the depth of relief. The patient remains there for 1 hour and then the same decompression schedule is used. If the recurrence is at a depth less than

60 ft, table no. 6 can be considered.

PART III Formulae and Protocol Formation

A. Master Atmosphere Equation

$$\text{Atmospheres} = \frac{\text{depth} + 33}{33}$$

Emergency Gas % Limits (decimal) $= \dfrac{1.6}{\frac{\text{depth} + 33}{33}} \geq O_2\% \geq \dfrac{0.21}{\frac{\text{depth} + 33}{33}}$

(% obtained by multiplying by 100)

Selection of $O_2\%$ for diver (decimal) for semi-closed UBA $= \dfrac{1.2A}{\frac{\text{depth} + 33}{33}}$

This is for the primary or the umbilical mixture. The depth is the deepest depth of the dive (i.e., excursion depth)

in decimal $O_2\% = \dfrac{2.0A}{\frac{\text{depth} + 33}{33}}$ This is for the O_2 in a bottle as an emergency mode.

Master Bag Level Formula For Semi-Closed UBA

$$B = \frac{MS - C}{M - C}$$

B = inhalation bag level (decimal)
M = flow in L/min
S = $O_2\%$ in supply mixture (decimal)
C = O_2 consumption in L/min

This master bag level formula can be algebraically solved for any of the above variables, i.e.

$$M = \frac{C(1-B)}{S - B}$$

Usually the formula is used to calculate flow rate, and in that case the bag level is known. In saturation diving the bag level must be in percent decimal. This is obtained by solving the following equation:

$$\text{Bag level in \% decimal} = \frac{0.42A}{\frac{\text{depth} + 33}{33}}$$

For the O_2 consumption a value of 3 L/min is used for added safety although it is recognized that an upper limit of 2 L/min is more realistic for moderate work.

Some people solve for M (flow) in two ways and then select the larger value. Namely solving for flow by: (1) utilizing a bag level of 0.21A and an O_2 consumption of 3 L/min; and (2) utilizing a bag level of 0.42A and an O_2 consumption of 2 L/min. This probably gives a better flow rate (M).

Example Protocol Formation Considering MK11 semi-closed UBA.

With proposed depth known (deepest depth) solve for the total atmospheres. Determine the supply mixture by solving for an O_2% *which would give 1.2 - 1.3A at the depth of excursion.* Using this O_2% and an O_2 consumption of 3 L/min solve for the liter flow (M). This will be the liter flow for the bottle emergency mode. The umbilical will be 100 PSI greater. Empirically these calculations have resulted in a bag level in the semi-closed mode with the MK11 using the umbilical supply of 1.0 - 1.2A O_2. Emergency gas %'s are decided with the help of the above equations. Then with the help of the various levels or values given on the preceeding pages, and with a knowledge of the objective of the dive, one can write a protocol. Oriface selection and other technical considerations can be found in the appropriate technical manuals. Abort schedules are found in appropriate EDU reports.

PART IV Excursions

A. UPWARD: The PTC may be decompressed upward an equivalent of 20 ft of inert gas. Obviously the PTC pO_2 is crucial in this regard. For safety sake, a figure of 20 ft maximum upward decompression is generally utilized. Divers do not rise above the PTC. If the PTC has been decompressed 20 ft prior to the exit of the divers, then the divers do not rise above the gas water level in the PTC! Upward as well as downward excursions are taken into consideration when decompression is anticipated within 24 hours.

B. DOWNWARD: See tables 1-A, 1-B, 2, and 3. Repetitive group designator is taken from appropriate table. This designator is then applied to table 2 for the designator after the surface interval. The exact or next greater time is used. This final letter designator is then applied to table 1-A or 1-B to find the residual helium times or the time the excursion diver must consider he has already spent on the bottom when he starts his repetitive excursion.

In the use of these tables time and depth are always exact or next greater value. Ascent rate is 60 ft/min.

A bag level pO_2 of 0.40A has been used for calculating these tables.

TABLE 1-A*

Depth of Excursion from Saturation Exposure	No Decompression Limits (Min.)	Repetitive Group Designation					
		A	B	C	D	E	F
Plus 25 feet		60	150	300	600		
50	270	30	60	100	150	210	270
75	150	20	40	65	90	120	150
100	60	10	20	30	40	50	60

No-Decompression Limit Table, Repetitive Group Designation Table, and Repetitive Excursion Timetable for Excursions from Saturation Exposure at a Depth between 150 Feet and 300 Feet of Seawater Gauge Depth

*See Reference 1.

TABLE 1-B*

Depth of Excursion from Saturation Exposure	No Decompression Limits (Min.)	Repetitive Group Designation					
		A	B	C	D	E	F
Plus 25 feet	–	60	150	300	600		
50	270	30	60	100	150	210	270
75	150	20	40	65	90	120	150
100	100	15	30	45	60	80	100
125	75	10	20	30	45	60	75
150	60	10	20	30	40	50	60

No-Decompression Limit Table, Repetitive Group Designation Table, and Repetitive Excursion Timetable for Excursions from Saturation Exposure at a Depth between 300 Feet and 600 Feet of Seawater Gauge Depth
*See Reference 1.

TABLE 2*

	Repetitive Group at the End of the Habitat Interval (Before Repetitive Excursion)					
Repetitive Group at the Beginning of the Habitat Interval (From Previous Excursion)	F	E	D	C	B	A
F	To 1:00	2:30	4:00	6:30	12:00	24:00
E		1:30	3:00	5:30	10:00	24:00
D			2:00	4:00	8:00	24:00
C				2:30	6:30	24:00
B					4:00	24:00
A						24:00

Habitat Interval Credit Table For Saturation Exposure at a Depth between 150 Feet and 600 Feet of Seawater Gauge Depth
*See Reference 1.

TABLE 3*

Repetitive Group Designation	Feet of Initial Ascent
–	30
A	25
B	20
C	15
D	10
E	5
F	0

Initial ascent table for decompression from saturation-excursion operations

*See Reference 1.

Part V Workman Decompression Calculations

The Workman method is not the only method for calculating tissue tensions and decompression schedules. However, it is useful and examples are given.

A. General: The Workman Method solves the general decay formula in the form:

$$P_2 = P_1 + P_{gradient}\left(1 - e^{-.693t/t\frac{1}{2}}\right)$$

and by utilizing various M values, gives a schedule for decompression. The M values as presented represents the feet of inert gas which is the lower limit necessary to stay at a particular stop. In other words the M value given represents the feet of inert gas which a particular tissue must be equal to or less than to leave the stop.

(new inert gas level – old inert gas level) = inert gas gradient

(inert gas gradient) X (time function) = new inert gas picked up

The time function is the solution for the decay formula knowing the time interval. The time unit (U) is the number of half times of a given tissue in a given time interval. The table of time function vs. the time unit solves the relationship: $F = 1 - \frac{1}{2}^{u}$

Therefore to obtain the time function for exposures longer than 150 minutes (which is covered by the time function table) one must divide the exposure by the tissue half time. This gives the time unit (U). This time unit is then utilized to find the time function with the time unit table.

During and travel (i.e., between stops) the new inert gas level is considered to be the arithmetic mean between the inert gas level at each stop.

Of particular significance for saturation diving is the (M) value given for the 240 minute tissue for helium. This value is 53 feet of helium for the 10 ft stop. In other words this is the maximum amount of helium with which the diver may surface without clinical bubble enucleation. (The M value is the level which the person must have less than in order to leave the stop.) Subtracting atmospheric pressure (33 ft) gives a value of 20 ft of helium. Thus the 240 minute tissue can tolerate a level of helium which is 20 ft more than the hydrostatic pressure. In this case the hydrostatic pressure is 33 feet and the safe helium level is 53 feet.

In general in saturation diving it has been found expedient to calculate gas pickup using the 200 minute tissue and to calculate gas loss using the 240 minute tissue.

B. Practical Examples

1. Table No. 3 represents the feet of initial ascent at the 10 ft/hr rate for decompression after excursion dives. The repetitive group designator after the surface interval is correlated with the distance the complex can be decompressed at the 10 ft/hr rate. It is possible for the medical officer to calculate this by using the Workman Method. The basic idea is to find the level to which the complex can ascend at the 10 ft/hr rate so that in the 240 minute tissue there would be less than a +20 ft differential between the hydrostatic pressure and the inert gas content.

Assume an 800 ft dive with a $pO_2 = 0.3A$; excursion to 850 ft for 60 min. PTC $pO_2 = 0.6A$ and diver $pO_2 = 1.0A$ (always greater than 0.6A). Therefore the original inert gas:

800 ft
+33 ft
833 ft total pressure
−10 ft of O_2
823 ft original inert gas in the tissues

33 ft sea water in one atmosphere
.3 A pO_2
9.9 ft O_2 rounded to 10 ft

At excursion depth:

850 ft
+33 ft
883 ft total pressure
−20 ft O_2
863 ft of inert gas

33 ft of sea water = one atmosphere
.6 A pO_2
19.8 ft O_2 rounded to 20 ft

Time function for 60 min interval with the 200 min tissue (from table) = 0.188. If the interval had been greater than 150 min, one would have had to divide the interval by the half time (in this case by 200 min) to get (U), or the time unit. The time function then could be found from the time unit table.

863 ft new total pressure
−823 ft old tissue pressure
40 ft inert gas gradient

inert gas pickup = (gradient) X (time function)
7.52 ft inert gas = (40 ft) X (0.188)
rounded to 8 ft

823 ft original tissue pressure
+8 ft picked up
831 ft new tissue pressure

Assume 4 hour interval before decompression starts:

831 ft new gas pressure tissue
823 ft inert gas in chamber
8 ft inert gas gradient

$$\text{time unit (U)} = \frac{240 \text{ min (the time interval)}}{240 \text{ min (tissue half time)}}$$

time unit (U) = 1 and from the time unit table
time function = 0.500

gas lost = (gradient) X (time function)
4 ft = (8 ft) X (0.500)
therefore at the start of the decompression the inert gas tension in the tissues (the 240 min tissue) is 831 ft − 4 ft = <u>827 ft</u>
With the 827 ft one could ascend to a level where the

hydrostatic pressure is 20 ft less than this, i.e.,

827 ft
−20 ft
807 absolute feet
−33 ft/atmosphere
774 ft actual depth

Thus one could use the 10 ft/hr rate to 774 feet. Some additional inert gas would be lost during the decompression, but for safety sake, 780 ft could be accepted. This is the same value obtained from Table No. 3.

2. If an excursion dive surpasses the no decompression limits, one can calculate at which depth a stop must be made before getting the divers back to the original saturation depth. Of course the whole complex should be compressed instead and that is the safest move. At any rate one can calculate the depth where the hydrostatic pressure is 20 ft less than the inert gas level in the 240 min tissue. The divers can return to the saturation depth when their 240 min tissue inert gas level is less than the original saturation depth inert gas level plus 53 feet (20 feet + 33 feet). Uptake will be calculated using the 200 min tissue and gas loss will be calculated using the 240 min tissue.

Assume a saturation dive to 800 ft with a $pO_2 = 0.3A$; and an excursion to 900 ft for 150 minutes (no decompression limit = 60 min). PTC $pO_2 = 0.6A$, and diver $pO_2 = 1.0A$.

chamber depth	excursion depth	gradient
800 ft	900 ft	913 ft
+33 ft	+33 ft	823 ft
833 ft	933 ft	+90 ft
−10 ft O_2	−20 ft O_2	
823 ft inert gas	913 ft inert gas	

time function from the table is:
0.405 for the 200 min tissue

inert gas pickup = (gradient) X (TIME FUNCTION)
36 ft inert gas = 90 ft X 0.405

Inert gas level which would allow the diver to return to the saturation depth 800 ft + 33 ft + 20 ft = 853 ft
The new inert gas level, however, is 823 ft + 36 ft = 859 ft.
Therefore the divers must stop. The stop is calculated as that depth which the hydrostatic pressure is 20 ft less than the inert gas level (859 ft − 20 ft = 839 ft). This 839 ft is absolute depth and actual depth is: 839 ft − 33 ft = 806 ft. Therefore the

divers will stop at 810 ft to lose additional inert gas (4 ft added safety factor). It has already been shown that the inert gas level in the 240 minute tissue must be 853 ft or less before the diver can return to the 800 ft saturation depth level.

Travel from 900 ft to 810 ft at 60 ft/min. Time is 1'30". Average inert gas tension is 90 ft divided by 2 = 45 ft (arithmetic mean). 823 ft + 45 ft = 868 ft.

The difference is: 868 ft – 859 ft = 9 ft gradient.

Time function for 200 min tissue for 2 min = 0.007

0.007 X 9 ft = 0.06 ft which is a negligable increment.

To leave the stop must have 853 ft inert gas in 240 min tissue.

Since there is 859 ft, then the diver must lose 6 ft of inert gas.

At the stop (810 ft) the total pressure is 810 ft + 33 ft = 843 ft.

Subtracting the O_2 pressure (which is 0.6A X 33 ft = 20 ft) 843 ft – 20 ft = 823 ft inert gas pressure in the PTC at the 810 ft stop. The gradient is 859 ft – 823 ft = 36 ft of inert gas.

(36 ft) X (time function) = 6 ft Solving for the time function for the 240 min tissue = 6 ft/36 ft = 0.17

From the time function table one finds that this is equivalent to a time interval of 54 minutes. Hence the divers remain at 810 ft for 54 min before ascending at 60 ft/min to mate with the chamber.

Table of Maximum Allowable Tissue Tension (M) of Helium for Various Half-time Tissues*

Depth of Decompression Stop										
D (ft)	10	20	30	40	50	60	70	80	90	100
A (ft)	43	53	63	73	83	93	103	113	123	133
H (min)	(M) (Feet of Sea Water Equivalent)									
5	86	101	116	131	146	161	176	191	206	221
10	74	88	102	116	130	144	158	172	186	200
20	66	79	92	105	118	131	144	157	170	183
40	60	72	84	96	108	120	132	144	156	168
80	56	68	80	92	104	116	128	140	152	164
120	54	66	78	90	102	114	126	138	150	162
160	54	65	76	87	98	109	120	131	142	153
200	53	63	73	83	93	103	113	123	133	143
240	53	63	73	83	93	103	113	123	133	143
ΔM/ Δ10 feet depth										
H (min)	5	10	20	40	80	120	160	200	240	
ΔM (ft)	15	14	13	12	12	12	11	10	10	

*See Reference 2.

TIME FUNCTIONS*

(Percentage Decimal)

For determination of tissue pressure in 5, 10, 20, 40, 80, 120, 160, 200 and 240-minute tissues during exposures up to 150 minutes.

Exposure Time Minutes	Tissue Half Time (Minutes)								
	5	10	20	40	80	120	160	200	240
1	.129	.066	.034	.017	.009	.004	.004	.002	.002
2	.242	.129	.066	.034	.017	.011	.009	.007	.004
3	.340	.187	.098	.050	.026	.017	.013	.011	.009
4	.425	.242	.129	.066	.034	.022	.017	.014	.011
5	.500	.293	.158	.083	.042	.028	.022	.018	.014
6	.564	.340	.187	.098	.050	.034	.025	.021	.017
7	.621	.384	.215	.114	.059	.039	.030	.024	.020
8	.669	.425	.242	.129	.067	.045	.034	.027	.022
9	.712	.463	.268	.144	.075	.050	.037	.031	.025
10	.750	.500	.293	.158	.083	.055	.042	.034	.028
11	.782	.533	.317	.173	.091	.061	.045	.038	.031
12	.811	.564	.340	.187	.099	.066	.050	.041	.034
13	.835	.593	.362	.201	.107	.072	.055	.044	.036
14	.857	.621	.384	.215	.114	.078	.059	.047	.039
15	.875	.646	.405	.229	.122	.083	.063	.051	.042
16	.892	.669	.425	.242	.129	.088	.067	.054	.045
17	.906	.692	.445	.254	.137	.093	.071	.057	.047
18	.918	.712	.463	.268	.144	.096	.074	.061	.050
19	.927	.732	.482	.280	.152	.103	.078	.064	.053
20	.937	.750	.500	.293	.158	.108	.084	.067	.055
21	.945	.766	.516	.304	.165	.114	.087	.070	.059
22	.953	.782	.533	.317	.173	.119	.090	.073	.061
23	.959	.797	.548	.328	.181	.124	.094	.077	.064
24	.963	.811	.564	.340	.187	.129	.099	.081	.066
25	.967	.824	.579	.351	.196	.134	.102	.083	.069
26	.972	.835	.593	.362	.201	.139	.107	.086	.072
27	.977	.847	.607	.373	.209	.142	.110	.089	.075
28	.980	.857	.621	.384	.215	.149	.114	.092	.078
29	.982	.866	.633	.395	.222	.154	.118	.096	.081
30	.985	.875	.646	.405	.229	.158	.122	.099	.083
31		.884	.657	.415	.235	.162	.125	.102	.085
32		.892	.669	.425	.242	.168	.129	.105	.088
33		.899	.681	.425	.249	.173	.132	.108	.090
34		.906	.692	.445	.255	.178	.137	.111	.093
35		.912	.702	.454	.262	.183	.141	.114	.096
36		.918	.712	.463	.268	.187	.144	.117	.098
37		.922	.722	.473	.275	.192	.148	.120	.101
38		.927	.732	.482	.280	.197	.151	.123	.103
39		.932	.741	.491	.287	.201	.154	.126	.106
40		.937	.750	.500	.293	.206	.159	.129	.108
41		.941	.758	.508	.299	.210	.162	.133	.111
42		.945	.766	.516	.304	.215	.166	.136	.114
43		.949	.774	.525	.311	.219	.169	.139	.116
44		.953	.782	.533	.317	.224	.173	.141	.119
45		.956	.790	.541	.323	.228	.177	.144	.121
46		.959	.797	.548	.328	.233	.180	.147	.124
47		.960	.804	.556	.335	.237	.184	.150	.126
48		.963	.811	.564	.340	.242	.188	.153	.129
49		.965	.817	.572	.346	.248	.192	.156	.131
50		.967	.824	.579	.351	.250	.195	.159	.134
51		.970	.830	.586	.357	.255	.198	.162	.137
52		.972	.835	.593	.362	.259	.201	.165	.139
53		.974	.841	.600	.369	.264	.205	.168	.141
54		.977	.847	.607	.373	.268	.208	.171	.143
55		.978	.852	.614	.379	.272	.211	.174	.146
56		.980	.857	.621	.384	.277	.215	.176	.149
57		.981	.862	.627	.390	.281	.218	.179	.151
58		.982	.866	.633	.395	.285	.222	.182	.154
59		.984	.873	.639	.400	.289	.226	.185	.156
60		.985	.874	.646	.405	.293	.229	.188	.159
61			.880	.652	.411	.297	.233	.191	.161
62			.884	.657	.415	.300	.235	.193	.164
63			.888	.664	.421	.304	.238	.196	.166
64			.892	.669	.425	.309	.242	.199	.169
65			.895	.675	.431	.313	.244	.201	.171
66			.899	.681	.435	.317	.248	.204	.173
67			.902	.686	.440	.321	.251	.207	.175
68			.906	.692	.445	.324	.255	.210	.178
69			.909	.697	.450	.328	.259	.213	.180
70			.912	.702	.455	.332	.262	.215	.183
71			.915	.707	.459	.336	.264	.218	.185
72			.918	.712	.464	.340	.268	.221	.187
73			.920	.717	.469	.342	.271	.224	.190
74			.922	.722	.473	.347	.274	.226	.192
75			.925	.727	.478	.352	.278	.229	.194

Exposure Time Minutes	Tissue Half Time (Minutes)						
	20	40	80	120	160	200	240
76	.927	.732	.482	.354	.280	.232	.197
77	.930	.736	.487	.359	.284	.235	.199
78	.932	.741	.491	.362	.287	.237	.201
79	.934	.745	.495	.368	.289	.240	.203
80	.937	.750	.500	.373	.293	.242	.206
81	.939	.754	.505	.374	.296	.245	.208
82	.941	.758	.508	.377	.299	.247	.210
83	.943	.763	.512	.381	.302	.250	.212
84	.945	.766	.516	.384	.305	.253	.215
85	.947	.770	.521	.387	.308	.256	.217
86	.949	.774	.524	.391	.310	.258	.219
87	.951	.778	.528	.395	.313	.261	.222
88	.953	.782	.533	.399	.317	.263	.224
89	.955	.786	.537	.402	.319	.266	.226
90	.956	.790	.541	.405	.323	.268	.228
91	.957	.794	.545	.408	.325	.271	.231
92	.959	.797	.550	.411	.328	.273	.233
93	.959	.797	.554	.415	.332	.275	.235
94	.960	.804	.557	.419	.334	.278	.237
95	.962	.807	.561	.423	.337	.281	.239
96	.963	.811	.565	.425	.340	.283	.242
97	.964	.814	.569	.428	.342	.285	.245
98	.965	.817	.573	.431	.346	.288	.248
99	.966	.820	.576	.435	.348	.291	.249
100	.967	.824	.580	.439	.352	.293	.250
101	.968	.826	.584	.442	.355	.295	.253
102	.970	.830	.587	.445	.357	.298	.255
103	.971	.832	.591	.448	.359	.301	.257
104	.972	.835	.594	.451	.363	.303	.259
105	.973	.838	.597	.455	.365	.305	.262
106	.974	.841	.601	.458	.368	.307	.264
107	.976	.844	.605	.461	.371	.310	.266
108	.977	.847	.608	.463	.374	.312	.268
109	.977	.849	.611	.466	.377	.314	.270
110	.978	.852	.615	.469	.379	.317	.272
111	.979	.854	.618	.472	.381	.320	.274
112	.980	.857	.622	.476	.384	.322	.277
113	.980	.859	.625	.479	.386	.324	.279
114	.981	.862	.628	.482	.390	.326	.281
115	.982	.864	.631	.484	.393	.329	.283
116	.982	.866	.634	.487	.395	.331	.285
117	.983	.868	.637	.491	.398	.333	.287
118	.984	.870	.640	.494	.400	.336	.289
119	.984	.873	.644	.497	.403	.338	.291
120	.985	.875	.647	.500	.405	.340	.293
121		.877	.650	.503	.407	.343	.295
122		.880	.653	.506	.411	.345	.297
123		.882	.656	.509	.413	.347	.299
124		.884	.659	.512	.416	.349	.300
125		.886	.662	.515	.418	.351	.302
126		.888	.665	.517	.421	.354	.304
127		.890	.668	.520	.424	.356	.306
128		.892	.670	.523	.426	.358	.309
129		.894	.673	.525	.428	.361	.311
130		.895	.676	.528	.431	.363	.313
131		.898	.679	.531	.433	.365	.315
132		.899	.682	.533	.436	.367	.317
133		.900	.685	.536	.438	.370	.319
134		.902	.687	.539	.440	.372	.321
135		.904	.690	.542	.443	.374	.323
136		.906	.693	.545	.445	.376	.324
137		.908	.695	.547	.447	.378	.326
138		.909	.698	.550	.450	.380	.329
139		.910	.701	.552	.452	.382	.330
140		.912	.703	.555	.455	.384	.332
141		.913	.705	.557	.457	.387	.334
142		.915	.708	.560	.459	.389	.336
143		.916	.711	.562	.462	.391	.338
144		.918	.713	.565	.464	.393	.340
145		.919	.715	.567	.466	.395	.342
146		.920	.718	.570	.469	.397	.344
147		.920	.720	.572	.471	.399	.346
148		.922	.723	.575	.474	.401	.347
149		.924	.725	.577	.476	.403	.349
150		.925	.728	.580	.478	.405	.352

*See Reference 2.

TIME UNIT (Second decimal place)

TIME UNIT (Integer and one decimal place)

TIME FUNCTION (Three decimal places)

	0	1	2	3	4	5	6	7	8	9
0.0	——	.007	.014	.021	.027	.034	.041	.047	.054	.061
0.1	.067	.073	.081	.086	.092	.099	.105	.111	.117	.123
0.2	.129	.136	.141	.147	.153	.159	.165	.171	.176	.182
0.3	.188	.193	.199	.204	.210	.215	.221	.226	.232	.237
0.4	.242	.247	.253	.258	.263	.268	.273	.278	.283	.288
0.5	.293	.298	.303	.307	.312	.317	.322	.326	.331	.336
0.6	.340	.345	.349	.354	.358	.363	.367	.372	.376	.380
0.7	.384	.389	.393	.397	.401	.405	.410	.414	.418	.422
0.8	.426	.430	.434	.438	.441	.445	.449	.453	.457	.460
0.9	.464	.468	.472	.475	.479	.482	.486	.490	.493	.496
1.0	.500	.503	.507	.510	.514	.517	.520	.524	.527	.530
1.1	.533	.537	.540	.543	.546	.549	.553	.556	.559	.562
1.2	.565	.568	.571	.574	.577	.580	.583	.585	.588	.591
1.3	.594	.597	.600	.602	.605	.608	.610	.613	.616	.618
1.4	.621	.624	.626	.629	.632	.634	.637	.639	.642	.644
1.5	.646	.649	.651	.654	.656	.659	.661	.663	.666	.668
1.6	.670	.672	.675	.677	.679	.681	.684	.686	.688	.690
1.7	.692	.694	.697	.699	.701	.703	.705	.707	.709	.711
1.8	.713	.715	.717	.719	.721	.723	.725	.726	.728	.730
1.9	.732	.734	.736	.738	.739	.741	.743	.745	.747	.748
2.0	.750	.752	.754	.755	.757	.759	.760	.762	.764	.765
2.1	.767	.768	.770	.772	.773	.775	.776	.778	.779	.781
2.2	.782	.784	.785	.787	.788	.790	.791	.793	.794	.796
2.3	.797	.798	.800	.801	.803	.804	.805	.807	.808	.809
2.4	.811	.812	.813	.815	.816	.817	.818	.820	.821	.822
2.5	.823	.824	.826	.827	.828	.829	.830	.833	.833	.834
2.6	.835	.836	.837	.839	.840	.841	.842	.843	.844	.845
2.7	.846	.847	.848	.849	.850	.851	.852	.853	.854	.855
2.8	.856	.857	.858	.859	.860	.861	.862	.863	.864	.865
2.9	.866	.867	.868	.869	.870	.871	.872	.872	.873	.874
3.0	.875	.876	.877	.878	.878	.879	.880	.881	.882	.883
3.1	.883	.884	.885	.886	.887	.887	.888	.889	.890	.890
3.2	.891	.892	.893	.893	.894	.895	.896	.896	.897	.898
3.3	.899	.899	.900	.901	.901	.902	.903	.903	.904	.905
3.4	.905	.906	.907	.907	.908	.909	.909	.910	.910	.911
3.5	.912	.912	.913	.913	.914	.915	.915	.916	.916	.917
3.6	.918	.918	.919	.919	.920	.920	.921	.921	.922	.923
3.7	.923	.924	.925	.925	.925	.926	.926	.927	.927	.928
3.8	.928	.929	.929	.930	.930	.931	.931	.932	.932	.933
3.9	.933	.934	.934	.934	.935	.935	.936	.936	.937	.937
4.0	.938	.938	.938	.939	.939	.940	.940	.941	.941	.941
4.1	.942	.942	.943	.943	.943	.944	.944	.944	.945	.945
4.2	.946	.946	.946	.947	.947	.947	.948	.948	.949	.949
4.3	.949	.950	.950	.950	.951	.951	.951	.952	.952	.953
4.4	.953	.953	.953	.954	.954	.954	.955	.955	.955	.956
4.5	.956	.956	.957	.957	.957	.957	.958	.958	.958	.959
4.6	.959	.959	.959	.960	.960	.960	.960	.961	.961	.961
4.7	.962	.962	.962	.962	.963	.963	.963	.963	.964	.964
4.8	.964	.964	.965	.965	.965	.965	.966	.966	.966	.966
4.9	.967	.967	.976	.976	.967	.968	.968	.968	.968	.969
5.0	.969	.969	.969	.969	.970	.970	.970	.970	.970	.971
5.1	.971	.971	.971	.971	.972	.972	.972	.972	.972	.973
5.2	.973	.973	.973	.973	.974	.974	.974	.974	.974	.974
5.3	.975	.975	.975	.975	.975	.976	.976	.976	.976	.976
5.4	.976	.977	.977	.977	.977	.977	.977	.977	.978	.978
5.5	.978	.978	.978	.978	.979	.979	.979	.979	.979	.979
5.6	.979	.980	.980	.980	.980	.980	.980	.980	.981	.981
5.7	.981	.981	.981	.981	.981	.981	.982	.982	.982	.982
5.8	.982	.982	.982	.982	.983	.983	.983	.983	.983	.983
5.9	.983	.983	.984	.984	.984	.984	.984	.984	.984	.984

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NATIONAL GEOGRAPHIC

At Home in the Sea

Pioneering a new underwater world for man, French oceanauts live for a month in a submerged colony on a Red Sea reef

By CAPT. JACQUES-YVES COUSTEAU

I AM FINISHING an enjoyable meal with my wife Simone and a tableful of good companions in a snug lodge we have built in a remote and primitive part of the world.

No one has lived in such a place before. In a corner of our bright, pentagonal *salon* there is a large electronic console that looks like a spaceship control center. Four rooms radiate from ours in a design suggesting the name of our lodge—Starfish House.

One arm contains the kitchen and laboratory, from which the chef is passing us fruit, cheese, and coffee. I light one of my reeking Tuscan cigars and look out the windows at a black, virgin wilderness where moving phantasms barely suggest themselves, and where lights that are not lights softly gleam.

"Commandant, regardez," says the man at the console. He turns off the inside lights, then flicks on powerful lamps outside. In a magical transformation, our windows turn into treasure chests lined in zenith blue—the blue of the undersea world. Jewel trays drift slowly past in a half-knot current. There are tiny crustaceans, larval jellyfish, swimming worms, and many-faceted hatchetfish that have migrated from the abyss to dazzle our eyes. Beyond is a somber, shifting tapestry of big pelagic fish, the far-riding predators. They strike singly into the little ones, snap them up, and speed back to the shadows.

A thick school of sardinellas prances into view. We watch, spellbound, as they execute in unison a dance as precise as that of the Rockettes, then vanish as if the stage had fallen in.

We are in Continental Shelf Station

equipment, and at a far more remote site.

The control panel in the corner is actually the command center of the entire Conshelf Two expedition. Its operator has a three-camera closed television circuit, intercom, ultrasonic underwater wireless, and telephone. He issues instructions not only to the station but to the ships overhead. Forty-five men, above and below, follow these directions.

The controller also communicates with a strange building near Starfish House, an onion-shaped dome on stilts. It is the hangar of our two-man hydro-jet submarine, the diving saucer *DS-2*, which voyages a thousand feet down from its submerged shelter—the first submarine vessel to operate from a base on the ocean floor (page 502).*

The underside of *DS-2*'s hangar is open to the water so that the saucer pops up into the air inside, to be hoisted into the dry by an electric winch, discharge her crew, and receive maintenance and battery recharges. Like Starfish House, the hangar is filled by a hose from *Rosaldo* with air compressed to 30 pounds per square inch, slightly more than double atmospheric pressure, to equal that of the surrounding water.

Simone and I get up from the table and have a look at the console. The gas-analysis indicators show that our air is pure. So is the atmosphere of helium and air in our Deep Cabin, a rocket-shaped underwater chamber 90 feet down on the reef below, where two men will presently attempt to live and work for a week without surfacing (pages 500-501). We check meters showing direction and velocity of the current outside. The temperature in Starfish House reads 27° centigrade (80.6° F.), and the humidity is 85 percent.

Undersea Scientists Go for a "Stroll"

The 38-year-old director of the undersea station, Prof. Raymond Vaissière, chief of the biological division of the Oceanographic Museum at Monaco, asks us, "Care to join our evening promenade?"

The men go to one of the branching wings of Starfish House to don their gear.

When the professor is dressed for his "stroll"—part of the scientific program that requires our oceanauts to spend several hours a day in the open water outside the station—he pauses at the console and starts a clock next to his name on the personnel roster. Each name has a clock that records the time a man spends outside in the water.

The next man to clock out is a sprightly 30-year-old, Claude Wesly, chief diver of Conshelf Two. He is called *"l'ancien,"* the veteran, because he was one of the two occupants of Conshelf One.

André Folco, 33, starts his clock. He is a slender, handsome industrial designer with a calm, restrained personality, which is helpful in unprecedented living conditions like these. The fourth man in the night-diving party is Pierre Vannoni, 31, a former customs inspector with literary tastes.

Simone, only a temporary visitor like myself, comes out of a bedroom in her foam-rubber diving tunic, designed as a gift for her by a fashionable Paris couturier. She shoulders her lady-sized Aqua-Lung.

"Coming?" she asks.

"Later," I reply. "I am going to join Falco in the hangar." Albert Falco, not to be confused with André Folco, is the saucer's pilot.

Handouts Win Chef a Devoted Friend

There is no door in the foyer from which the diving party is to depart. Wesly steps over to a circular blue section of the deck—and descends into it. It is open water, the sea itself, held down by internal air pressure. One by one the divers disappear through the open sea hatch.

The fifth man in the permanent underwater party stays inside with me and clears the table. He is our bearded chef, Pierre "Pierrot" Guilbert, 43. Pierrot is veritably the morale officer of this village beneath the sea. His cuisine bolsters the others, and he inspires himself with a grand collection of photos of his wife, two children, parents, relatives, and friends tacked over his bunk.

Pierrot taps on the window with his signet ring. A large triggerfish appears in the window, eyes him (page 485), and disappears. Pierrot moves to the sea hatch and holds some food scraps above the water. The triggerfish sticks its head up and grabs the offering.

Pierrot made friends with the fish when he first arrived. The trigger lives 100 feet away in a recess of the reef. It quickly recognized Pierrot as the dispenser of free lunch and associated only with him. Let another man rap on the window, the fish will come, but, recognizing an impostor, will at once go back home. When Pierrot is out swimming

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*Captain Cousteau described his first undersea saucer explorations in "Diving Saucer Takes to the Deep," NATIONAL GEOGRAPHIC, April, 1960.

with three or four other men dressed in identical head-to-foot suits, their features completely hidden by masks, helmets, and mouthpieces, the triggerfish will unerringly come to the cook.

I go to the console and call, on the intercom: "Starfish to Saucer Hangar. Over."

Falco answers, "Davso and I are checking the batteries on the diving saucer." Armand Davso, the saucer's chief mechanic, has dived from *Calypso* to join Falco.

I reply, "I'm coming over." I shoulder an Aqua-Lung and go down the ladder into water that feels like warm silk. Starfish House stands seven feet above the coral sand on five stilts. Steel bars that surround the ladder protect us against sneak shark attack when entering or departing (pages 481 and 487).

I swim toward the lighted ports in the yellow onion dome. Down the reef I see the flashlights of the professor and the night prowlers.

Man Who Works Magic in the Depths

I swim under the tripod legs of the diving saucer hangar and play my flashlight up into the big hatch. My distorted reflection ripples in a mirrorlike effect on the tissue of air and water above (page 503). It looks exactly like an inverted swimming pool into which I am diving upside down in slow motion. My mask breaks through to the air. The saucer is above me, and Falco and Davso are standing on the walkway, sweating over the battery boxes.

Sturdy, quiet Albert Falco, 35, besides being the pilot of the diving saucer, is diving chief of Calypso Oceanographic Expeditions—and an underwater magician. Time after time in this hazardous business of establishing an undersea village and making it work, it is a decisive act by Falco that saves the day. Without seeking power, he has become the indispensable man of Conshelf Two.

Falco's 20 years as a free diver and his week below with Wesly in Conshelf One are ancestral lore to people in Starfish House; his more than a hundred depth cruises in *DS-2* make him the most experienced scientific submariner in the world. Yet Falco is wholly unambitious. He is content with plain, hard living, and is never so happy as when he is roaming around the bottom studying things with no particular object in mind.

My own job in Conshelf Two is as over-all supervisor of the expedition, with Commandant Jean Alinat as my alternate. Our ship operations are conducted by Capt. Christian Perrien, marine superintendent of our five-vessel research flotilla. And my old comrade Frédéric Dumas is topside with me as expert adviser. Prof. Jacques Chouteau heads the medical staff of the effort.

What is the purpose of the Continental Shelf Station? To begin with, I have long felt that undersea exploration is not an end in itself. It must lead to scientific research, to prospecting for wealth, and to greater utilization of the oceans. Finally, it must lead to human occupation of the sea floor—not only for the brief moments man has known before, but for days, weeks, even months at a time. Life is short: I wanted to hasten these processes of exploration, of prospecting and occupation, push them together, and establish a working, manned undersea station in the richest and most accessible region of the ocean—the continental shelf.

Coastal Shelves Equal Area of Africa

The continental shelf is the submerged portion of the land mass before it assumes oceanic characteristics in the continental slope and the abyss. Most nations consider the offshore contour line where the depth is 600 feet to be the boundary of the continental shelf, and many nations have proclaimed their submerged littoral as sovereign territory. The total area of the world's continental shelves is equal to that of all Africa.

There are many economic reasons for colonizing the continental shelf. The shoal waters of the world are rapidly acquiring offshore wells of oil, natural gas, and liquid sulphur. Troves of fine gem diamonds are being dredged from the South African continental shelf. Manganese nodules in almost pure state litter some ocean bottoms. Undersea fish farms, analogous to stock ranches on land, are now challenging man's imagination.

Theories for sea-bottom stations have existed for half a century. Prof. John Scott Haldane and the British Admiralty Deep-water Diving Committee established in 1907 that man can live in twice the density of the atmosphere for a long period and be decompressed rapidly without danger. Recently, Capt. George F. Bond, a United States Navy surgeon, drew up detailed plans.

In fact, pressure has no direct effect on human tissue short of a hundred atmospheres, such as occurs at depths of more than 3,000 feet in the sea. The only known handicap in extreme pressure would be respiratory fatigue. In 1962 we demonstrated in Conshelf One that lung fatigue was hardly a factor for two men living for a week in two atmospheres of pressure.*

Conshelf Two was not only planned to deploy more men for a longer stay in two atmospheres of pressure, but to leap forward by placing two men for a whole week in a Deep Cabin at a depth of 90 feet. To alleviate the strain on their lungs by air compressed to nearly four atmospheres, we planned to furnish them with a mixture of air and the second lightest gas, helium.

It is theoretically possible to push the working station down to 660 feet by using a mixture of the lightest gas, hydrogen, with a smaller amount of oxygen. Our long-range Conshelf plan is to do exactly that (page 469).

These manned stations exist only to permit men to work in the open water much longer and deeper than they can in surface-to-surface dives. Indeed, the shelf station does away with tedious and time-wasting decompression. If they live underwater, divers no longer need to decompress; they simply finish their work and return directly to the undersea billet. Only when they leave the undersea world altogether must they decompress.

We chose to plant Conshelf Two in the inhospitable Red Sea because it was far away, hot, and hard to supply. If we could build and maintain a sea-bottom station there, we could do it almost anyplace in the world.

To select the site, Albert Falco made launch cruises out of Port Sudan, diving for nearly a month on the reefs along an 80-mile front. He searched for fairly level ledges at the proper depths for the main station and the Deep Cabin on the landward, more sheltered side of the reefs, with good anchorage for the floating base, *Rosaldo*, and a reasonable distance from port for *Calypso*'s supply runs.

Falco selected Sha'ab Rūmi, a reef 25 miles northeast of Port Sudan. It was actually a spindle-shaped coral lagoon lying outside the two main reef chains in the western Red Sea. Why it had been named the "Roman Reef," nobody in Port Sudan could tell us.

The four structures in our undersea hamlet were prefabricated of steel in Nice by the Perona metal works and taken out to Port Sudan in *Rosaldo*. We assembled them on the waterfront with the aid of Sudanese workers.

Three of the submersible buildings—Starfish House, the Deep Cabin, and the Saucer Hangar—were designed by Jean Alinat to stand on telescopic legs. The legs could be adjusted to give us dead-level openings for the bottom hatches that would remain open to the water. Only the "wet" tool shed—a chamber open to the sea where we stored fish traps and other equipment—had no telescopic legs (page 488). We brought along 200 tons of lead pigs to sink the village.

On the blistering waterfront at Port Sudan we struggled to float the buildings and ballast them for the 25-mile tow to Sha'ab Rūmi.

Building an undersea village may sound romantic, but the job itself was anything but glamorous. To begin with, we had to clear off humps of compacted sand and coral knobs to level the site for Starfish House and the Saucer Hangar (page 483). It was like breaking ground for a housing development ashore. We improvised a sort of plow, drawn by a rope which passed through a block made fast to the reef and ran up to a winch on *Calypso*'s afterdeck. It took two days to level the lot.

Mooring Sea Blimps in a Gale

Placing the houses in the hamlet with a half-knot current running was somewhat like trying to tie down so many blimps in a gale. Our big steel bubbles were defiantly buoyant. They had to be sunk on an even keel to avoid flooding inside installations. This meant juggling tons of lead ballast.

In addition, one of our critical calculations for Starfish House was wrong. It needed 100 tons of lead, but the available ballast space under the floor would take only 80 tons. We had to build a 10-foot-wide rack on Starfish to hold the 20 extra tons of lead. We groaned and sweated through a day of suspense while sinking the main house, until finally it rested triumphantly on its telescopic stilts.

Then we lowered the hangar for *DS-2*. There was a crunching and a boil of bubbles as one of the legs gave way. The dome tilted over, and all three legs collapsed. It took four days of unremitting labor to unload ballast, take off legs, repair them, and restore the hangar to even keel.

During the whole expedition we all lost weight. My share was almost 20 pounds. Occasionally a man would faint at his job, for there was no air conditioning on either *Calypso* or *Rosaldo;* we were dedicating our only air conditioner to Starfish House.

Accidents seemed almost part of the daily routine. Many were so nearly fatal, I wonder what dispensation we had. For example, take the accidents to the Deep Cabin. At its proper depth—90 feet—the only feasible perch on the reef was about a yard square, not large enough for its tripod legs. We had to anchor it and reinforce it with a mooring cable to a section of the reef above it to ensure the cabin against sinking. When this difficult lash-up was finished, the mooring pulled out and the cabin sank. We fished it up from 140 feet, with marvelous work by Bosun Maurice Léandri on *Calypso*'s hydraulic crane. The cabin sank several more times. Let me tell about just one of the sinkings.

Whenever the cabin took off, it ripped out electrical, television, phone, and instrument cables. It would have taken weeks to hoist the rocket out of the water each time and repair it.

After one such misfortune our electricians, Jacques Roux and Pierre Servelo, volunteered to do the job underwater. Servelo was diving for the second time in his life. The uppermost of the cabin's two compartments was still dry, and they could work there. A highly experienced diver, Raymond Coll, went down with them to do some outside repairs.

Roux and Servelo crawled up to the "nose room" and reconnected the phone to Starfish House. Just then Deep Cabin began to rock. It rumbled. With a snarl of bubbles, it began sliding down the steep slope of the reef, with two men trapped in the nose and Coll outside, entangled in a storage rack.

Servelo yelled over the wire to Starfish House: "What is happening?"

The controller relayed the distress call to *Calypso.* Commandant Alinat said, "I'm coming down." Then the phone line ripped out.

During the sinking, Roux scuttled down to the bottom hatch, thinking that Servelo was following. He dived clear, watching with horror as the cabin thudded on down the reef with one of his messmates inside and the other carried along, struggling, on the outside. The reef face fell off for 1,000 feet. Luckily, the Deep Cabin struck a ledge 140 feet down and came to a stop, leaning against the reef.

Men Escape From Near Death

Coll was pinned outside. Inside, Servelo felt the chamber settle and composed himself. Water had flooded up through the lower room, but the upper room was only a quarter filled. He had a pocket of air, he still had his Aqua-Lung, and he reposed a world of confidence in the last words he had heard on the phone, Alinat's "I'm coming down."

Servelo heard banging and scuffling outside; Coll's Aqua-Lung was clamped to the reef by the steel cabin. He was cutting away his diving harness.

Coll could not work one of his flippers loose, so he pulled his foot out of it. He took a last lungful of air, abandoned his Aqua-Lung, and started a free ascent of 140 feet. Alinat and Falco came stroking down toward the sunken cabin and passed a nonchalant character with no breathing gear and one fin who was rising slowly with distended cheeks, blowing a bead of bubbles from his pursed lips. Coll was gradually lowering the pressure in his lungs as he passed through progressively lower water pressure. To have retained more pressure inside than that outside would have fatally ruptured his lungs.

Coll arrived on the surface unhurt but tired. Alinat and Falco went on to the cabin and conducted young Servelo up to safety.

Divers Hold Off Army of Sharks

In previous expeditions to the Red Sea we had gained considerable respect for its sharks, and this time came prepared to coexist with them. Coexistence began even before we arrived at the Roman Reef. In the Gulf of Aden we stopped to dive on Arab Shoal, an interesting rock reef near the Gulf of Tadjoura off French Somaliland.

We launched the two-man diving saucer to reconnoiter, and the little submarine was picked up and escorted closely by about 30 large and bold sharks. Pierre Goupil, our cinematographer, and his three teammates dived at night to get some footage, with the antishark cage along just in case.

At a depth of 100 feet the floodlamps held by Raymond Coll and Christian Bonnici picked up the glittering eyes of a dozen big sharks. As Goupil and his assistant Gilbert Duhalde prepared to film them, the pack circled our team, moving in and growing in numbers until there were maybe 70 sharks.

Now Goupil was confronted with a fateful decision: The antishark cage would hold only three men, and the fourth man might well be taken by the sharks. Goupil rang the alarm to have the cage raised, then grabbed his assistant, who was the least experienced diver, and shoved him inside. Then he, Coll, and Bonnici got on top of the cage and sat back-to-back, facing all angles of attack.

The sharks broke their circle and flew at the men head on, confident as wolves of their superior numbers. The divers struck back with cameras, lights, and shark billies as we winched them up. The cage broke water. The men were unhurt. The frustrated killers thrashed on the surface in a frenzy.

Goupil wanted to film the diving saucer in the middle of the maddened pack. So we rigged two powerful floodlights on the front of the anti-shark cage, and he and Daniel Tomasi, the still photographer, went down in it, while Falco and I took the diving saucer down through the sharks.

Falco and I hovered near the cage at 80 feet. We were astonished to see Goupil and Tomasi suddenly abandon their cameras and dance crazily, slapping their ankles and leaping. Around them, picked out in the lights, innumerable white dots were swirling, like gnats around a lawn lamp in summer.

The cage was quickly hoisted out of our sight, apparently in answer to the alarm bell from Goupil. Falco and I later emerged from the submarine to find *Calypso*'s work deck slippery with blood and the cameramen laid up with bandaged ankles. To my knowledge this was the first instance of bloodshed from attacks by "sea mosquitoes," agile planktonic crustaceans, probably isopods, as vicious for their size as the fearsome piranhas.

Goupil and Tomasi had been entirely protected by their diving suits—except for their ankles. On the way up, they had swatted away at the little monsters as the sharks followed. Léandri, on the crane, stopped the cage ten feet from the surface for the obligatory five-minute decompression stop. During the halt, said Goupil, "I was suffering such tortures from the mosquitoes that I felt like opening the door and going out in the middle of the sharks."

Although we set up our antishark cages at Sha'ab Rūmi, we saw few sharks there. Throughout our stay, we had to swim well out of sight of the station to see one. Apparently the sharks were equally impressed by us. And that is the way I hope it remains.

Silver Suits Mark Undersea Exiles

After weeks of aggravations, setbacks, and galling labor in steaming weather, Continental Shelf Station Number Two was finally ready for human occupancy.

The five oceanauts dressed for departure. I talked with them on the diving deck. They were dressed in flexible diving suits of gleaming silver, actually aluminized nylon-neoprene. The romantic armor had practical origins. Reflecting fabric could be seen farther at night, and it was vital that any of these five be instantly distinguished from the dozen or so black-suited servant divers and technicians who would be working with them.

The silver livery of the oceanaut was a sort of convict suit—the wearers were sentenced to one month in a watery dungeon and could come to the surface only at peril of their lives. During their prolonged stay in two atmospheres, including lengthy dives down to pressures of three and a half atmospheres, the silver men would become heavily saturated with nitrogen and could not rise into lighter pressures without decompressing, lest the gas bubble into their blood streams and kill or cripple them with embolisms.

The rest of us, wearing black diving dress, must always watch the silver oceanauts and never let one of them accidentally drift above the sunken village, possibly to his death.

At the end of a month, we planned to administer to the oceanauts a mixture of gases containing the minimum amount of nitrogen permissible, so as to lower the nitrogen saturation of their bodies and to allow them to swim nonstop to the surface. In case of an emergency, we were equipped to take a man immediately to the surface in a pressurized can and transfer him under pressure to a decompression chamber on *Rosaldo.*

The five men standing in front of me, sweating in their silver suits in the tormenting Red Sea sun, were not exceptional physical specimens. For Conshelf One I had picked two crack divers in top physical condition, but for this longer and more grueling trial in debilitating heat and humidity, I chose five unexceptional men. They averaged more than 35 years of age. Two were not very experienced divers. All were married, with a total of six children. One was pudgy and had minor arteriosclerosis. The only thing out of the ordinary about the oceanauts was loyalty to one another as Calypsonians and pride in being selected for Conshelf Two.

The second day that our contingent was living in Starfish House, I went down for dinner. Davso was still rigging the air conditioner, but even without it, the undersea house was noticeably more comfortable than *Calypso.* After coffee Professor Vaissière introduced me to the magical evening's entertainment they had discovered on the first night—house lights out, external floodlamps on. I suspect that looking out into the searchlighted sea will be something of which men in future undersea settlements will never tire.

DS-2 Takes to the Deep

Starfish House was a stationary viewing gallery. The beauty of the diving saucer, among other things, is its mobility.

We loved to take the saucer out at night because of the exotic creatures that come out then, and because of our long-held interest in the mysterious deep scattering layers that rise and fall in the depths of the sea. Here is the log of one of my Red Sea dives with Falco before we arrived at Sha'ab Rūmi:

"It is 2:00 a.m. Henri Plé, officer of the middle watch, awakens me and, despite the sultry clime, I pull on a blue nylon coverall. It will be cooler below.

"On the afterdeck, the diving saucer is lying in her cradle. Falco and I step on bathroom scales and the divemaster chalks the weights on the blackboard. Davso reads the weights and adds a little water ballast to *DS-2*'s inner tank to attain neutral buoyancy.

"We climb in. While Falco dogs fast the top hatch, I start the oxygen recirculation system and check over the control panel. On the phone Falco answers the pre-dive catechism of the divemaster. Everything is O.K.

Sharks Keep the Saucer Company

"Maurice Léandri, at the controls of the hydraulic crane, picks us neatly off *Calypso*'s deck and, with a velvet swish, the saucer is in the sea. I switch on the headlights. A couple of sharks are hanging around. Christian Bonnici, keeping an eye on them, ducks under to wipe off our Plexiglas ports. At a thumbs-up signal from Falco, the diver gets on top of the submarine, pulls out the phone jack, and casts off the lifting tackle. Bonnici lends his weight to pressing us under, and our voyage begins.

"One hundred and sixty feet down, the echo sounder sketches the bottom of the first reef—a gray slope of rock fragments. We land briefly. Falco adjusts our buoyancy and we go slaloming down the coral bank.

"We come to the very sharply defined drop-off line of the second reef. We leap into the void beyond and circle back to sink along the animate wall, our lights picking up the delicate pastel colors of coral and alcyonarians.

"Two hundred feet down we encounter the first deep scattering layer—DSL—a huge accumulation of micro-organisms that has risen at night from its daytime position 600 or more feet deep. From above and below small squids and many gill rakers come to graze in this plankton pasture. One of the things that makes night diving so profitable is these glimpses of deep creatures feasting in the DSL.

"We reach a depth of 325 feet and encounter there a phenomenon of the Red Sea reefs that has never been detected before, even by robot cameras or echo sounders. It is a well-defined horizontal ledge from six to 30 feet wide, running continuously along the vertical reefs. We have seen this ribbony shelf at every single place the saucer dived in the Red Sea.

"*Calypso*'s echo sounders had not given the slightest hint of this hard, level 'Andean highway' ranging the reefs of the Red Sea, always found about 325 feet down. The winding *corniche* seems constructed of hard, dead coral. The only explanation we can think of for the ledge is that it marks a sea level during one of the glacial epochs, a level eventually overcome by water. [Our geologists are busy now trying to solve that riddle.]

"Now *DS-2* sinks along the vertical wall of the third reef. We are conscious of the overhanging ledge above us. Four hundred feet down, *DS-2* stops on her own.

" 'It's the thermocline,' says Falco. We have touched the thin border layer between hot and cold water, and we are floating on top of the denser cold fluid.

"We can dive again, of course, by admitting a few pounds of water to our trimming tank, but we take time to let nature make the adjustment by cooling us off. The thermometer falls from 95° F. to 79° F. Falco pulls on a sweater. Again we are on our way down.

Squids Whirl Like Sea Dervishes

"We reach the floor 900 feet down, and Falco cruises on a sloping sandy bed strewn with great boulders, perhaps fragments of the fossil shelf far above. The water is very clear. In our headlights, we can see objects 100 feet away. We watch spiny lobsters with grotesquely long antennae excavating nests in the sand with their tails. Our lights turn small squids into whirling dervishes. The squids pivot on their heads in the sand, twirling their mantles and tentacles like carrousels.

"At the base of the reef, the sea floor is hidden under a tangled and struggling bed of living crabs, each averaging the size of a human fist. There must be hundreds of millions of them. Above, in the lands bordering the Indian Ocean, are hundreds of millions of half-starved people. Falco and I muse that while men are trying to reach the moon, it also might be well to find out how to fish these crabs.

"It is now dawn, time to go up. Falco drops a ballast weight, and we soar aloft. Soon we are in green water, then dazzling sunshine. Divers put on the lifting tackle and Léandri hoists us aboard. The voyage is over."

Divers Tend Undersea Stock Pens

Perhaps the main achievement of Conshelf Two was to operate a submarine boat entirely from a submerged base for the first time. At Sha'ab Rūmi, *DS-2* was safe and efficient, stealing in and out of her sunken onion dome. No wind or wave menaced her, as often happened when *Calypso* launched or lifted her. Based on the bottom, she was never immobilized by bad weather.

Conshelf Two was a realistic approach to an industrial station under the sea, and the daily routine of the oceanauts was one of work. Housekeeping was shared among the quintet. They took turns standing watches at the control console and performed daily outside assignments for Professor Vaissière.

Every day a team turned out to scrub fast-growing tropical seaweed and algae from the dome of the Saucer Hangar and the "tentacles" of Starfish House. The field work consisted of capturing live specimens for the biologist and putting them in the fish pens, steel frames fitted with plastic panels (page 493).

The divers captured live specimens by winding gill nets around a coral head. When fish had emerged and become enmeshed, the collectors gently disengaged the captives and placed them in plastic bags full of sea water. The men carried the fish in these invisible cages to the stock pens (page 488).

One time a powerful red snapper struck at a fish that Falco was carrying in a plastic bag. The sharp teeth slashed the bag and left the snapper with a mouthful of ripped plastic. The intended victim, thus dramatically liberated, jumped safely into a hole in the reef.

Professor Vaissière had none of the usual frustrations of the marine biologist—the difficulties of obtaining live specimens. He simply flippered out to the fish pens, picked the ones he wanted for the laboratory, and chose others to be air-expressed in oxygen-charged plastic bags to the Aquarium at Monaco.

Chef Pierrot did not use captives from the fish pens. In order to retain an innocent environment for Vaissière's biological researches, we enforced a nonaggression policy around the station. Seaman Antonio Lopez fished for the pot on distant reefs. I found out early in *Calypso* expeditions that easy access to fish does not increase one's appetite for them. We had a substantial red-meat dinner twice a day on *Calypso* and in the submerged house.

If you are planning a manned underwater station, don't forget to lay in a bunch of pressure cookers. They are the ideal containers for fetching and carrying between the surface and the bottom. They were invented to keep pressure in, but they also keep it out. We carried medical instruments, a broken television tube, mail, biscuits, and even a live parrot in them.

Just as miners once took canaries into the pit and submariners took mice into the boat to give early warning of high concentrations of carbon gases, for the same reason we took along the parrots, Claude (after Claude Wesly) and Armand (for Davso). We took two just in case we lost one.

Standby Parrot Never Goes Below

Claude was selected as the first parrot under the sea, although Professor Vaissière disliked the idea. He was sure Claude was going to disturb his repose by squawking out sailors' blasphemies.

Wesly put his namesake in a pressure cooker and carried him down. Claude bore the dive well and settled calmly into his new quarters (page 495). He was not caged—Starfish House was escape-proof for a bird. The professor slept the sleep of the contented savant, and Claude came up at the end of the experiment in good health. The standby parrot, Armand, was never called to duty.

Our youthful doctor, Jacques Bourde, swam down and checked the men every day. Although his average patient was nearing middle age, Dr. Bourde found little to treat.

Once Vannoni complained of the incessant physicals. "I feel fine. What good are all these checkups?" Bourde explained that they went into the clinical record that would be published for the use of other sea-floor establishments.

The peculiar experience of living inside the sea, cradled in man-made shells, cosseted by machines and cables, and nursed by many comrades on the surface, quickly became natural to the oceanauts. Falco and Wesly had found this to be true in the earlier experiment, Conshelf One. Man is a very adaptable species, especially when a new experience contains so much that is novel, beautiful, and exciting.

In recent years our underwater groups have been diving more and more at night because of the strikingly different face that darkness puts upon marine nature. The creatures of the day are withdrawn and asleep, and the night animals are out.

"Walking Shrub" Startles Hardened Divers

At Sha'ab Rūmi in the rich Red Sea, night showed us a secret world within the silent world. We used the ingenious stiletto light that our undersea research and development center at Marseille had built for Albert Falco. Its narrow, intense beam has the power of mesmerizing fish in midwater, so that the divers can gather unharmed specimens with their bare hands.

The parrot fish did not come out after dark. These daytime strollers lodged safely for the night, asleep in the sheltering arms of poisonous fire coral, to whose sting they seem immune. When we came by, they rolled their lidless eyes about but did not stir. They were supremely confident of their formidable fortress.

At night there came into the open a creature that struck momentary fear even in our veteran *plongeurs*. Picture an animal shaped like a small bush with five main branches, a great tangle of sub-branches and thousands of twigs. You find it standing on top of a coral head. It begins to writhe, twisting its slimy branches in cobralike motions. Play your light on it, and the weird creature shrinks and makes fast to the coral. Then, before your eyes, it walks away, contracts, squeezes into a crevice, and vanishes. This nightmare of the enchanted forest, which we saw only at night, is the basket star, or Gorgon's head, a member of the starfish family.*

On previous Red Sea explorations we had been intrigued by rare observations of a large type of parrot fish that we nicknamed "the bumpfish," because it has a big buffer on its forehead as hard as the brow of a bison. The fish weighed from 60 to 80 pounds and traveled in herds, chewing up coral hunks the size of a fist to get at tiny animals living in the coral maze.

The bumpfish would swim over a coral block, dive swiftly, and butt it heavily with the hard bumper, dislodging the *plat du jour*. Occasionally it would defecate large clouds of white sand, the end product of its menu.

During our first dives at the Roman Reef, we spotted a school of about forty mature bumpfish that appeared to be in residence, although they whipped off when we tried to take their pictures. Then, thanks to the privilege of actually living under the sea, we discovered where the bumpfish stayed at night. Investigating grottoes in the reef, we came upon them sleeping singly or in pairs.

Holding the hypnotic flashlight in their eyes, we were able to examine them closely. They were a bright, flashing blue-green and orange in hue, but their teeth were covered with seaweed. We saw them emerge from caves in the morning and rub themselves vigorously against the sand to clean off parasites before moving off to graze. That accounted for their pristine bodies, but there was no natural toothbrush to demoss their teeth.

When we were in the caves with the bumpfish at night, we could feel their heads and look into their mouths, but one touch on the tail sent them flying. One night Falco entered a bumpfish lair behind a big coral boulder and accidentally brushed the tail of an 80-pound specimen. The fish leaped past him and crashed head-on into the boulder. The coral, which must have weighed a ton and a half, overturned and rolled down the slope. The fish went on, apparently unhurt. Falco is convinced that if a diver had been in the way of the mad escape he would have been killed instantly.

Our divers have seen plenty of sea urchins in their years below, but they never dreamed of the species they found one night near Conshelf Two—a large urchin with the usual mess of radial spines, but with the startling addition of a radarlike scanner on top. This appendage turned back and forth in what seemed to be a full circle, for all the world like the radar atop *Calypso*'s mainmast.

Quite a few large triggerfish lived around the undersea hamlet. We saw the females lay grapelike clusters of pink eggs in hollows dug in the sand, then stand on their heads and blow streams of water on the eggs to oxygenate them. The male circled around protectively, prepared to strike at any intruder, be he shark or man.

We saw sharks turn tail and flee before an angry triggerfish, although the latter's teeth can deal no more than a peck to a shark or a painful nip to a man. Bernard Marcellin, Goupil, and myself were bitten to the blood by heroic males we blundered upon.

One of the most amazing creatures the divers found in Sha'ab Rūmi they dubbed the "bulldozer crab." It resembled a two-inch-long miniature lobster and spent its time shoving sand and coral around to construct homes and repair damages by intruders or currents.

Journal of a Modern Jules Verne

While Professor Vaissière kept the formal log of Conshelf Two, Vannoni, the meticulous ex-customs inspector, kept a rough, informal log—"What It Is Like to Live and Work Inside the Sea."

When he first popped his head up through the watery carpet in Starfish House, Vannoni had a "wonderful feeling of comfort and well-being" despite the "dreadful" heat and humidity. Indeed the accommodations were the best he had ever lived in—a cozy sitting room, delectable meals, a luxurious bed, and boon companions.

Of the work outside—the shifting of tons of lead ballast from the ballast rack to the large footplates of Starfish—Vannoni wrote: "In the water it is child's play to carry lead bars which would weigh a hundredweight on the surface. It is not long before we finish the job and return to the house fresh and well. But we do just a few light jobs, for we are still adapting to our new surroundings."

By the end of the first week of total submersion, Vannoni and his messmates had settled into "the usual daily chores"—such as setting up colored panels on the reef to see if fixed fauna and fish were attracted to certain hues; building Professor Vaissière's underwater aquariums; and scrubbing down the outside of the buildings. Vannoni noted that "the professor is becoming more dangerous day by day"—at chess. He wrote:

"June 21—We've been down for a week. I feel pretty well, but we've all had an earache in just one ear. Odd that it should be just one ear. I suspect the air ventilators which blow on our faces during the night. The doc [Bourde] is skeptical. But otherwise we're in pretty good form."

One morning, Vannoni wrote, he and Pierrot the cook were alone in Starfish House when "a triggerfish comes to look through the window into our living room. Guilbert torments him by holding a chicken leg against the glass. The fish bites at the window. We have a good laugh at the zoological textbook that claims the only way to study triggerfish is to kill them with depth charges or poison."

Submarine Pests Shun Bathless Diver

Vannoni looked forward to the night strolls in the coral mazes—"aesthetic orgies," he called them. The oceanauts went out in the dark, shrimping with hand nets: "Sorry we don't have an extra pair of eyes in the back of our heads." Once a barracuda swooped into the torchlights and seized a jack, which struggled desperately to free itself. "It disappears a moment later," wrote the diarist, "gulped down by the toss of the head and something like a yawn."

Always and everywhere in our liquid plantation we were surrounded by tiny beings—plankton—and were able to study them in situ, greatly enlarged with a movie camera devised by our research and development center in Marseille. One man would sweep a fine silk net through a fog of plankton and transfer living specimens to a clear plastic container the size of a matchbox. The container fits precisely into a theatrically lighted receptacle before the lens of the submarine cinecamera. The cameramen would then film in color the normal movements of wonderful life forms that dwell by the megatrillions in the world oceans.

Underwater people at Sha'ab Rūmi were tormented by stings from almost invisible siphonophores—stringy colonies of gelatinous animals that suffused the water. These tiny pests are armed with a remarkable weapon. Coiled inside a single cell called a nematocyst is a hollow poison tube. When the nematocyst makes contact with an alien body, the tube uncoils and drives deep into the victim, discharging venom. Smaller prey are paralyzed or killed. Divers itch cruelly and often become infected.

The siphonophores concentrated on areas where our diving dress didn't protect us, especially on our ears. After a while, we noticed that one of the black-suited divers was never bothered. It developed that he, excusably enough in a place where every drop of fresh water was precious, did not wash too often. The natural wax in his ears protected him from stings. Some of his friends at once joined the water-conservation movement.

Wounds Heal Almost Overnight

The new life under the sea that is beginning to summon man will have a new hygiene. A fascinating avenue of medical research is opening in continental shelf stations. On shipboard, for example, in the burning miasma of Sha'ab Rūmi, ordinary cuts took as much as three weeks to heal. Below, in Starfish House, the same wounds disappeared in two days. Was this due to an excess of oxygen under doubled pressure, a difference in bacterial life, or what?

Vannoni noted in his journal: "Day by day we notice that our visitors are losing weight and getting rings under their eyes. The effort demanded from everyone above is enormous. We follow all this from our sunken castle as powerless onlookers, rosy and plump, idle and pampered."

Arabs in dhows passing the dreaded Roman Reef at night must have counted their black coral prayer beads at the sight of the Conshelf expedition. A small diesel ship rode in an impregnable lagoon, throwing off the racket of generators and compressors. A white ship lay outside the lagoon, its crew working like galley slaves. Camera crews, toting apocalyptic floodlamps, lighted up the sea above and below, giving the whole scene a supernatural air.

Nobody worked harder than our electricians Bernard Marcellin, Jacques Roux, Pierre Servelo, and Louis Bidegant, who is called "P'tit Louis." They became so dazed with fatigue they made fun of it.

One morning Simone, the only woman among 45 men, wearing her most feminine sunsuit, encountered Bidegant in a narrow alleyway and *bonjour*-ed him cheerfully. The electrician squeezed past her with no reply.

"Alors, P'tit Louis," said Simone in a hurt tone. He turned, deadpan. "Oh, pardon, Madame. I didn't recognize you."

Barracuda Becomes a Mascot

The black-suited servants shuttling back and forth between the ship and shelf became accustomed to a loiterer—a six-foot barracuda that hung under the midships rail ten feet down to receive chef Jacques Morgan's garbage. Falco named the scavenger "Jules" and said, "He's old and bitter, almost unable to make a living."

A visitor arrived from France and eagerly donned an Aqua-Lung. As he started down the ladder, Simone said, "Look out for Jules." The visitor put his faceplate under. Jules was yawning. The guest suddenly lost interest in diving.

Simone thereupon got her lung and conducted the visitor safely through Jules's territory.

Rosaldo's captain, Louis Sinagra, was rowing lazily one day over the outer rim of the lagoon when he noticed a pale ringlike form protruding from the shallow coral table under the boat. He reached in and felt the neck of an ancient amphora, or earthenware jar.

We excavated the jar from its coral bed and found it surrounded by shards of other amphorae. It closely resembled third-century B.C. Rhodian cargo jars we had found in the ancient wreck at Grand Congloué.* The presence of these broken jars hinted at the wreck of a Hellenic ship on Sha'ab Rūmi. Was the reef itself misnamed for this wreck of two millenniums ago? If so, it is the only Hellenic shipwreck so far found in the Red Sea, and how it got there no one knows.

Depth Trial Begins 90 Feet Down

Ninety feet under stood our rocketlike Deep Cabin for two men (pages 500-501). It had two vertical rooms, the lower containing diving gear, tools, and the open sea hatch; the upper containing two bunks, kitchenette, intercom, phone, and a TV camera connected with the monitor in Starfish House.

The two men in the Deep Cabin were to breathe a recirculating mixture of air and helium—next-to-lightest gas in the atomic table. Many years ago U.S. experiments proved that helium would permit divers to go deeper than with ordinary compressed air. We intended to use a helium environment as a jumping-off base for deeper working dives with compressed-air Aqua-Lungs.

Our computations promised that the two men in the rocket could drop out of their bottom hatch and perform useful labor down to 165 feet, and that they could safely bring off short dives to 330 feet without too great a risk of nitrogen narcosis, or "rapture of the deep." We calculated conservatively that two men could spend a solid week in and out of the Deep Cabin.

I must here stress that we were not trying to break diving records, but simply testing, methodically and cautiously, the theory that a helium booster station could convey divers to deeper encampments on the continental shelf. The main point was to see if the deep men could work with clear brains in this stratum, and not be overcome by rapture of the deep.

The previous sinkings of the Deep Cabin did not daunt the two men who were to stay there a week. Raymond Kientzy, 33, is a splendid diver who has been ten years with our team. He is a robust, equable, reliable man. His companion was André Portelatine, 46, the volatile and highly accomplished director of the famous free-diving school at

Nice, the Aventure Sous-Marine. Their first hour in the Deep Cabin was a harbinger of the torments they were to meet.

The worst was the humidity. We had not provided air conditioning for the cabin, because we thought that the 90-foot depth would be in colder water below the thermocline. Also we had planned the expedition for March, when the Red Sea is nearly as cold as it ever gets. Now, it was July—hot July—and our thermocline data was wrong. The torture cabin was standing in water temperature of 86° F. with 100 percent humidity inside.

Deep Cabin Gear "Does Not March"

Kientzy was the diarist of the Deep Cabin. His first day's entry in "The Sauna," or Finnish bath, is datelined 5 July and notes, *"Le téléphone ne marche pas."* Other things that did not march included the refrigerator and the emergency oxygen system, because of repeated flooding and reassembly.

The deep men dined lightly the first evening and turned in at 7:30. They tossed sleeplessly all night. Kientzy got up once and found water risen in the lower story—there was a leak somewhere.

On the second day Portelatine could eat no breakfast. Kientzy managed coffee and jelly bread before they went out in the sea. Portelatine had severe ear pains and had to return to the cabin, while his cellmate swam around. They lunched on tomato salad, turkey (which Kientzy called "desert ostrich"), spinach, cheese, fruit, and wine. *"L'appétit marche bien,"* Kientzy noted.

That night Portelatine slept a little and Kientzy was out for eight hours. They perspired incredibly. I visited them and was appalled at the Finnish-bath environment. I promised to send down some cakes of ice.

Dr. Bourde, who was making daily visits to the pair, reported generally good reactions: Their health was not in danger, although the Deep Cabin was a supreme trial of well-being.

The third night was the worst thus far. Kientzy said they "perspired like fountains." Several times he went out for strolls to cool off. He saw a pair of sharks that had been hanging around the rocket. He played his flashlight on them.

"Their eyes were brilliant in the night, like cats' eyes," Kientzy noted.

The next day the deep men went down to 175 feet, to a dim forest of black coral that grew at the foot of their cliff perch. There they peered at another drop-off extending down, how far they could not tell. Despite his constant ear pain, Portelatine was as determined as Kientzy to attain the depth they had planned together, 330 feet.

They were seldom hungry or thirsty and forced themselves to eat and drink. Portelatine suddenly hated the taste of coffee. Kientzy forswore his beloved pipe because they were living in a recirculating breathing system that could not eliminate smoke.

A big laugh came whenever the controller in Starfish House spoke on the intercom with men in the Deep Cabin. Helium has a hilarious effect on the human voice. The gas is so light that it cannot fully resonate the vocal cords, and the most manly male produces a high-pitched twitter.

I tape-recorded reports from Sha'ab Rūmi for French radio during the expedition and airmailed them home. Later I heard what happened in Paris when one of the "helium" tapes went on the air. The sound engineers heard a normal voice answered by soprano chirps. They stopped the machine, and the announcer apologized for the "technical difficulty." The sound men reasoned that the tape operator had accidentally speeded up when recording, so they slowed the tape. This time my voice went into a horrible, cavernous drawl, and the reply from Deep Cabin was like nothing ever heard on land or sea.

The fourth night in the Deep Cabin was another bad one for the almost sleepless Portelatine, and in the morning they found the water once more rising in the rocket. Kientzy wrestled a bottle of helium off the outside rack and released the gas in the chamber, pushing the water back down with the added pressure. The mysterious leak persistently threatened to flood them in their sleep, although there would still be enough air compressed into a pocket in the nose cone to give them time to arrange escape.

Kientzy's terse narrative for the fifth day mentions a temperature of 89° F., humidity unknown (the hygrometer did not march).

"The water continues to rise in our house," he noted. "André slept a little and I did, too. *Tout va bien* [All goes well]."

Electrician Pierre Servelo, who had once been trapped in the rocket, came up with a theory about the leaks. "Is it possible that helium is seeping into the television cable and escaping through it to the surface?" he asked.

I had a strong inner seal put on the stuffing box. Servelo had the answer. The TV cable had been merrily conducting the superbuoyant helium to freedom in the world above.

During the week of the Deep Cabin trials, the men in Starfish House were completing their month underwater. Aboard *Calypso* Simone announced to me in tones that implied argument-will-get-you-nowhere, "I am going down to see them."

I said, "I'll have Davso go with you."

Before the mechanic could charge his bottles, she was down the ladder. The lady who came for supper at Starfish House enjoyed the evening illuminations. Quietly two of the inhabitants evacuated a bedroom and doubled up with others so she could stay overnight. It turned into quite a visit. Simone might not be up yet, except that the fifth day was the close of the project.

Simone's subaqueous sojourn included our 26th wedding anniversary. I was invited down for the occasion. The champagne was terribly flat—doubled pressure tended to keep the bubbles imprisoned in the wine.

On the fifth day, the men in the Deep Cabin swam down through changing visibility and contradictory currents to the black coral copse and reconnoitered the region they would visit on the climactic 330-foot dive. Below, said Kientzy, "the water was crystalline and unmoving. I was near to vertigo." They returned to the Deep Cabin, confident they could make 330 feet.

It was a good day. Portelatine's ears felt better. A moray snatched a plastic bag of lunch leftovers out of Kientzy's hand and swallowed it, plastic and all. For the first time both men were able to enjoy a siesta.

"The surface world interests us only because of our friends up there," wrote Kientzy. "The rest, the world, France, we do not think of. What day is it? I think it is the fifth day we have been here. It is of no importance."

After the nap, the pair went down again and reached a sandy slope at a depth of 250 feet—only 80 feet short of their goal. Hundreds of little eels stood on their tails in the sand, their bodies arched into question marks. When the men got within six feet of them, they vanished into the floor.

The sixth day was the one planned for the Aqua-Lung dive to 330 feet, a depth much too hazardous for compressed-air dives from the surface. However, dwellers in undersea stations could, we reckoned, attain the depth with clear heads and perform useful work there. Our calculations proved right.

Kientzy and Portelatine drilled down through the lambent depths to 300 feet. There, looming below, stretched the ribbony coral shelf, the "Andean highway" that we had discovered with the diving saucer. The deep men looked over the edge of the shelf; below 325 feet the cliff fell straight down.

At this depth the divers were breathing 11 times the volume of air that they would on the surface, and even their four-tank Aqua-Lungs were quickly becoming exhausted. They shot up to Deep Cabin. They had not experienced rapture of the deep—nitrogen narcosis—despite the extreme depth. In the log Kientzy entered 330 feet as their greatest depth. Not until a week later did he confess to me that they had actually gone to 363 feet.

In the forenoon of their seventh day, Kientzy and Portelatine went out for their last swim, while black-suited divers rigged special gas masks over their bunks in the Deep Cabin to prepare them for a safe ascent to Starfish House. The pair put on the masks and breathed a mixture of 50 percent oxygen and 50 percent nitrogen for three and a half hours. This reduced the helium saturation in their bodies to a safe level. When Kientzy stuck his grinning face through the wet carpet in Starfish House, Wesly stuck a lighted pipe in his mouth.

Diarist Vannoni in Starfish House wrote: "Our stay draws to a close. Honestly, we don't think of our return to the surface as a relief. To continue our experiment further beyond the limits planned would not be difficult, but would prove nothing beyond what has been shown already."

In order to give the deep men room for an overnight stay to pass off gases, Vannoni and André Folco surfaced after 29 days below. The other three stayed until the 31st day, then breathed a mixture of 80 percent oxygen and 20 percent nitrogen—inverse proportions of these gases in the atmosphere—for 15 minutes. They took 15 minutes off, then a half hour back on, a half hour off and an hour on, and they were ready to go.

The last silver helmet passed through the blue floor, and they swam up to the roseate blaze in which other people live.

The manned undersea research station is a revelation to oceanography. Ocean scientists of the past like Prof. Henri Milne-Edwards of the Sorbonne, the first biologist to dive—in a clumsy and dangerous bucket helmet in 1844—would turn sea-green with envy over our Professor Vaissière's privilege of spending a lordly month in the fishes' habitat with his own collecting staff, underwater cameras, stock pens, and field laboratory.

The Red Sea demonstration was especially interesting to the petroleum industry because of its offshore operations. Indeed, the main sponsor of Conshelf Two was Bureau de Recherches de Pétrole, the French national petroleum office. We believe that placing marine oil wells and their personnel on the sea floor will be cheaper and safer than maintaining offshore drilling platforms. Professor Vaissière is confident that his oceanographic colleagues all around the world will sooner or later demand ocean-bottom laboratories.

Military applications of manned undersea stations include antisubmarine warning installations, coastal defenses, and submerged bunkering stations for submarines.

Conshelf One and Conshelf Two have convinced our underwater team that industrial and scientific sea-bed stations will become a routine thing in our lifetime.

A hundred practical applications will undoubtedly be found for submerged stations. Yet for us the greatest reward for the toil at the Roman Reef was none of these, but the ever-enchanting realization that we were living inside the sea. THE END

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REVUE TRIMESTRIELLE — N° 1 - 1963

L'OPÉRATION PRÉ-CONTINENT N° 1

Aspects physiologiques de la vie sous-pression

Dr X. FRUCTUS et Pr J. CHOUTEAU (Marseille)

L'exploitation extensive des fonds marins, tout au moins en ce qui concerne le socle continental, ne pourra être menée à bien que si l'homme est capable d'y séjourner assez longtemps d'abord, assez profondément et longtemps ensuite pour participer à la vie benthique. Alors tout lui sera possible : une archéologie exhaustive, des observations biologiques patientes et fructueuses, des études géologiques plus précises et bien d'autres activités que nous ne faisons qu'entrevoir.

Les conséquences de cette conquête seront immenses et, quant à nous, nous pensons que le benthos sera plus profitable que le cosmos à *l'homme de demain.*

La colonisation de la zone sublittorale implique un ensemble de solutions à une série de problèmes dont les deux données fondamentales sont la profondeur et la durée du séjour.

Obligés de nous résumer, nous nous en tiendrons à quelques exemples. *La première question étant résolue : alimentation en air* à la pression hydrostatique, l'homme a pu observer, explorer et travailler sous la mer.

MAIS :

1°) Si l'ouvrier dans sa cloche de plongeur peut travailler 8 h par jour à —10 mètres, il ne pourra séjourner que 3 h par jour à —25 mètres et cela au prix d'une durée de décompression de plus de 2 h, sous peine d'accidents.

2°) Si le plongeur en scaphandre autonome veut relever les amphores d'un site archéologique situé à —43 m il peut s'y consacrer au maximum 15 minutes 3 fois par jour (avec à chaque temps de

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Nous ne saurions continuer sans remercier ici tous ceux qui nous ont apporté bénévolement une aide considérable dans cette entreprise matériellement difficile, qui fut inspirée et contrôlée par le Commandant Cousteau :

Le Professeur Grebus (Chaire de bactériologie, Faculté de Pharmacie) ; les Docteurs Girolami, Andrac et Latrabe, biologistes ; le Dr Regis et Mme Charles, du Centre St-Paul (Pr Gastaut) ; le Dr Hugonenq, neuro-psychiatre ; le Dr Curel, cardiologue de la consultation de Médecine sportive (Pr Audier) ; M. Bondil, biochimiste du Centre de Transfusion de Marseille (Pr Ranque) ; la Maison Alvar (électrocardiographie), les Laboratoires Roussel, Specia, Delalande ; sans oublier la Chambre de Commerce de Marseille dont les Services Techniques se sont dépensés sans compter !...

remontée un petit palier de 2 minutes), ce qui, compte tenu des temps de descente et de remontée, représente 40 minutes par jour de travail effectif au fond.

Si, voulant accroître son rendement quotidien, il fait une première plongée de 50 minutes le matin, il n'en pourra faire qu'une deuxième de 46 minutes dans la soirée, au prix d'une heure de paliers (à 9, 6 et 3 m) par plongée, ce qui est pratiquement impensable.

3°) Nous ne ferons qu'évoquer le plongeur qui doit faire une intervention rapide à —80 m. Non seulement il doit être d'une classe peu courante, mais encore ne pourra-t-il agir que 3 minutes environ à cette profondeur (avec 4 minutes de palier à la remontée).

4°) A partir de ce niveau doit intervenir l'utilisation de mélanges gazeux respirables, appauvris en oxygène et en azote, pour que la descente laisse espérer une remontée possible.

Mais si le Suisse KELLER, dans sa cloche, entouré de multiples bouteilles contenant de mystérieux mélanges, descend à 200 m et y séjourne 10 minutes, l'on sait, d'une part, que sa remontée devra durer environ 1 heure avec des paliers assez profonds, mais, d'autre part, l'on ne sait pas s'il pourrait prolonger son séjour au fond sans risques graves pour son organisme. Sa dernière expérience de 1962 est malheureusement loin d'être concluante.

Entre ces deux extrêmes, se situe notre tentative : l'opération pré-continent n° 1.

Si nous reprenons les deux données fondamentales du problème, la durée du séjour et la profondeur, nous nous efforcerons d'abord d'augmenter la durée du séjour.

Etant donné le faible rendement des plongées renouvelées, à cause de leur durée limitée, imposée par les risques d'accidents de décompression, il était légitime d'envisager la plongée continue.

A partir de principes purement physiques (loi de Dalton et de Henry, période de saturation des tissus vivants, rapport critique de Haldane), et sur lesquels nous ne pouvons nous étendre ici, deux faits sont à retenir :

1°) la saturation de tout l'organisme en azote est complète au bout de 12 heures et, pratiquement, au-delà de 6 heures le séjour au fond ne nécessitera pas plus de délais de décompression à la remontée, qu'il dure une semaine, six mois ou trois ans ;

2°) le rapport critique de Haldane n'intervient que relativement près de la surface. Par conséquent, un plongeur pourra, par exemple, autant qu'il le voudra, prolonger son activité à —25 m, il ne risquera jamais d'accidents de décompression s'il remonte se reposer et se détendre le reste du temps à —10 m.

La maison sous la mer à cette profondeur le libère donc d'une servitude considérable.

Naturellement, pour une activité sous-marine plus profonde, elle devra être aussi plus profonde.

Si nous prenons l'exemple de 4 h de travail par jour sur un chantier archéologique à —50 m, la maison devra fort probablement se situer dans les —20 m.

Mais tout le problème de la vie sous la mer n'est pas résolu pour autant, car la 2ᵉ donnée fondamentale que nous évoquions au début intervient aussi.

Pour l'homme respirant de l'air à la pression ambiante, profondeur égale pression, et au-dessus de la pression atmosphérique l'action chimique des gaz respirés peut commencer assez tôt à se faire sentir.

L'expérimentation encore inédite pratiquée au G.E.R.S. cette année, a permis de préciser les conditions de survie d'un animal, le rat blanc en atmosphère comprimée, en caisson.

Cette survie est brève.

Toutes choses étant égales par ailleurs, l'animal meurt au bout de :

18 h	à une profondeur	fictive	de 80 m = 9 k.
30 h	»	»	de 60 m = 7 k.
50 h	»	»	de 30 m = 4 k.
300 h (12 à 13 jours)	»	»	de 10 m = 2 k.

Cette expérimentation a été globale. Elle n'a pas permis de préciser la cause de la mort, mais il a été démontré que la survie était notablement prolongée par la réduction du pourcentage d'oxygène dans l'air du caisson.

L'augmentation de la Pp 02 est certainement le facteur léthal prépondérant.

Compte tenu de certains précédents humains plus rassurants (travail des tubistes, recompression thérapeutique), le Cdt COUSTEAU a estimé qu'il était temps de voir si les avantages de la vie sous la mer n'étaient pas contrebalancés par des inconvénients pires.

Nous avons donc tenté l'expérience, considérant :

1°) que l'homme est le plus adaptable des animaux, ce qui a, d'ailleurs, permis son expansion géographique ;

2°) qu'il était possible de tâter cette adaptabilité en choisissant pour commencer une profondeur modérée (—10,5 m) et un temps de séjour raisonnable (7 jours) ;

3°) qu'il était indispensable de tirer le maximum d'enseignement de cette première expérience en explorant à fond les réactions d'adaptation nerveuses, organiques, biologiques, des sujets qui y étaient soumis.

L'épreuve s'est déroulée en rade de Marseille, du 14 au 21 septembre 1962. Les perspectives que nous avons évoquées plus haut justifient sa dénomination :

Opération pré-continent n° 1.

LES SUJETS CHOISIS

Ceux que nous appellerons les deux **bathynautes** devaient, pour que l'expérience soit valable et puisse donner lieu, par la suite, à des applications pratiques extensives, à la portée d'une population de plongeurs :

a) être plongeurs eux-mêmes, pratiquement **professionnels** ;

b) ne pas être considérés comme des **recordmen** ou des individus exceptionnels ;

c) mais être **motivés,** pour cette expérience, par leur vocation de **pionniers** dans le domaine sous-marin.

Sur le plan de la personnalité, ils devaient être des **hommes comme les autres, valorisés par leur métier** et animés davantage par **l'esprit de progrès** que par **l'esprit d'aventure.**

Le Commandant COUSTEAU a choisi (F) qui a choisi à son tour (W) pour faire équipe avec lui. Ils ont participé activement à l'installation de leur « maison sous la mer ». Ils se trouvaient plutôt surmenés les derniers jours avant l'épreuve.

Nous ne pouvons reproduire ici leur fiche d'identité médicale naturellement très complète. Retenons simplement que :

(F) - 35 ans, est de type méditerranéen
(W) - 32 ans, est de type alpin

tous deux :
médiolignes sthéniques
(sportifs entraînés).

Tout est sensiblement normal chez eux, sauf que :

(F) est un dyspeptique, colitique, qui surveille son alimentation ;

(W) est un hépatique qui s'ignore, grand consommateur de lait et de corps gras (cholestérolémie : 2,48 g - Mac Lagan = 40° V. - lipides sanguins : 8,7 g).

Leur profil psychologique est différent :

(F) est du type mûr, consciencieux, stable, prudent, efficace, avec une tendance à l'anxiété bien contrôlée ;

(W) est du type juvénile, idéaliste, efficace, mais affecté d'une émotivité à teinte obsessionnelle et d'un manque de confiance en soi qu'il tend à surcompenser.

LE MATERIEL ET L'ORGANISATION

L'habitat était constitué par un cylindre métallique horizontal de 5 m de longueur et 2,55 de diamètre. Il comportait au milieu de sa partie inférieure, un puits d'accès cylindrique de 1 m de diamètre.

Il avait été rendu habitable par un revêtement intérieur eu polyuréthane mousse, un plancher et, naturellement, la ventilation permanente (100 l/m), l'éclairage électrique, le chauffage aux infrarouges, l'eau douce, la radio, la télévision, les interphones.

L'espace intérieur se divisait en deux parties :

— d'un côté de l'entrée, la chambre d'habillage pour les plongées, avec les deux caissons de recompression monoplaces (en prévision d'accidents possibles) ;

— de l'autre côté, la salle de séjour, avec les deux couchettes, des étagères, un guéridon, etc.

Son « cordon ombilical » le reliait aux installations de surface situées sur l'île de Pomègues, mais presque à la verticale, au-dessus de lui, il y avait un chaland servant de base avancée pour les plongées et le ravitaillement.

Il était immergé dans la baie de Pomègues, à l'abri des vents de nord-ouest, sur un fond de 13 mètres, tenu par 8 chaînes et 34 tonnes de gueuses.

Son alimentation en air évacué au niveau de la partie inférieure du puits d'accès (le « couteau » en langage des tubistes), maintenait la pression intérieure à ce niveau hydrostatique, soit 10,5 m (2.05 k).

Tout était naturellement prévu pour que le ravitaillement sous toutes ses formes et la surveillance, non seulement à l'intérieur de la « maison » mais au cours des plongées des deux bathynautes, soient assurés de jour et de nuit.

Les deux navires océanographiques du Commandant COUSTEAU la « CALYPSO » et l' « ESPADON », ainsi que la vedette de la Chambre de Commerce de Marseille et divers engins légers, participaient à cette opération, qui était commandée par le Cdt ALINAT.

ETUDE PHYSIOLOGIQUE DES DEUX SUJETS EN EXPERIENCE

Avant l'expérience, les deux sujets ont été soumis à un certain nombre d'examens.

1°) **Examen clinique,** suivant le protocole adopté à notre consultation de médecine sportive, radiologie pulmonaire.

2°) **Examen neuro-psychiatrique,** avec interrogatoire psychiatrique, E.E.G., examens psychologiques, tests.

3°) **Exploration cardio-vasculaire :** clinique, électrocardiographique, avec test de Master et test de Flack.

4°) **Explorations biologiques,** portant sur : l'azotémie, la glycémie, l'uricémie, les protides et les lipides sanguins, le cholestérol sanguin total et estérifié, le protéinogramme, le lipidogramme, l'hémogramme, la vitesse de sédimentation, le thromboélastogramme, ainsi que l'hématocrite et l'ionogramme sanguin.

Dans les urines, en plus des examens classiques de dépistage, on a dosé l'urée, l'acide urique, les chlorures, la créatinine, le sodium et le potassium.

On a mesuré aussi l'élimination des métabolites hormonaux : 17 cétostéroïdes, par la méthode de Zimmermann ; 17 hydroxy 20 céto, par la méthode de Porter et Silber, et les corticoïdes réducteurs totaux, selon la technique de Jayle au bleu de tétrazolium ; ainsi que les catécholamines totales.

On a dosé également l'excrétion d'uropepsine.

La plupart de ces examens cliniques, psychotechniques et biologiques, ont été renouvelés plusieurs fois (mais moins souvent que nous ne l'aurions souhaité), durant le séjour sous la mer et le deuxième jour après la sortie.

Nous avons réuni ainsi le plus possible d'éléments susceptibles de nous éclairer sur le comportement physiopathologique des deux sujets pendant une semaine de vie en atmosphère comprimée, sous la mer, et respirant un air dont la pression partielle d'oxygène était sensiblement le double de celle existant à la surface.

L'évolution de ces divers éléments fait l'objet d'un volumineux rapport que nous allons tâcher de résumer.

Parmi les signes cliniques, nous passerons rapidement sur le poids (léger amaigrissement) ; le pouls et la température, stables ; la tension artérielle qui a légèrement fléchi chez (W) ; les épreuves cardio-vasculaires qui sont demeurées remarquablement normales.

Le comportement, que nous avons suivi de très près (nous étions, en moyenne, 4 h par jour auprès d'eux), mérite une certaine attention.

Nous envisagerons LE COMPORTEMENT DE FOND, d'une part, LES EPISODES CRITIQUES, d'autre part.

A - Comportement de fond

Si certains incidents sont venus, au cours de l'expérience, modifier certains aspects du comportement des sujets, on n'en enregistre pas moins une certaine stabilité dans :

— leur volonté de poursuivre l'expérience ;

— leur coopération aux examens médicaux ;
coopération qui, comme chez tous les sujets sportifs, en bonne santé, est loin d'être parfaite, laisse toujours la porte ouverte à certaine négligence, s'accompagnant toujours d'une incompréhension de la rigueur qui doit présider aux prélèvements et aux examens (exemple : le refus de prendre la température autrement qu'axillaire a eu lieu dès les premières 24 heures), mais tout cela n'a été ni aggravé ni amélioré par le séjour sous-marin ;

— l'absence apparente de claustrophobie, et toujours apparemment du moins, l'attitude diamétralement opposée d'agoraphobie ;

— parallèlement à cette agoraphobie, l'absence d'exhibitionnisme et des attitudes se tenant dans les limites du naturel, surtout chez (F), en présence d'une observation pourtant constante ;

— l'absence d'occupations intellectuelles et le peu d'intérêt manifesté pour les émissions de radio et de télévision ;

— bref, un certain détachement du milieu terrestre qu'ils avaient quitté, et cela pour tous les deux, sans aucune crise, si brève soit-elle, de regret ou de nostalgie, seulement l'obsession — modérée sans doute et peu formulée, mais permanente, — de la période de transition lors du retour à la surface, avec les accidents possibles qu'elle pourrait comporter ;

— pas de surexcitation particulière comme on aurait pu s'y attendre à cause de l'hyperoxie, sauf peut-être le matin du deuxième jour où, au moment du petit déjeuner, ils manifestaient une euphorie un peu excessive par rapport à leur comportement habituel ;

— mais plutôt le contraire, une certaine nonchalance, un ralenti à peine sensible dans l'action, quelques manifestations, sinon de fatigue, du moins d'asthénie ou peut-être de paresse relative dont nous aurons à reparler, mais qui n'ont pas évolué au cours du déroulement de l'expérience ;

— en revanche, pas du tout de ralentissement dans la nage sous l'eau, simplement, dans le travail sous l'eau, des efforts, pour eux habituels, leur ont paru un peu plus pénibles.

B - **Crises.**

Sur ce fond de stabilité se détachent des crises.

Les crises (si l'on peut employer ce terme pour des réactions, somme toute modérées, dans le comportement des deux bathynautes) se sont manifestées de la façon suivante :

— Pour (F), un cauchemar à teinte fortement anxieuse au cours de la première nuit ;

— Pour (W), rien de nettement apparent, mais, le soir du 2ᵉ jour, les deux sujets ont trouvé la plongée nocturne fatigante bien qu'elle n'ait duré que 55 minutes, ce qui est peu au regard de leur entraînement et du programme établi (5 h par jour, alors qu'ils n'ont plongé que 4 h ce jour-là).

Le 3ᵉ jour, ils ont trouvé fatigant le maniement des gueuses sous l'eau et ont demandé à être dispensés de plongée de nuit. Cette attitude contraste avec celle du 4ᵉ jour où, malgré leurs troubles digestifs et les crises gastriques de (F), ils ont exécuté leur programme assez allégrement (4 h 50 de plongée).

Le 5ᵉ jour, ils n'ont travaillé sous l'eau que 3 h 30, mais sans se plaindre.

Le 6ᵉ jour : 4 h 50 ; le 7ᵉ jour : 4 h 5', mais avec beaucoup plus d'entrain et les plongeurs qui les accompagnaient ont pu admirer l'aisance et la vitesse de leurs évolutions sous l'eau.

La crise de fatigue, ressentie par (F) le matin de la sortie, a naturellement modifié son comportement pendant les dernières heures, mais cette crise avait certainement une composante psychique : inquiétude pour l'un de nous (Pr CHOUTEAU) qui s'était soumis à un délicat exercice d'évacuation en caisson monoplace, et peut-être, crainte inavouée d'accidents imprévisibles lors de leur retour à la surface.

Quoi qu'il en soit et globalement, le comportement des deux bathynautes s'est plutôt amélioré, stabilisé lors des derniers jours de leur séjour sous la mer.

Reste toujours sur le plan clinique ce qu'il nous faut bien appeler : LES INCIDENTS PATHOLOGIQUES.

Les deux sujets étaient légèrement enrhumés au départ. Ils ont présenté de petits signes de rhino-pharyngo-trachéite. Pharyngite plus accentuée chez (W), le 4ᵉ jour, trachéite plus marquée, mais antérieure à l'expérience, et plus persistante chez (F).

Ces manifestations se sont produites surtout les cinq premiers jours, pour s'atténuer considérablement à partir du 6ᵉ jour.

A la sortie, aucun des deux sujets ne présentait de signes d'irritation pulmonaire.

Les troubles les plus manifestes ont été d'ordre digestif. ,

Dès le 3ᵉ jour (F) et (W) se plaignaient de ballonnement après les repas, de gêne inhabituelle lors de l'habillage, de pesanteur digestive.

Le 4ᵉ jour (F) a présenté des troubles gastriques toute la journée, couronnés par une véritable crise après le repas du soir avec des aigreurs, du pyrosis, des nausées, au cours de la plongée nocturne, le tout n'étant calmé que par des compresses chaudes sur la région épigastrique, vers 22 heures.

Le ballonnement et les troubles dyspeptiques étaient considérablement atténués par quelques mesures diététiques, à partir du 6ᵉ jour.

Ici, une remarque s'impose : nous n'avons pas voulu ni pu prendres de mesures diététiques strictes vis-à-vis de deux bathynautes les premiers jours de l'expérience. Ils étaient plutôt boulimiques au début, consommant largement la cuisine du bord. (F), toujours plus réservé vis-à-vis des aliments gras, (W) consommant allégrement sa portion de camembert au petit déjeuner et ses deux litres de lait par jour.

Dès qu'ils se sont rendu compte des inconvénients de cette alimentation, nous avons pu la modifier en réduisant le volume alimentaire, les farineux, les corps gras, le lait et en les remplaçant par des mets sucrés directement assimilables : confiture, miel, confit d'amandes, ainsi que des viandes rouges et du poisson.

Leur estomac a répondu de façon favorable à cette modification de régime qui comportait quand même 3 000 calories par jour, et leur permettait d'assurer confortablement leur thermogénèse, en plongée.

Au cours de ce séjour, nous n'avons pas pu noter de fatigue objectivable, sauf le matin de la sortie pour (F).

Le sujet s'était dépensé musculairement et nerveusement au cours de l'exercice d'évacuation en caisson monoplace.

Lorsque nous avons demandé à (F) de s'allonger pour respirer de l'oxygène à 80 % afin de se dénitrogéner avant la sortie, il présentait un pouls à 96, persistant, il avait le visage fatigué et manifestait un essoufflement qui a mis plus de 10 minutes à s'apaiser sous oxygène.

(W) paraissait, en revanche, en pleine possession de ses moyens et beaucoup plus détendu.

Il reste à signaler quelques incidents cutanés.

D'abord, une sensibilité accrue de l'épiderme au rasoir électrique chez les deux sujets. Un peu de prurit et de cuisson au niveau des conduits auditifs externes et, enfin, de petites manifestations infectieuses, sous forme de pyodermites, apparues le jour de la sortie chez tous les deux.

Nous avions d'ailleurs prévu la possibilité d'une pollution de l'atmosphère du caisson par des bactéries pathogènes, du fait de la température, de l'humidité et de l'absence d'insolation ; malgré la ventilation satisfaisante.

L'examen bactériologique a montré une contamination de l'air de la chambre :

— Contamination totale	: 65 colonies
— Staphylocoques totaux	: 35 colonies
— Staphylocoques pathogènes	: 12 colonies.

Nous ne dirons que quelques mots des réactions psychomotrices qui ont été tout particulièrement scrutées à l'aide de nombreux tests (échelle d'intelligence de Wechsler-Bellevue, figure complexe et ordination de chiffres de Rey, test de rétention visuelle de Benton, ainsi que des tests de performance et la mesure des temps de réaction).

Ne pouvant entrer dans le détail, nous citerons simplement la conclusion de la psychologue :

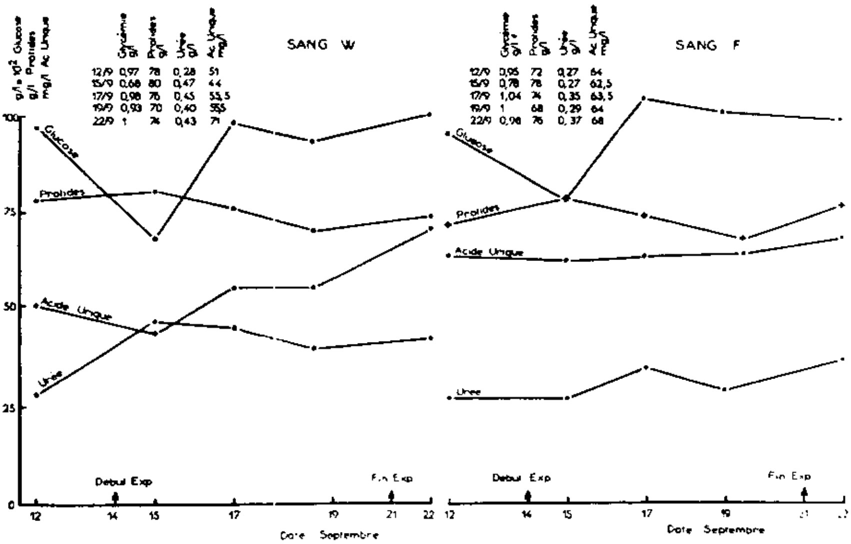
« Nous n'avons pas mis en évidence, au cours de l'expérience, « de troubles intellectuels ou psychiques, susceptibles d'entraver « en quoi que ce soit l'adaptation des sujets.

« Les fluctuations de l'efficience ont été légères et pas toujours « concordantes. L'effet d'apprentissage, signe d'adaptation, s'est ma« nifesté de façon évidente. »

Mais il était nécessaire de pousser plus loin nos investigations et les résultats des E.E.G. et des examens de laboratoire sont peut-être plus riches d'enseignement.

Si les examens neurologiques n'ont révélé aucune modification, les E.E.G. n'ont pas été tout à fait indifférents. Ils étaient normaux avant l'épreuve chez les deux sujets.

Refaits le lendemain de la sortie, ils mettaient en évidence, chez (F) comme chez (W), des rythmes de fond moins amples et plus fragmentés. Le rythme α s'organisant en bouffées sporadiques.



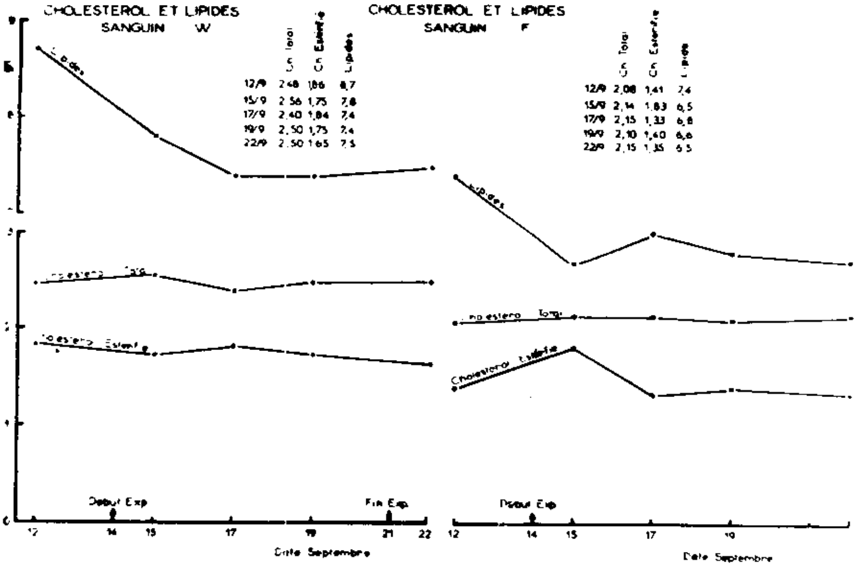
SANG W

	Glycémie g/l	Protides g/l	Urée g/l	Ac. Urique mg/l
12/9	0,97	78	0,28	51
15/9	0,68	80	0,47	44
17/9	0,98	76	0,45	55,5
19/9	0,93	70	0,40	555
22/9	1	74	0,43	71

SANG F

	Glycémie g/l	Protides g/l	Urée g/l	Ac. Urique mg/l
12/9	0,95	72	0,27	64
15/9	0,78	78	0,27	62,5
17/9	1,04	74	0,35	63,5
19/9	1	68	0,29	64
22/9	0,98	76	0,37	68

Fig. 1



CHOLESTEROL ET LIPIDES SANGUIN W

	Ch. Total	Ch. Estérifié	Lipides
12/9	2 48	1,86	8,7
15/9	2 56	1,75	7,8
17/9	2,40	1,84	7,4
19/9	2,50	1,75	7,4
22/9	2.50	1 65	7,5

CHOLESTEROL ET LIPIDES SANGUIN F

	Ch. Total	Ch. Estérifié	Lipides
12/9	2,08	1,41	7,4
15/9	2,14	1,83	6,5
17/9	2,15	1,33	6,8
19/9	2,10	1,40	6,6
22/9	2,15	1,35	6 5

Fig. 2

L'hyperpnée, la S.L.I. et l'E.A. ne révélaient rien de plus.

L'impression du neuro-biologiste est que ces E.E.G. se présentent comme ceux de sujets dont le tissu nerveux a souffert d'hypoxie, naturellement à minima, et sans manifestations cliniques. Cette remarque est avancée avec prudence par le Dr REGIS ; elle n'en est pas moins intéressante et montre que l'E.E.G. est une des méthodes d'exploration les plus précieuses dans ce genre d'expérience.

Parmi les CONSTANTES SANGUINES, certaines demeurent stables.

Chez les deux sujets :

Les protides totaux, le protéino et **le lipidogramme,** à quelques nuances près, **l'uricémie** et la **cholestérolémie,** la V.S.G., ne bougent pas (fig. 1 et 2).

Les lipides totaux baissent nettement dès le début pour se stabiliser ensuite (fig. 2).

Il n'en est pas de même de **l'azotémie** qui, normale au départ, augmente assez régulièrement sans toutefois atteindre les taux élevés enregistrés au cours de l'effort sportif (fig. 1).

La glycémie s'infléchit brutalement le 2ᵉ jour, plus exactement 18 h après le début, pour revenir rapidement à la normale (fig. 1).

L'hémogramme témoigne d'une diminution assez régulière des globules rouges et des granulocytes. Le 7ᵉ jour (W) a perdu près de 1.100.000 hématies par mm^3 et (F) près de 400.000. La récupération s'amorce, d'ailleurs, dès le lendemain de la sortie : les deux sujets ont déjà retrouvé 200.000 hématies par mm^3.

Il en est de même des polynucléaires neutrophiles dont le pourcentage diminue notablement chez (W) plus que chez (F) et cela malgré la petite infection cutanée présentée par les deux plongeurs (fig. 3).

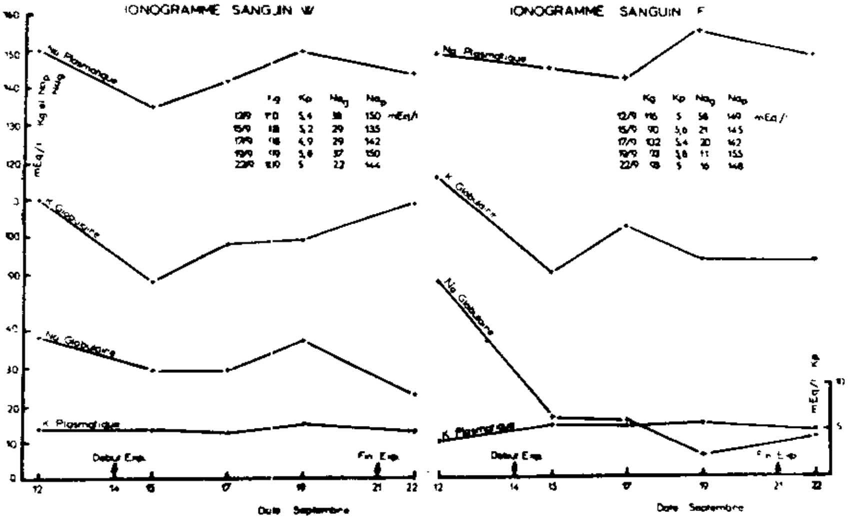
Le mouvement des électrolytes sanguins n'est pas très important. Toutefois, **chez les deux sujets :**

La kaliémie monte assez régulièrement jusqu'à 5,8 mEq le 7ᵉ jour, tandis que la **natrémie** baisse d'une quinzaine de mEq entre le 2ᵉ et le 4ᵉ jour et que **le potassium globulaire** marque une fuite nette mais transitoire le 2ᵉ jour (fig. 4).

Le dosage du **sodium globulaire** étant plus sujet à caution, nous négligerons ses variations apparentes (fig. 4).

DANS LES URINES, **chez les deux sujets,** les taux de **l'urée, de l'acide urique** et **des chlorures** sont à peu près constants.

L'élimination des **électrolytes Na et K** est oscillante comme la diurèse mais non parallèle à celle-ci. Elle se caractérise par un débit accru, au début de l'expérience surtout en ce qui concerne le sodium. (La natrurie atteint 242 mEq chez (W), le 2ᵉ jour.) (Fig. 5.)



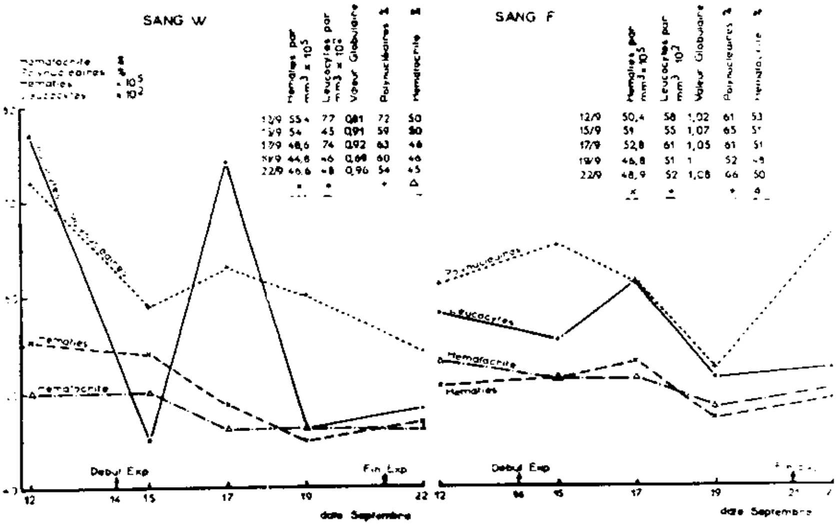
IONOGRAMME SANGUIN W

	Kg	Kp	Na_g	Na_p	
12/9	110	5,4	38	150	mEq/l
15/9	88	5,2	29	135	
17/9	98	4,9	29	142	
19/9	99	5,8	37	150	
22/9	110	5	22	144	

IONOGRAMME SANGUIN F

	Kg	Kp	Na_g	Na_p	
12/9	116	5	58	149	mEq/l
15/9	90	5,0	21	145	
17/9	102	5,4	20	142	
19/9	93	5,8	11	155	
22/9	93	5	16	148	

Fig. 3



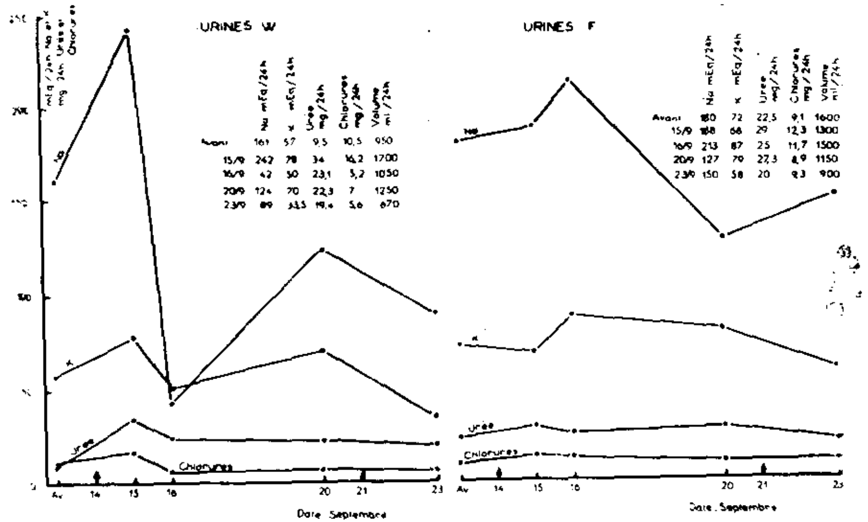
SANG W

	Hematies par mm3 × 10^5	Leucocytes par mm3 × 10^2	Valeur Globulaire	Polynucléaires %	Hematocrite %
12/9	55,4	77	0,81	72	50
15/9	54	45	0,91	59	50
17/9	48,6	74	0,92	63	48
19/9	44,8	46	0,69	60	46
22/9	46,6	48	0,96	54	45
	×	●		+	△

SANG F

	Hematies par mm3 × 10^5	Leucocytes par mm3 10^2	Valeur Globulaire	Polynucléaires %	Hematocrite %
12/9	50,4	58	1,02	61	53
15/9	51	55	1,07	65	51
17/9	52,8	61	1,05	61	51
19/9	46,8	51	1	52	49
22/9	48,9	52	1,08	66	50
	×	●		+	△

Fig. 4



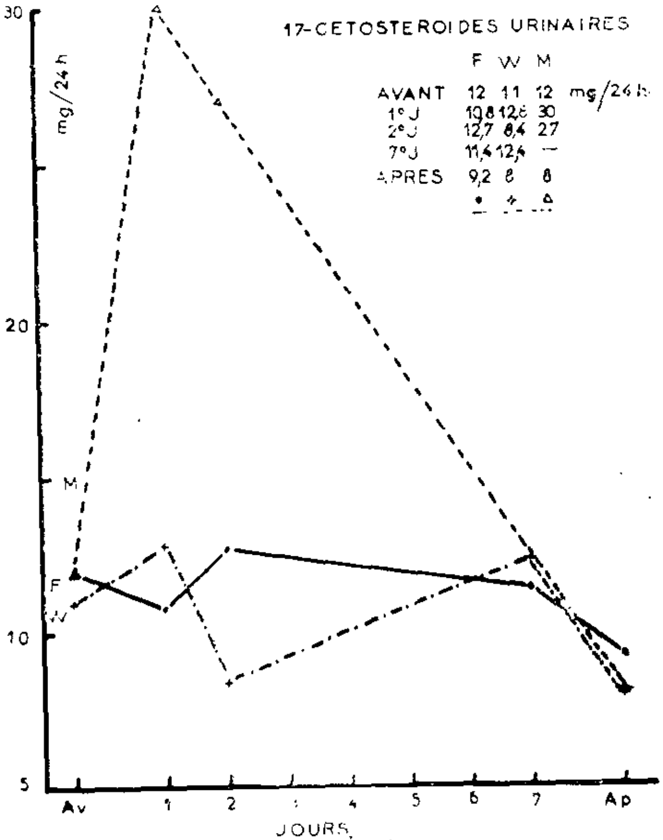
URINES W

	Na mEq/24h	K mEq/24h	Urée mg/24h	Chlorures mg/24h	Volume ml/24h
Avant	161	57	9,5	10,5	950
15/9	242	78	34	16,2	1700
16/9	42	50	23,1	5,2	1050
20/9	124	70	22,3	7	1250
23/9	89	33,5	19,4	5,6	670

URINES F

	Na mEq/24h	K mEq/24h	Urée mg/24h	Chlorures mg/24h	Volume ml/24h
Avant	180	72	22,5	9,1	1600
15/9	188	68	29	12,3	1300
16/9	213	87	25	11,7	1500
20/9	127	79	27,3	8,9	1150
23/9	150	58	20	9,3	900

Fig. 5



	F	W	M	
AVANT	12	11	12	mg/24 h
1° J	10,8	12,6	30	
2° J	12,7	8,4	27	
7° J	11,4	12,4	—	
APRES	9,2	8	8	
	●	+	△	

Fig. 6

17-HYDROXYCORTICOIDES URINAIRES

	F.	W.	M.	
AVANT	8,8	5,2	7	mg/24h
1° J	5,1	3,4	7	
2° J	4,5	2,1	6	
7° J	6,2	4,3	–	
APRES	5,2	2,7	4	
	•	+	Δ	
	—	— —	- - -	

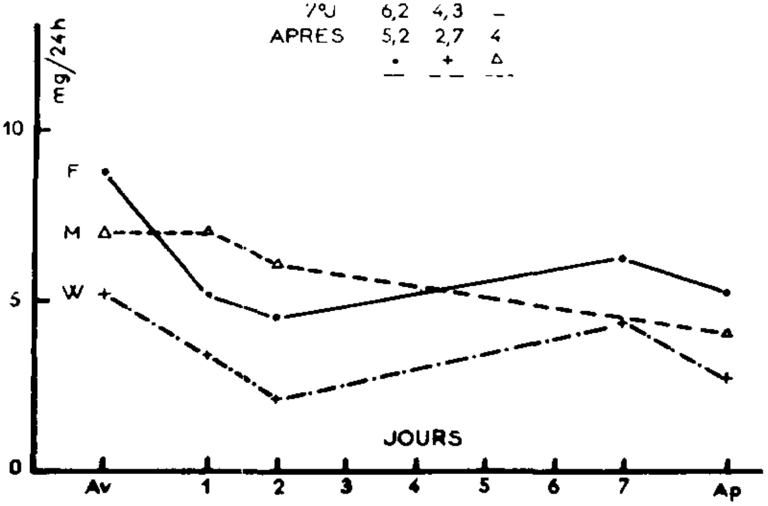


Fig. 7

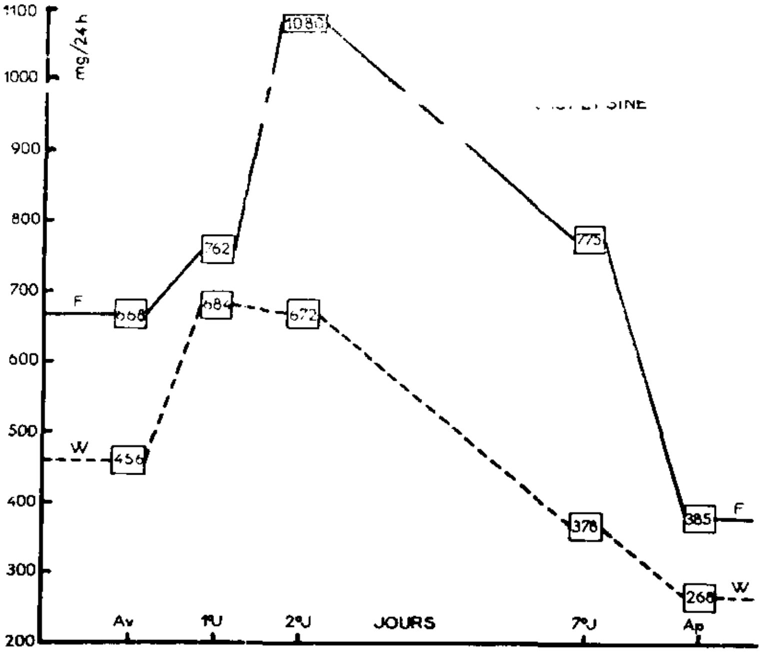


Fig. 8

Les variations modérées du taux des **17 cétostéroïdes** n'ont rien de comparable à celles que l'on enregistre au cours de l'effort sportif (fig. 6).

Mais les **17 OHCS** subissent une déflation nette, relativement transitoire le 2ᵉ jour, tandis que **les corticoïdes réducteurs totaux** ne présentent pas des variations tout à fait parallèles (fig. 7).

Rien à dire des **catécholamines totales,** normales le 5ᵉ jour, ni de la **réaction de Donaggio** qui ne fut positive qu'une fois après la sortie, chez (W).

Le taux de l'uropepsine dessine, en revanche, une courbe caractéristique, dont le sommet, très élevé chez (F), le 2ᵉ jour précède la violente crise digestive ressentie par celui-ci. Chez (W), uropepsinurie et crise digestive sont parallèles, mais moins fortes (fig. 8).

⁂

De cet ensemble de faits se dégagent quelques remarques qui ne prétendent pas expliquer toutes les réactions observées mais qui nous permettront d'envisager les précautions à prendre lors de la prochaine expérience, certainement plus sévère par sa profondeur ou par sa durée.

Ce qui donne toute sa valeur à l'épreuve, c'est le remarquable parallélisme du comportement des deux sujets, surtout en ce qui concerne les réactions biologiques. Plus vives chez (W), plus amorties chez (F), mais comparables.

Chronologiquement, nous distinguerons trois phases :

1ʳᵉ phase, très précoce, avec crise d'adaptation caractérisée par :

- de l'angoisse, très contrôlée par (F) (sauf dans le sommeil) surcompensée par (W) (ce qui en aggrave les effets) ;
- une asthénie modérée, à tout prendre et peut-être euphorique ;
- un ensemble de réactions métaboliques et hormonales, pouvant être pour la plupart apparentées au Syndrome d'Alarme, avec :
  - chute de la glycémie ;
  - légère baisse des 17 CS ;
  - baisse plus marquée des 17 OHCS ;
  - fuite du potassium globulaire ;
  - élimination excessive du sodium (ainsi que du potassium, ce qui est moins explicable).

Tout cela transitoire, trop tôt apparu et trop vite corrigé pour être la conséquence d'une agression par l'action chimique d'O2 ou de N2 sous une Pp double de la normale. Il est difficile d'interpréter cette crise autrement que comme un stress psycho-neurogène.

2ᵉ phase. Du 2ᵉ au 4ᵉ jour, l'adaptation s'affirme, la vie paraît décidément possible, l'activité redevient sensiblement normale. Mais une crise gastro-intestinale se développe, avec forte uropepsinurie, témoignage d'une deuxième crise d'adaptation, plus particulière, celle de l'alimentation, à ce genre d'existence.

Ou, peut-être, simple remous neuro-végétatif à prédominance vagale, consécutif au premier stress. Il est difficile de se prononcer à coup sûr.

3° phase. Les trois derniers jours, tout se passe comme si, détachés de la surface, les bathynautes avaient trouvé leur régime de croisière. Ils envisageraient favorablement un séjour beaucoup plus long. Plus rien n'altère leur dynamisme, sauf le souci de la remontée.

Toutefois, que ferait leur azotémie si l'expérience se prolongeait ? Et cette anémie relative de compensation à une Pp O2 double de la normale ne risquerait-elle pas d'entraîner à la longue une sidération de l'hématopoïèse ?

L'irritation cutanée et ses petits foyers pyodermiques ne pourraient-ils pas évoluer vers une infection staphylococcique plus grave, faute d'air sec et de soleil ?

Et que faut-il penser des très légers signes de souffrance corticale révélés par l'E.E.G. ?

Ces points d'interrogation, à vrai dire, ne sont pas suffisants pour nous priver d'optimisme.

⁂

Nous pensons, en effet, que, jusqu'à —20 m (peut-être —25) la plupart des difficultés entrevues aujourd'hui seront aplanies par :

- — le fait que le premier stade sera dépassé et la collectivisation de l'expérience ;
- — une diététique logiquement adaptée à ce mode de vie ;
- — une protection de la peau et une désinfection de l'habitat sous-marin par du soleil artificiel ;
- — et peut-être quelques médicaments (vitamines, inhibiteurs de la M.A.O., stimulants de l'hématopoïèse, etc.).

A des profondeurs plus grandes, l'atmosphère devra être obligatoirement appauvrie en oxygène et d'autres problèmes se poseront que nous n'avons pas le loisir d'évoquer ici.

⁂

TECHNICAL MEMORANDUM UCRI 731

NOAA OPS I & II

FORMULATION OF EXCURSION PROCEDURES FOR SHALLOW UNDERSEA HABITATS

by

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Final Report
to the Office of

Manned Undersea Science and Technology
National Oceanic and Atmospheric Administration

U.S. Department of Commerce

under

Contract 2-35479

to

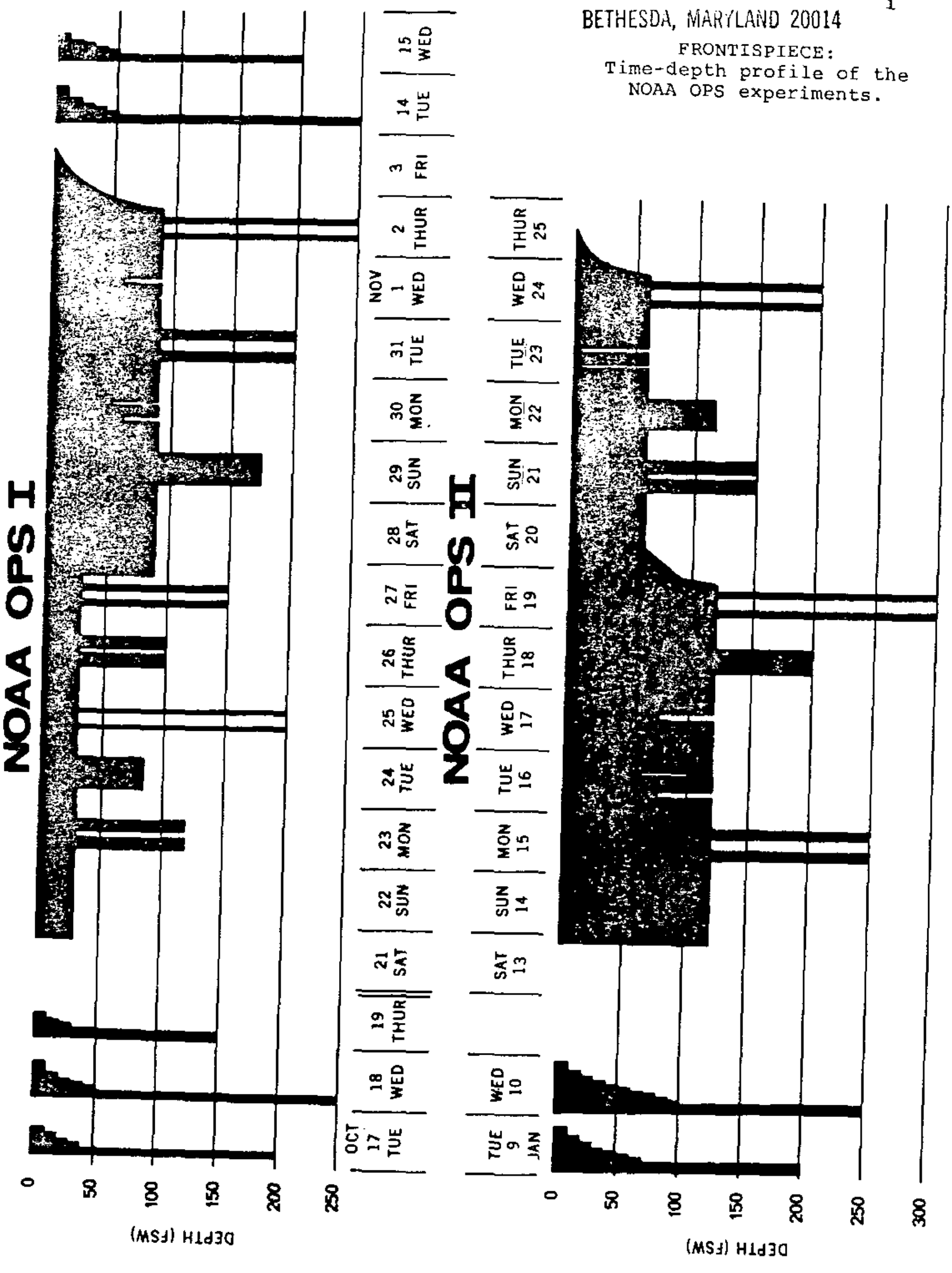
Union Carbide Corporation

ENVIRONMENTAL PHYSIOLOGY
LABORATORY

UNION CARBIDE TECHNICAL CENTER
TARRYTOWN, NEW YORK 10591

31 July 1973

FRONTISPIECE:
Time-depth profile of the
NOAA OPS experiments.



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VIII. CONCLUSIONS

We can extract from this verbal haystack a few salient conclusions:

1. Using data from appropriate previous dives can be an effective method for advancing to new diving modes. The NOAA OPS method for doing this has been demonstrated.

2. Descending no-stop excursion dives with air, for a depth change of up to 180 fsw, can be made from saturation at depths up to 120 fsw in a normoxic nitrogen atmosphere. These excursions became more efficient with increasing habitat depth.

3. Efficient decompression from saturation with nitrogen can be accomplished without the breathing of pure oxygen by mask.

4. Ascending excursions of operationally useful times and depths have been shown to be possible, from the nitrogen habitat.

5. Momentary surfacing should be considered as an option for a lost or disoriented diver saturated at depths as great as 100 fsw.

6. Adaptation to a nitrogen habitat should enable a diver to work safely while breathing air at a depth greater than he could from sea level. The extra depth is approximately equal to that of the habitat. This does not seem to apply to excursions as deep as 300 fsw; 250 fsw might be a good stopping point.

7. Because our observations were confused by previously-contracted illness of divers saturated at 120 fsw, we cannot draw firm conclusions regarding the tolerance of subjects to saturation with normoxic nitrogen at greater depths than this.

Technical Memorandum B-411

Saturation Diving to 650 Feet

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Page

A. SUMMARY

Ocean Systems, Inc. has conducted the deepest, longest chamber dive on record. Two divers, Arthur D. Noble and Robert W. Christensen attained an equivalent depth of 650 feet for 48 hours and two minutes. This dive was conducted between August 6 and 14, 1965 at Ocean Systems' Diving Research Facility at Tonawanda, New York, in an effort to demonstrate for the first time that man can function for extended periods of time at the pressure prevailing at the deep boundary of the continental shelf. Detailed medical, physiological and psychological measurements taken in the course of this dive show beyond a reasonable doubt that man can reside for prolonged periods of time anywhere on the continental shelf without acute or latent detriment to his health and without a significant impairment of his functionality.

The ultimate physiologic and psychologic depth limit of man's existence in the sea remains to be determined in future experimentation.

C. INTRODUCTION

The diving research program of Ocean Systems, Inc. is aimed at extending commercial diving operations to maximum depths compatible with the maintenance of human health and performance capability.

The initial goal of this program is the attainment of an operational capability for the performance of useful work at the deep boundary of the continental shelf.* In order to justify the technical efforts necessary to develop decompression procedures for dives to depths of up to 200 meters (656 feet) with bottom times of operational significance, it became necessary to prove beyond a reasonable doubt that man can not only withstand exposure to pressures associated with such depths without detriment to his health, but in addition can remain capable of performing useful work of a physical as well as mental nature. To this end, an unprecedented chamber dive was conducted at Ocean Systems' Diving Research Facility at the Tonawanda Research Laboratory of Union Carbide Corporation.

Following a series of 57 chamber dives to increasing depths, including four dives with two subjects each to 650 feet with a bottom time of 40 minutes, Dive 58 was launched on 6 August 1965 with two divers on board. This dive, with a programmed bottom time of 48 hours at a depth of 650 feet represents the deepest and longest manned

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* Convention On The Continental Shelf Done At Geneva, April 29, 1958, And Entered Into Force, June 10, 1964

ARTICLE 1:

"For the purpose of these Articles, the term 'Continental Shelf' is used as referring; (a) to the seabed and subsoil of the submarine areas adjacent to the coast but outside the area of the territorial sea, to a depth of 200 meters or, beyond that limit, to where the depth of the superjacent waters admits to the exploitation of the natural resources of said areas; (b) to the seabed and subsoil of similar submarine areas adjacent to the coasts of islands."

pressure exposure ever attempted. It also marks the latest in a series of increasingly deeper saturation dives performed in support of Mr. Edwin A. Link's "Man-in-the-Sea" program which is now being conducted under his guidance by Ocean Systems, Inc.

Much of the inspiration for this advanced diving experiment was derived from the pioneering efforts of the French Oceanauts under Captain Jacques-Yves Cousteau and the Aquanauts of Sea Lab I and II of the United States Navy under Captain George F. Bond. It was Dr. Bond who first conceived the idea of saturation diving and who demonstrated its physiological and technical feasibility. A special debt is owed to him and to his early associates Drs. Robert D. Workman and Walter F. Mazzone.

In view of the potential importance of our dive experiment to the United States' effort in the deep submergence field, the Office of Naval Research and its contractors were invited on 3 June 1965 to participate in this research undertaking.

The dive followed an experimental plan outlined in Figure A. Except for minor changes necessitated by operational problems, this plan was adhered to. This report describes in detail the theoretical, operational, medical, physiological and psychological aspects of Dive 58.

Although not described in the body of this report, one experiment was conducted on board this dive which deserves special attention. The dive crew was asked to prepare and study during decompression, while still at considerable depth, xenon hydrate, a compound not stable at atmospheric pressure. This modest but successful experiment illustrates the feasibility of conducting, as it were, in situ pressure experiments not easily performed at sea level. Studies of physical and chemical as well as biological phenomena under pressure with direct access of the investigator to the object of his attention may in the future become important adjuncts to saturation diving.

The men selected for Dive 58 were Arthur D. Noble and R. W. Christensen, members of Ocean Systems, Inc. These divers were selected on the basis of their open sea and chamber deep diving experience, their scientific and practical training, and their superior motivation. It is unlikely that Dive 58 could have succeeded in attaining its objectives without the quiet dedication these men displayed to the trying and sometimes distasteful tasks* at hand.

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* A schedule of tasks performed by the divers during one 24-hour period under maximum pressure is shown in Appendix B-4.

PHYSIOLOGICAL EVALUATION OF SEALAB II:
EFFECTS OF TWO WEEKS EXPOSURE TO AN UNDERSEA 7-ATMOSPHERE HELIUM-OXYGEN ENVIRONMENT

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Captain George F. Bond, MC, USN; and
Captain Walter F. Mazzone, MSC, USN.

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For invaluable assistance in final preparation of this report, thanks are due to scientific and technical personnel of Northrop Space Laboratories. Dr. Advani, in cooperation with Dr. Webb, of Webb Associates, made the mathematical analysis of respiratory heat loss. Doctors Demetriou, Roy, Martell, and Sullivan, with Herman Roth, read and helped in revision of final drafts of this paper, with Ted Tagami providing graphic inputs, and Jack Beattie completing the statistical analysis. Finally, Mary Jane Hiskey typed all of the five drafts, with their cryptic interlineations.

In the last analysis, our greatest thanks must go to the Aquanauts, together with their resident medical officer and medical technicians. These adventurers not only accomplished their assigned work projects in a hostile ocean environment, but invariably managed to provide the biologic products essential to the body of this report. It is hoped that the negative nature of our findings will be a source of solace and reassurance to these men and others of their breed.

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FOREWORD

At best, operational research has always been a difficult and unsure venture. In undersea operations such as SEALABS I and II, the fundamental purpose of our physiological observations was to monitor the aquanauts as they lived and worked in the most hostile environment of man's experience. The following report represents an evaluation of the data acquired in the latter experiment.

The physiological information which is presented in this report was not easy to obtain. In most cases, biomedical tests could be achieved only at the expense of other, possibly more important, scheduled undersea operations. Acquisition of the data which comprise this report reflects the aggressive ingenuity of dedicated aquanaut investigators and the selfless assistance of men who elected to be subjects for the physiological study phase of the experiment.

The foregoing relates to problems in the broad frame of the experiment. The very real hardships, however, remained with the aquanaut subjects. These men, dedicated to the successful performance of useful undersea tasks, were required at unpredicted intervals to alter planned procedures, and to submit themselves, body, blood, and mind, as human guinea pigs. This they did without protest.

Finally, it must be taken into account that the overall plan of physiological data acquisition lacked orderliness, and therefore must be subject to considerable after-thought criticism. Nonetheless, it is our feeling that the physiological findings here reported are worthy of record, albeit presented in a "bare-bones" manner.

CONTENTS

CONCLUSIONS

1. SEALAB II was emplaced at 205 feet depth at La Jolla, California. Pressure was thus 7.2 atmospheres absolute, or approximately 105 psia.
2. Temperature in the water around SEALAB was between 44 and 56° F. Time of year was late August to mid-October of 1965.
3. Atmosphere in SEALAB was composed of 188 to 268 mm Hg oxygen, less than 965 mm Hg nitrogen, less than 22 mm Hg Co_2, and helium to make up the balance of 5358 mm Hg of total pressure. In percentage, these become: 3.5 to 5% 0_2, less than 18% N_2, less than 0.4% CO_2, 77 to 79% He. Oxygen varied between 24 and 30% when converted to sea level equivalent (sealent) pressure.
4. Ambient temperature inside SEALAB was maintained between 85 and 89° F. Relative humidity was about 76%.
5. Twenty-eight men occupied SEALAB, in three teams of ten men each for 15 days. One man spent 30 consecutive days, and one man 15 days each with the first and third teams. Mean age of the men was 35 years, with range from 25 to 50 years.
6. Oral temperature rose immediately on exposure to SEALAB and continued to rise for 4 days. Peak temperature reached at this time showed mean of 100.0 ± 0.08° F, a rise of 1.5° F from the baseline mean value. A slow decline appeared after this, but temperature remained about 1° F above pre-exposure levels. Post-dive data showed rapid return to normal. The rise during occupation of SEALAB is highly significant statistically. This rise may be the result of higher heat loss due to the greater thermal conductance of helium, with consequent greater heat production, and new higher thermoregulatory setting.
7. Pulse rate increased during the dive period from mean of 71.4 ± 2.4 pulses/minute, to 84.9 ± 2.7 on Day 2. A general trend downward followed, but rates remained higher throughout the exposure than baseline values. These determinations were made on nearly all the men. Heart rate, as counted from electrocardiographic traces, showed a slight decrease, marked on Day 3. Only a small number of men were used for these heart rate determinations in contrast to the large number used for pulse rate. Thus the discrepancy between results must be ascribed to the relative numbers of subjects, and greater reliance placed on the pulse rate determinations. Slight arrhythmias were found in some ECG traces.
8. Systolic pressure rose slightly until Day 5, when mean was 133 mm Hg compared to baseline of 127. Diastolic rose from 80 to 86 mm Hg in the same period.

Values remained relatively constant for the duration of exposure, with a slight trend down in systolic pressure. These results probably indicate a slight cardiovascular response to stress.

9. Electroencephalography showed slight transient changes during the stay on the bottom. No changes of permanent nature were noted on post dive examination.
10. Erythrocyte number during the dive markedly decreased, from mean baseline value of 5.60 ± 0.22 million/mm^3 to 4.25 ± 0.13 on Day 3. These low levels were maintained until Day 9, after which a slow trend toward normal is manifest. The marked changes do not show statistical validity only because baseline and dive subjects were not always the same, and small numbers of subjects were used. Additional time in SEALAB, as exemplified by the one man who spent 30 consecutive days there, did not cause further rise toward normal values. The observed decrease in RBC may be a result of slightly increased ambient pO_2. This change is conjectured as due to fluid balance shifts, sequestration of cells in the spleen or other vascular compartment, or actual increased rate of erythrolysis.
11. Total leucocyte count showed no consistent change. Neutrophils showed a slight steady decrease, and a replacement of this number by a concomitant increase in lymphocytes. These changes may also be due to increased pO_2.
12. Hematocrit ratio changed relatively little, when the original baseline is considered. However, a second baseline taken immediately before the dive showed mean of 47.8 ml/100 ml, a fall to 45.6 on Day 2, and rise to 50.0 on Day 13, with post-dive value of 50.4. Hemodilution would explain the decreased values. It should be noted that the major decrease in erythrocyte count should normally be matched by a similar decrease in hematocrit. The fact that this did not occur points to a possible procedural error in the red blood cell count, or one of the other possibilities mentioned under the discussion for this parameter.
13. Hemoglobin level fell from baseline mean of 15.35 ± 0.15 gm/100 ml to low value of 13.0 ± 0.74 on Day 3. It rose slightly for the duration of the exposure, and returned to higher than normal values immediately post-dive. These changes may also be due to slightly increased pO_2.
14. Reticulocyte fall appears to indicate retarded erythropoiesis in the first days of exposure, followed by resumption of near-normal levels of cell production.
15. Platelet count increase was probably due to general stress. Sedimentation rate remained normal, although a slight decrease appeared evident.

16. Blood electrolyte changes included increases in serum sodium and potassium (on the basis of Horvath's figure immediately pre-dive). Calcium, chloride, and other measured parameters revealed no change. Serum CO_2 and other biochemical factors did not change. The electrolyte changes may reflect blood pH changes, although no data are available to substantiate this hypothesis. The lack of change in blood gases indicates normal physiological functioning in this respect in the SEALAB atmosphere.
17. Comparisons of exposure values with Horvath's baseline data taken immediately before the dive show a clear increase in serum glutamic oxaloacetic transaminase. Immediately on return to sea level normal values were resumed. Serum glutamic pyruvic transaminase also increased, as did lactic acid dehydrogenase. This general increase in all serum enzymes is probably a response to the multi-factorial environmental stresses, or alternatively, to the increased exercise under difficult and unusual conditions.
18. Urine volume showed initial increase, probably due to diuresis imposed by the cold water. The trend back to baseline may reveal poor urine collection methods only. Specific gravity increased slightly throughout.
19. Urine sodium appears to have increased, as did calcium and potassium. Phosphorus and creatinine may also have increased, but the erratic swings in value may indicate procedural errors. Such changes as did occur reflect stress, exercise, and/or dehydration..
20. Imposed exercise studies revealed no decrement in performance with time of exposure, although subjective feelings of lassitude and fatigue were reported.
21. Swimming in cold water caused marked reduction in extremity temperature and usually slight rise in central body temperature. On re-entering SEALAB, and especially following hot shower, rectal temperature fell markedly, presumably due to shunting of blood to the periphery due to vasodilation. This may in part explain the "paradoxical shivering" observed after the warming period.
22. Studies on erythropioesis revealed no significant changes.
23. Maximal work capacity decreased after the dive. Increase in metabolic response to cold stress with loss of body heat also occurred, thus indicating increased cold tolerance.
24. Neurological changes did not result from the SEALAB exposure, and psychophysiological studies revealed no prolonged deleterious effects of the exposure.
25. In general conclusion, the changes that were apparent in the measured physiological functions were of a mild, transitory nature. Where post-exposure data

were taken, it was found that immediate return to pre-dive levels occurred. A few changes, among them body temperature and erythrocyte number, reflect greater and probably significant change.

The multiple stresses imposed by the environmental conditions which constitute the SEALAB exposure all have their potential effects on the physiological responses. Elevated partial pressure of oxygen, high levels of exercise (and poor sleep?), high temperature and humidity, and swimming in cold water all appear to be implicated in the environmental factors operating to cause changes, either singly or in combination. The high helium content of the atmosphere does not seem to be implicated, except for its role in increasing heat loss through high thermal conductivity. High pressure per se does not appear to be directly implicated, but may be part of the general stress.

26. Although the SEALAB II exposure appears from this analysis of data to have had relatively innocuous effects on the participants, extension of these findings to greater depths or for longer periods of time must be done with care. The great success of this program to date insures the validity of its basic concepts, and its operational extension will now depend on the further careful progress that has characterized it to date.

MARINE TECHNOLOGY SOCIETY, WASHINGTON, D.C.

1967

The NEW THRUST SEAWARD

TRANSACTIONS OF
THE THIRD ANNUAL MTS
CONFERENCE & EXHIBIT

5-7 JUNE 1967
SAN DIEGO, CALIFORNIA

SATURATION DIVING: VERTICAL EXCURSION TECHNIQUES

Alan R. Krasberg

ABSTRACT

To date we have accumulated 1,130 man days of living at pressure and 4,670 hours of actual work in the water. This is approximately 50% more time living at pressure and a factor of 5 more water time than all other known field saturation dives combined. The divers live on the surface in a Deck Decompression Chamber and commute to work on the bottom in a Submersible Diving Chamber. In between field jobs this system has been used for experimental dives. The success of the first experimental excursion allowed the calculation of an Excursion Diving Table which has now been used during more than 4,000 hours of excursion dives in the field. Subjects in these experimental dives were given extensive mental testing, both before and during the excursions. There were no significant deviations in the scores. We foresee no major stumbling blocks to reaching depths beyond 600 feet using saturation methods for maximum diver safety and performance.

To date, during 33 operational saturation dives, we have accumulated 1,130 man days of living at pressure (including decompression) and 4,670 hours of actual work in the water. This is approximately 50% more time living at pressure and a factor of 5 more water time than all other known field saturation dives combined. In addition, all of our dives have been of an operational nature, in water chosen not because of its clarity, temperature or nearness to shore, but because there was a job to be done.[1,2,3,4,5].

Unlike the Sealab and Conshelf bottom habitat experiments, the divers live on the surface in a large Deck Decompression Chamber and commute to work in a Submersible Diving Chamber. This is safest and cheapest and it reduces maintenance and logistics problems, permits the use of high explosives, allows heavy lifts to be made over the work area, and greatly increases the vertical and horizontal range of the diver. The system is shown in Figure I.

In between field jobs the system has been used for experimental dives. Thus the first experimental helium-oxygen excursions were performed during March 1966 in a lull between the Smith Mountain Dam and Gulf of Mexico (West Delta 117) operations.[6] The success of this experiment allowed the calculation of an Excursion Diving Table which has now been used during more than 4,000 hours of excursion dives in the field. The assumptions used for calculation of the tables are shown in Figure II and a few dives from the ninth week of operations in the Gulf of Mexico are shown in Figures III to VII. The generally horizontal line at the top denotes DDC depth at the very beginning and end, and SDC depth in the middle. The jagged line usually below this shows the depth and time course of the divers exposure while on the breathing apparatus. The excursion tables are designed to follow the diver as he changes depth rather than being based on his maximum depth. The importance of this can be appreciated by inspecting the dives.

A second experimental dive was performed during March 1967. Excursions of 200 feet to 300 feet were tested with storage depths ranging from 300 feet to 400 feet, and the working depth being 600 feet. The three subjects were each given a rather extensive (two hour) mental test at 0 feet, 250 feet, and 400 feet. There were no significant deviations in the scores.

Each subject did 20 minutes of work at 600 feet (average oxygen consumption 1.54 liters/minute) while on a prototype field model closed-circuit constant pO_2 diving apparatus.

Manual dexterity and mental ability tests[8] were performed at depth. These tests were chosen to allow a direct comparison with the results noted by the Royal Navy. The manual dexterity test consists of picking up ball bearings with a pair of tweezers and placing them in a tube. The score is the number of ball bearings in the tube after 60 seconds. The mental ability tests consisted of two digit by one digit multiplication with the scores being the number right and the number attempted after 90 seconds. Each test was done at least three times by each man to determine a point. One subject, a standby who replaced one one of the primes, showed some residual learning on both tests (about 4%). His predive baseline has been adjusted to the new level. The results and a comparison with the British data[7] are shown in Tables I and II.

TABLE I

Ball Bearing Test

	Westinghouse	Royal Navy[7]
Baseline	-	-
300 feet	-0.4%	-
600 feet (first dive)	-15.4%	-25%
600 feet (second dive)	- 1.2%	-25%
430 feet	+ 2.0%	-
400 feet	+ 1.4%	-

TABLE II

Arithmetic Test

	# Right	R.N.[7]	# Attempted	R.N.[7]
Baseline	-	-	-	
300 feet	+0.92%		+2.16%	-
600 feet (first dive)	[illegible]	-18%	-4.16%	-4%
600 feet (second dive)	+4.02%	-18%	+3.95%	-4%
400 feet	-1.83%	-	+0.80%	-
260 feet	+0.46%	-	+1.04%	-

The variable being tested in these dives is descent rate. Everything else is as much the same as possible. The Royal Navy used a rate of 100 feet/minute. Our first descent to 600 feet started from saturation at 100 feet and proceeded 200 feet/120 minutes, 250 feet/120 minutes, 300 feet/120 minutes, and then directly to 600 feet at 15 feet/minute. The second 600 foot dive started from saturation at 360 feet and depth was reached in less than five minutes. I think it is clear that most, if not all, of the decrease in performance noted by the Royal Navy at 600 feet is due to some kind of compression effect, and that our first descent, slow as it might be, was not slow enough to do more than cut the falloff in performance in half. It remains to be seen whether other "helium narcosis" observations made in the range of 600 feet to 1000 feet might not be attributable to this same cause.

In any case, it follows that for maximum diver safety and performance to depths beyond 500 feet, saturation methods with the vertical excursion held down to something like 300 feet, must be employed.

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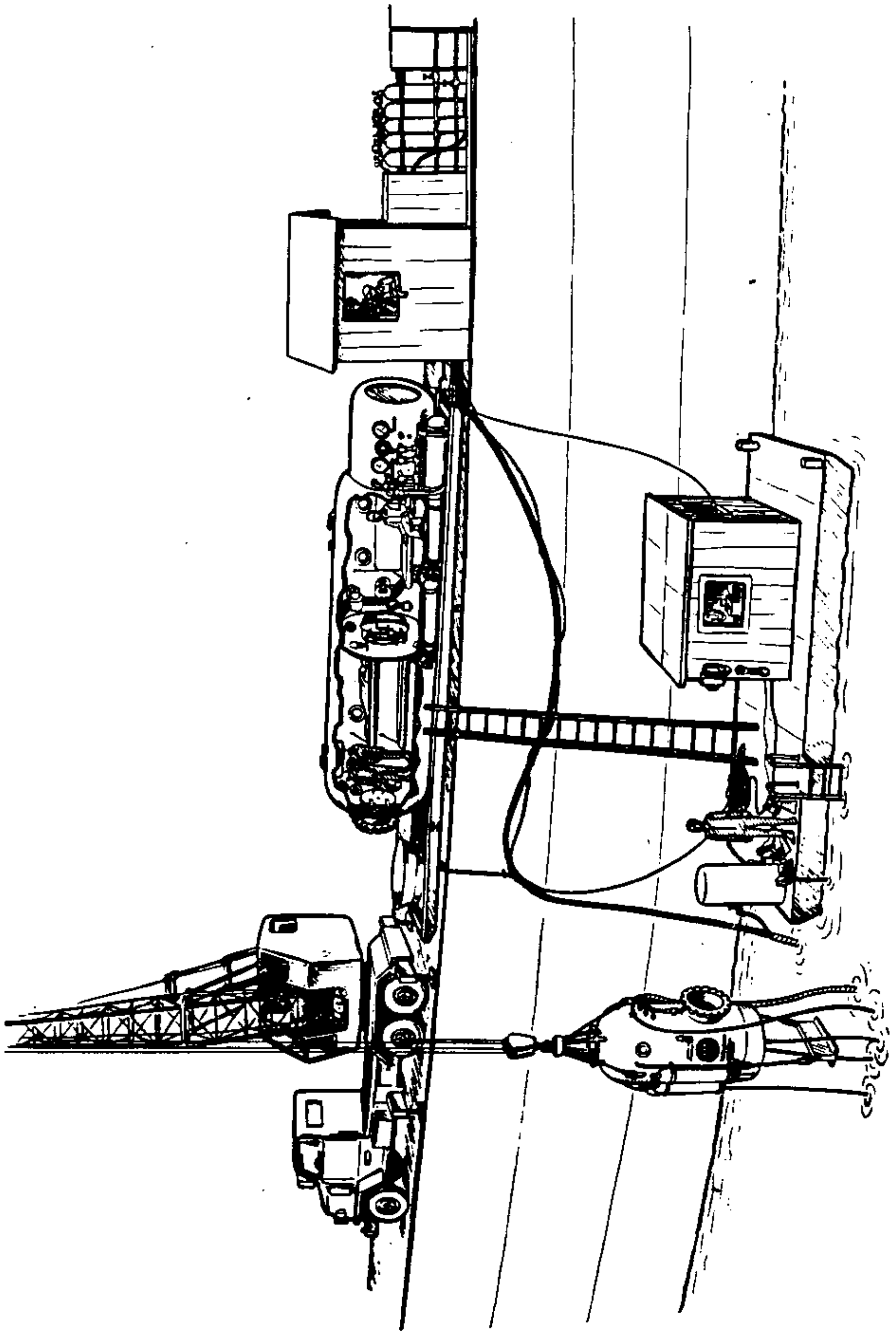

FIGURE I

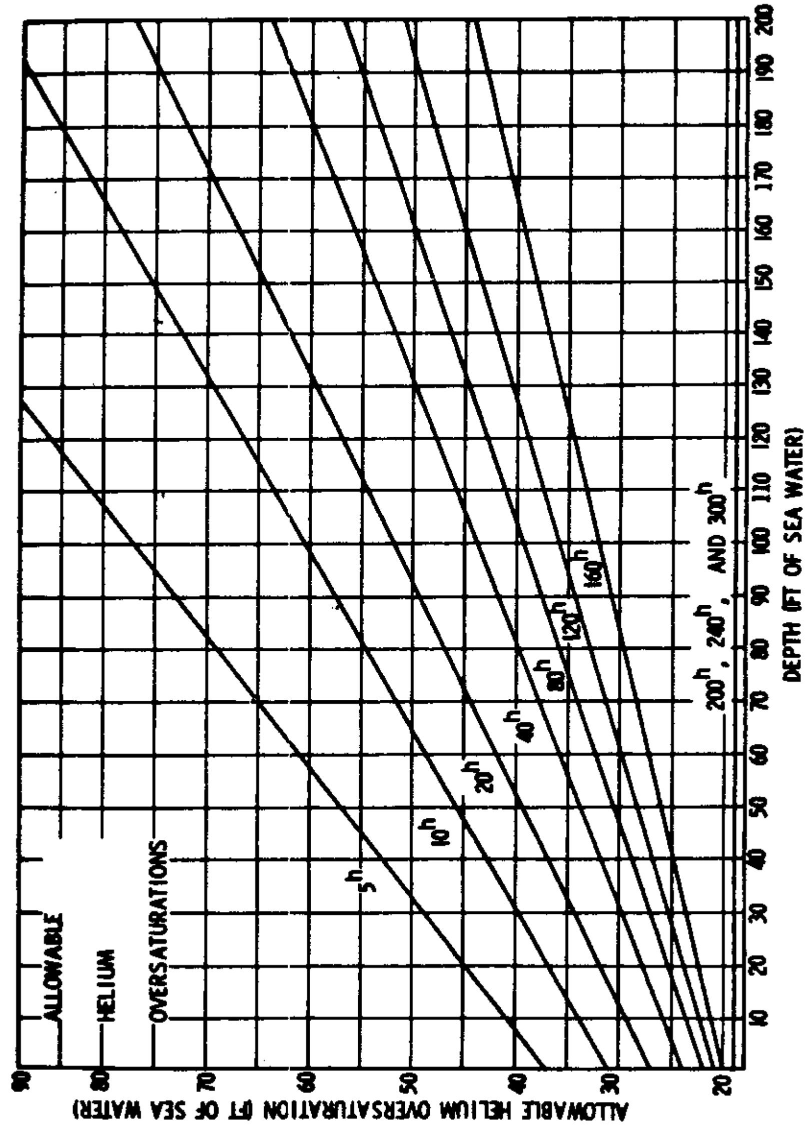
ALLOWABLE
HELIUM
OVERSATURATIONS
5h
10h
20h
40h
80h
120h
160h
200h, 240h, AND 300h
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
DEPTH (FT OF SEA WATER)
20
30
40
50
60
70
80
90
ALLOWABLE HELIUM OVERSATURATION (FT OF SEA WATER)

FIGURE II

7-14-66
Dive No. 3 (MK-8)

Diver No. 2

Start - 0520
Finish - 1143

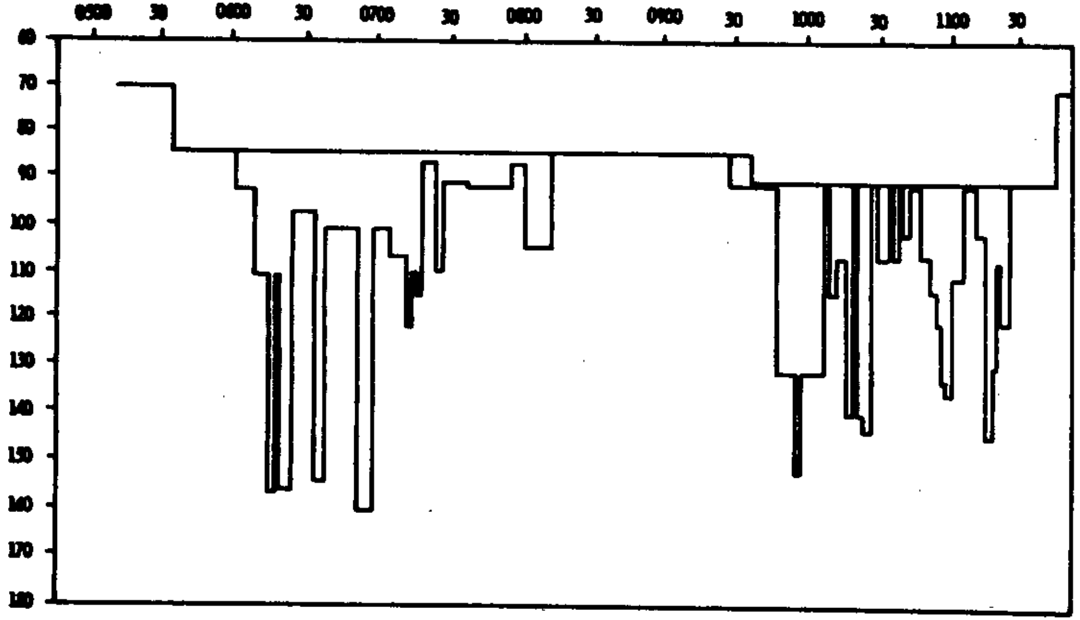

FIGURE III

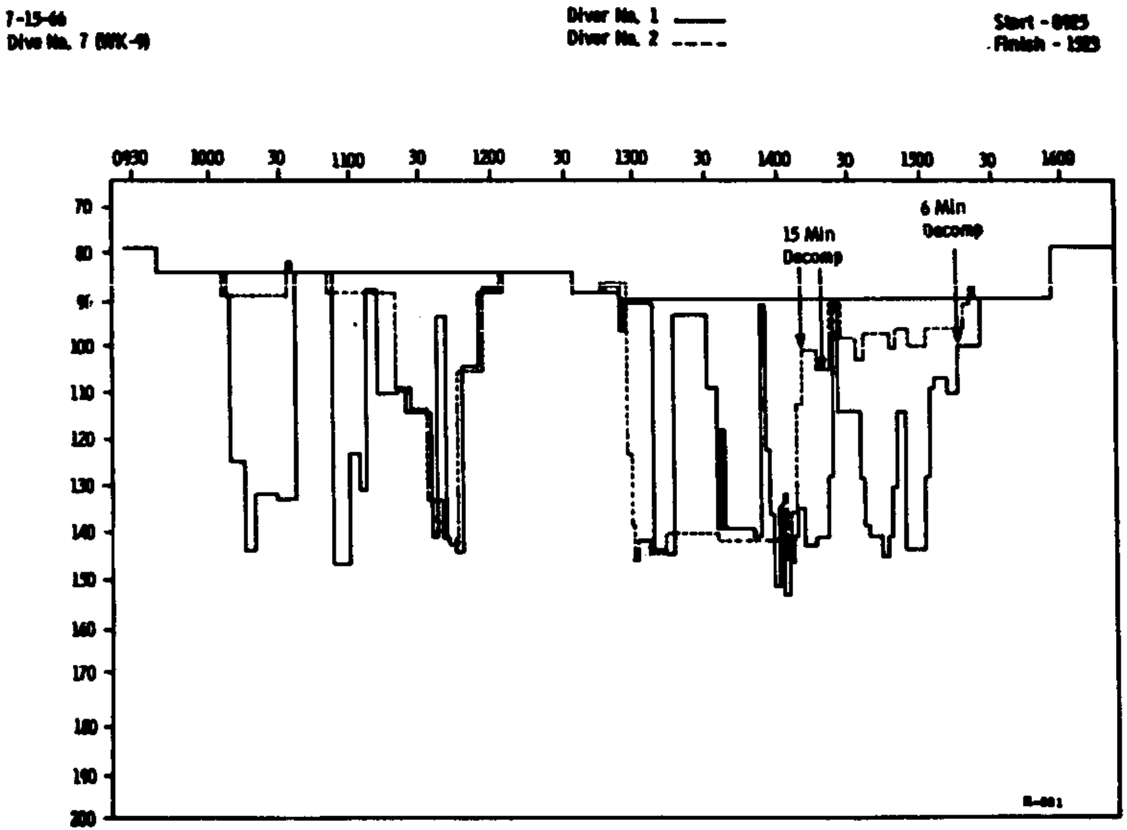
7-15-66
Dive No. 7 (MK-9)
Diver No. 1 ———
Diver No. 2 - - - -
Start - 0925
Finish - 1555
0930
1000
30
1100
30
1200
30
1300
30
1400
30
1500
30
1600
70
80
90
100
110
120
130
140
150
160
170
180
190
200
15 Min Decomp
6 Min Decomp
R-001

FIGURE IV

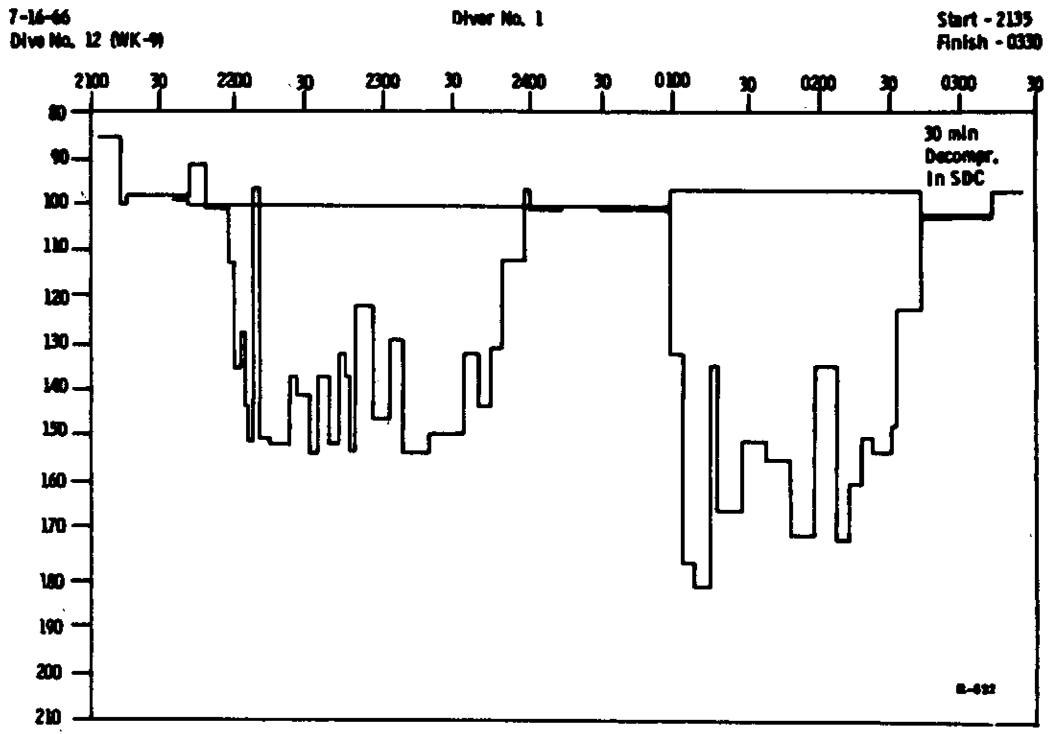
7-16-66
Dive No. 12 (WK-9)
Diver No. 1
Start - 2135
Finish - 0330
2100
30
2200
30
2300
30
2400
30
0100
30
0200
30
0300
30
80
90
100
110
120
130
140
150
160
170
180
190
200
210
30 min
Decompr.
In SDC

FIGURE V

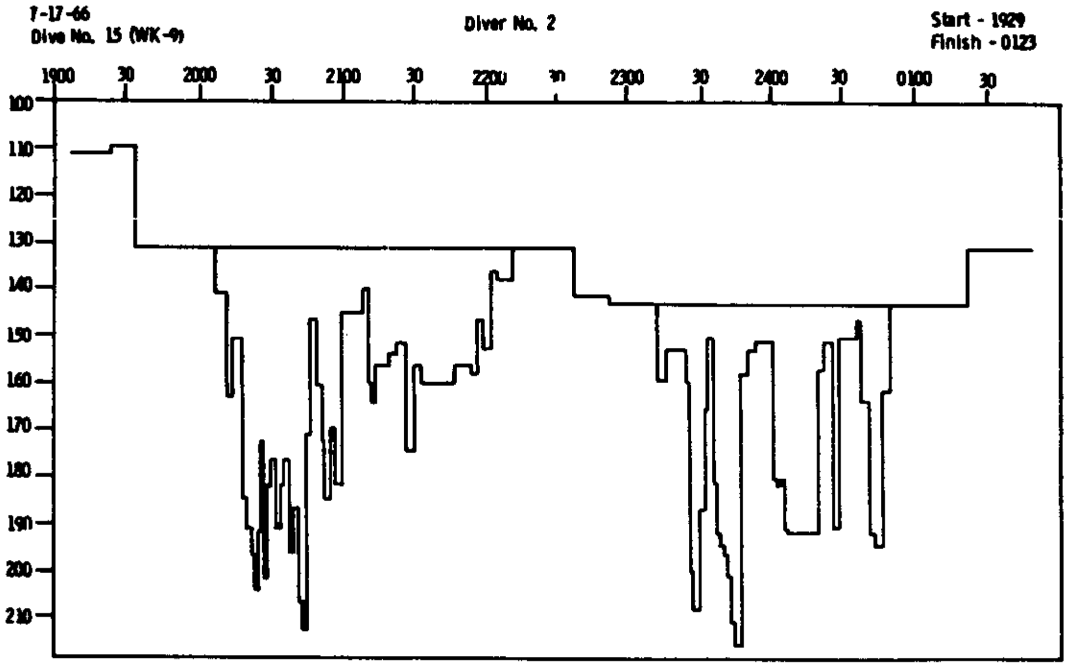
7-17-66
Dive No. 15 (WK-9)
Diver No. 2
Start - 1929
Finish - 0123
1900
30
2000
30
2100
30
2200
30
2300
30
2400
30
0100
30
100
110
120
130
140
150
160
170
180
190
200
210

FIGURE VI

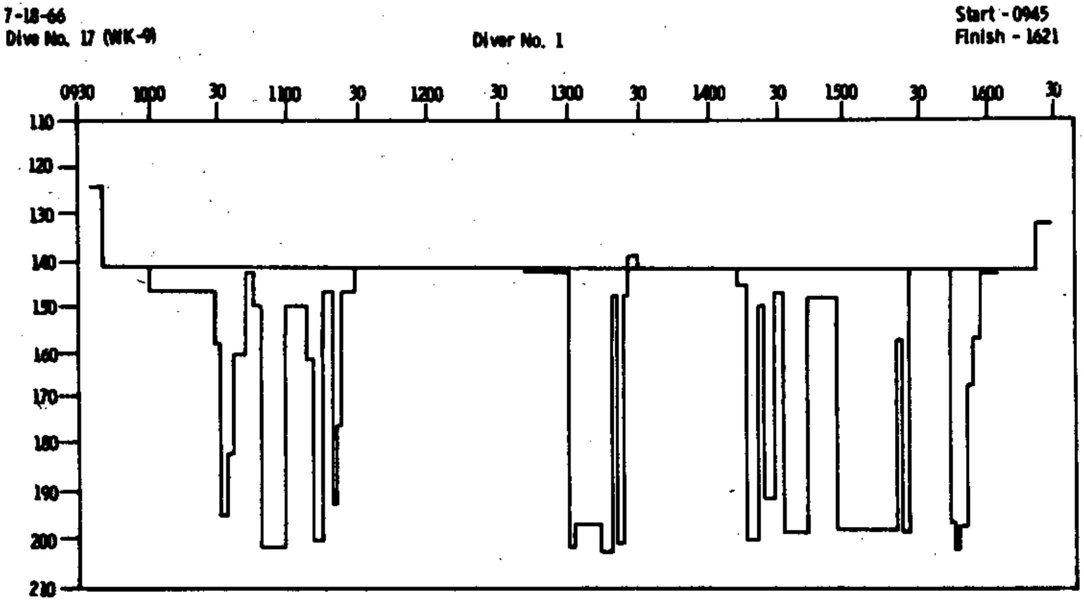

FIGURE VII

B-634

NATIONAL GEOGRAPHIC 123:713-717. 1963.

Revolutionary diving cylinder has opened the way to new and unexplored frontiers— the vast continental shelves, with their promise of mineral wealth and scientific riches

Our Man-in-Sea Project

By EDWIN A. LINK

ONE FEBRUARY DAY in 1962 I had the privilege of presenting to the National Geographic Society's Committee for Research and Exploration a project called Man-in-Sea.

The ultimate aim of this undertaking, I explained, was to enable men to live and work on the floor of the ocean at depths of 1,000 feet or possibly more for days, weeks, and even months.

"Working under water for weeks at a time!" I could feel a sudden tightening of attention in the room. These distinguished scientists and Society officers needed no one to tell them what such a development could mean to the world.

The average depth of the continental shelves is around 600 feet. If man could find a way to work there in safety and relative comfort, he would at once possess the key to more than 10,000,000 square miles of sea bed. He could tap the scientific secrets and mineral, animal, and vegetable wealth of these immense submerged plains, exploring ancient wrecks, mining diamonds or gold, farming the sea floor, feeding and herding fish like cattle.

Diver's Working Time Multiplied Manyfold

Most important, by *staying* down for long periods a diver would multiply many times the amount of useful work he could accomplish on the floor of the sea. No matter how long the dive, he would have to go through the time-consuming process of decompression only once. The time a diver on compressed air must spend in decompression after an hour at 300 feet, for example, is 7.63 hours—more than *seven and a half* times as long as he could spend in actual work. Man-in-Sea thus opened the prospect of intensive and continuous undersea work.

But I could feel a polite skepticism. How did I propose to solve the problems of nitrogen narcosis, the so-called drunkenness of the depths; and the dread decompression sickness, the bends?

In deep diving, man, not designed for living under water, faces grave dangers. Under pressure, his body absorbs gases contained in the air he breathes. Below 100 feet, nitrogen in the compressed air becomes narcotic, impairing the diver's faculties. His attention wanders, so that he forgets to take normal precautions. This is nitrogen narcosis, and it has cost many a life.

If the diver stays down for a long time, and then comes up too quickly, gases dissolved in his body do not have time to pass off normally, and form bubbles. In his body tissues, the bubbles may cause itching and excruciating pain. In his circulatory system, they may obstruct the flow of oxygen to vital nerve and brain centers, causing blindness, paralysis, even death.

Because of these physical facts, dives to great depths have had to be sharply limited in time. Long ago it was discovered that if an ascending diver stopped at certain depths for varying lengths of time, gases absorbed by his body would pass off harmlessly. The catch is that so much time must be spent in decompression.

One answer to the problems of deep diving, I pointed out, would be to replace normal atmospheric air with an artificial mixture of oxygen and a non-narcotic gas. Years ago the United States Navy found that, by replacing numbing nitrogen with helium, narcosis of the depths was eliminated.

Another Hazard—Oxygen Poisoning

If a man breathes high concentrations of oxygen for a long period, he risks oxygen poisoning, which usually begins with nausea, progresses to muscular twitching, and ends in a convulsion. To avert this peril, the proportion of oxygen in the artificial helium-oxygen atmosphere must be reduced as the depth of the dive increases. The object is to keep the absolute quantity of oxygen always the same as that at sea level.

The proposed long-range program was described to the committee as envisioning three major pieces of equipment: (1) an underwater pressure chamber affording houselike living conditions; (2) a smaller one-man chamber which would act as an elevator between the bottom dwelling and the surface; and (3) a large pressure-housing on the surface for comfortable decompression of several men at the same time (see drawing at left).

For the present we proposed to limit testing to the Stage 2 diving chamber, which would experimentally serve the function of the other two elements; besides carrying the diver from ship to bottom and return, it would double as a house from which he would emerge to the sea floor at will. It would also serve, aboard ship, as a decompression chamber.

Such a three-purpose diving chamber had already been built to my design through cooperation of the Smithsonian Institution and the Link Division of General Precision, Inc.

To this project the National Geographic Society now gave its powerful support, including a substantial grant of funds. First trials were planned for the summer of 1962.

Diver Exceeds 24 Hours at 200 Feet

"By the end of the year," I told the committee, "I hope to say that man can live and exist at 200 feet or more, coming back into this underwater house to eat or sleep, then going out to work or explore."

How this, and more, was accomplished off southern France last summer is told by Lord Kilbracken, in the following article.

We are grateful indeed to the U. S. Navy and its Sixth Fleet under Vice Adm. David L. McDonald for the fine cooperation given us in connection with these initial tests.

Besides the U. S. Navy and ourselves, other groups are working on diving problems.

The Swiss mathematician and diver, Hannes Keller, has gone as deep as 1,000 feet, but remained minimal time on the bottom, surfacing with drastically reduced decompression, using mathematical computations based on a secret mixture of gases.

Jacques-Yves Cousteau, the noted French undersea pioneer, has kept two divers in an underwater dwelling for a week, at a depth of 33 feet, from which they made sorties down to 80 feet.

Neither of these two approaches has combined the problems of remaining under water *at great depth for a long time.*

Thus far we have been able to achieve both considerable depth and substantial duration—200 feet for 24 hours, 15 minutes in the dive described by Lord Kilbracken.

This summer we shall continue our experiments with animals at 400 feet for 24 hours or longer, in preparation for a program of manned dives.

During these experiments, which we shall conduct on the American side of the Atlantic, we plan also to test our Stage 1 large underwater housing for the first time. We are constructing it of rubberized fabric, instead of the steel originally specified. Inflated and anchored to the bottom, this "underwater tent" will house four divers, enabling them to sleep, eat, and work in safety and comfort.

We plan to continue Project Man-in-Sea in this unspectacular scientific manner, checking each step with care before proceeding to the next.

* * *

ONR Report ACR-108

Project Sealab Summary Report

An Experimental Eleven-Day Undersea Saturation Dive at 193 Feet

Sealab I Project Group

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OFFICE OF NAVAL RESEARCH
DEPARTMENT OF THE NAVY
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CONTENTS

ABSTRACT

The Office of Naval Research, in conjunction with other U.S. Navy activities, has carried out an experiment in placing subjects in an underwater habitat for eleven days. An undersea, ambient-pressure, gas-filled, nine-foot-diameter by 40-ft-long laboratory was placed on the ocean floor off Argus Island near Bermuda. Four men occupied the laboratory. During this period of saturation "diving" on a He-O_2-N_2 gas mixture, the men performed work, ate, and slept within the dry laboratory and made working swims in the ocean spaces surrounding the laboratory. Physiological observations and measurements were made of the laboratory occupants. Logistic support was provided from the large covered lighter YFNB-12 and from Argus Island.

The aquanauts lived at ambient pressure equal to the depth of the habitat. The habitat, Sealab I, was designed and built at the U.S. Navy Mine Defense Laboratory, Panama City, Florida. It was utilized in an actual operation designed to examine, under open-ocean conditions, problems of men living and conducting work tasks under continuous high pressure in a set time frame, as compared with the time required for conventional divers to dress, descend, work, and ascend through decompression stops. During the period of Sealab I occupation, the aquanauts lived in the relative comfort of an underwater habitat, whereas with conventional systems the diver is exposed to the stress of being compelled to dangle on a stage in very cold and uncomfortable diving dress for several hours after accomplishing only a few minutes of useful work on the bottom.

The Sealab subjects reached a state of equilibrium (tissue saturation) with their breathing medium at depth during the first 24-hr period on the bottom. After this time, additional exposure did not increase the decompression schedule. Decompression time from a "saturation" dive to 200 ft may be as little as 30 hr, depending on conditions.

Sealab I project demonstrated:

1. That man can perform useful work at 200 ft and deeper with this technique of integrating the human more fully with his undersea environment, rather than having him make brief, expensive forays into it, always returning to surface pressure for his necessities of life.

2. No adverse physiological effects as a result of aquanaut exposure to the experimental conditions of the Sealab I project.

The men, during the occupancy of Sealab, accentuated their personal idiosyncrasies. During one period, excessive use of foul language developed, as well as an independent attitude with respect to the surface support. This attitude subsided, however. They showed little or no apparent tension with regard to the safe control of the environmental situation.

Blood samples, urine samples, electrocardiograms, and other physiological measurements were taken on a routine basis of the subjects during the occupation (see Appendix D for details). In general, it may be said that insofar as preliminary examination of the data is concerned, no adverse physiological effects were noted as a result of the aquanaut exposure to the experimental conditions of Sealab occupation.

During the occupation of the Sealab, the temperature was kept near 84° F and was comfortable with a relative humidity of, approximately 72 percent. It was found experimentally that air was quite adequate for atmosphere make-up during the occupation. From measurements of CO_2 and N_2 made during the occupation, it appeared that the sea-water interface in the entrance trunk served as a good absorber of both, thus making air make-up possible.

It is to be noted that during the occupation the helium speech unscrambler aided significantly in communication between the Sealab and the control station at the surface.

A dumbwaiter was installed to ease the problem of delivery of material to the Sealab from the surface. The general problem of supply and housekeeping during the eleven-day occupation consumed excessive time on the part of the subjects (as well as surface personnel).

A new concept of supplying breathing gas to swimmers operating out of the Sealab was attempted during the occupation. The system, dubbed both as a hookah and Arawac gear, consisted of a delivery and return hose leading to the swimmer from the Sealab. However, the experimental system used was found to be inadequate and needing further development. The basic concept, however, was felt to be of value in future Sealab-type operations.

RECOVERY OPERATIONS

On Wednesday, July 29, unfavorable weather predictions prompted termination of the experiment, and at 2356 Sealab was lifted off the bottom. The ascent, one foot every 20 min, was uneventful until Sealab was at about 110 ft, when wave forces began to make themselves felt again. The ascent was stopped at 100 ft for several hours, hoping for abatement of the seas, and finally started again. Sealab was brought to 81 ft, at which point shock loads in excess of 20 tons were being put on the crane. Further ascent was not considered safe.

The subjects were transferred to the submersible decompression chamber (SDC) (Fig. 26) and brought up on Argus Island. Sealab was floated off on the same four buoys that were used to transfer it to Argus and brought astern of the YFNB-12. Ballast weights were jettisoned until positive buoyancy was attained and Sealab floated. Once on the surface, it was secured for sea and towed back to port with the YFNB-12.

Sealab subjects were taken out of the decompression chamber at 0830, Aug. 1, and were flown by helicopter to Kindley Air Force Base Hospital for examination. All Sealab equipment was packed and stowed for shipment, and with a press conference and congratulations by RADM J.K. Leydon, Chief of Naval Research, at 1130 on Aug. 4, 1964, Sealab I was terminated.

Fig. 26 - Observer checking subjects after recovery of *submersible decompression chamber and completion of* decompression, before hatch opening

MAJOR FINDINGS

Systems

Handling System – It proved to be even more difficult than anticipated to handle the large high-drag mass of Sealab from a heaving platform, in attempting to place it on the bottom. The heaving of the barge in a fairly long-period sea (10 to 12 sec) placed severe strains on the handling lines and made a controlled descent from the barge unfeasible. While lowering Sealab from a fixed platform (Argus Island), dynamometer readings on the wire used to lower it indicated that, for this hull configuration and mass, wave action could be felt clearly at 120 ft (4 to 5 ft *seas, 10 to 12-sec period) and became of real concern by the time the hull was at 60 ft.* It was further demonstrated that unless a definite overpressure is maintained in the hull prior to lowering, some hull fitting, invariably left open, will cause flooding.

Initial Gas Filling of Sealab – The gas filling of Sealab I was accomplished as the Lab was being lowered. In fact, the lowering rate was limited by the rate at which gas could be bled into the Sealab to prevent water entry as the lab was lowered. This problem could be circumvented by pressurizing the Sealab prior to lowering. The habitat in this case, however, would have to be designed as a pressure vessel.

Gas Supply – Monitoring of the gas composition revealed that the nitrogen percentage steadily decreased, probably due to solution in the sea water. It was found possible to use compressed air for makeup of oxygen, since the nitrogen seemed to disappear about four times as fast as oxygen. No appreciable loss of helium was noted during the course of the operation.

Dehumidification – The installed dehumidifiers worked at near rated capacity, removing about 6 gal/day of water from the He-O_2 space. The humidity was maintained at levels varying from 68 to 74 percent. Contributory factors in these variations were open water surface in the entrance trunk, hot showers on completion of excursions, wet suits hung up, and moisture in exhaled breath.

Thermal Control – Much less heat was required to maintain comfort than had been predicted. The cork insulation in the $He-O_2$ space re-expanded to its initial 1-in. thickness within a few hours on the bottom, while that in the air space became compressed on the way down and never did expand. This difference is probably due to the increased diffusion rate of helium over that of nitrogen.

Swimmer Support – The wet suits which went down "dry" in Sealab quickly re-expanded to their original thickness. Those worn down by the subjects never did expand. The reason for this difference is unknown. Protection provided by even the re-expanded suits was inadequate to take full advantage of the time available for working excursions.

The hookah equipment, used to pump the Sealab atmosphere to and from a swimmer, failed to perform satisfactorily. The gas pumps were noisy, overloaded, and had to be placed in series to provide enough gas to support one swimmer. This concept is very attractive, but the present equipment is inadequate.

Subjects

The subjects (Appendix F) acclimatized to a chamber temperature of 84°F, somewhat lower than expected in this atmosphere, which enhances body heat removal. The exact effects of the presence of the small amount of nitrogen on this heating problem are still unknown.

The gas mixture was held close to 4 percent O_2 (200 mm), 17 percent N_2 (850 mm), and 79 percent He (3950 mm). The subjects expressed the general conclusion that this somewhat higher partial pressure of oxygen was desirable, although no specific performance measurements were made. The subjects' conclusion was based on a reported "increased sense of well being" immediately after oxygen additions, when the oxygen partial pressure was in fact somewhat higher.

During the first four days the subjects were somewhat uncomfortable, noting joint aches, etc. These were not serious, and did not debilitate the subjects, although a general slowdown of movement during this period was noted by the topside monitoring personnel.

There appears to be a significant increase in individual susceptibility to nitrogen narcosis after helium-oxygen saturation. This was noted when saturated subjects entered the air space in Sealab. LCDR Thompson noted that this narcosis was of a very uncomfortable variety which caused headaches and nausea.

Basic physiological parameters, i.e., blood chemistry, etc., did not deviate significantly from well-established baseline values. In previous chamber runs, deviations from baselines were noted, and baseline values were reapproached about the ninth day. This deviation did not appear to be the case in Sealab.

The personnel selection for Sealab is an open question. A comment has been made by attending psychologists that there were too many potential leaders and that this led to an unwarranted degree of independence below. Dr. Bond recognized this independence and noted that it probably was the cause of some neglect of the "buddy system" and what he considered undue use of breath holding during excursions from the lab. The subjects also commented on the feeling that the topside situation was somewhat confused and that this led to confusion in the relationship between the subjects and topside. This comment deserves careful consideration.

CONCLUSIONS

1. It is concluded that human subjects can live and work under pressure at 193 ft in the open ocean without significant physiological or psychological problems.

2. All major systems used in Sealab I worked in a fashion adequate for life support. Many of the systems were primitive, especially the habitat installation and retrieval systems.

3. The major mechanical problems, encountered in raising and lowering the habitat, were caused by surge of the habitat and surface ship. These problems were most serious from the *surface to 100-ft depth. A major engineering effort is required for solution of this problem.*

4. This concept offers a step toward increased efficiency in the utilization of human diver's time over existing techniques. Although, in this experiment, a maximum of four to five hours outside working time was maximum experienced, it appears that six hours outside work per man in each 24-hour period is practicable. The major losses of working time in this experiment were caused by inadequate preparation for housekeeping functions, and lack of adequate work schedules. Some working time was lost during the subjects' acclimatization period.

5. Techniques for largely overcoming the helium speech problem were demonstrated. However, fully satisfactory equipment is not yet in hand.

6. Provision for adequate body heating while swimming remains a major problem. Although this experiment was conducted in 69°F water, to which the subjects acclimatized to a significant degree, lack of heating for swimming imposed restraints on the subjects during excursions.

7. The submersible decompression chamber performed adequately for the purposes of this operation, but difficulty of handling it points up the desirability of a more compact unit which can be married to a larger surface chamber.

RECOMMENDATIONS

1. Major changes in habitat design and/or handling procedure must be initiated for future Sealab work.

2. A higher degree of independence from surface support must be achieved. A smaller, permanently attached umbilical cord must be provided. Specific items which must be improved are:

Gas supply

Gas control and monitoring

Power (at least for emergencies)

Communications.

3. As Sealab crews enlarge, at least one man must be *assigned full time to housekeeping* and equipment maintenance.

4. For further experiments, a major effort must be made in improvement of housekeeping (material and organization), and in time-and-motion studies and layout of work schedules.

5. Vehicles for swimmer transport must be provided. A usable one-man wet vehicle is now available; a two-man wet vehicle is anticipated. Consideration must be given to a dry vehicle with lock-in, lock-out capability to permit greater excursions in depth.

6. Physiological studies must be performed to determine the permissible time of depth excursions from saturation level under no decompression and under programmed decompression limits.

7. R&D must be performed to improve:

a. *Gas sensors - desirable limits are:* O_2 100 to 600 mm partial pressure, accuracy 10 mm

CO_2 5 to 50 mm partial pressure, accuracy 2 mm

b. Communication equipment - habitat to diver, diver to diver, diver to habitat, habitat to surface

c. Swimmer heating apparatus

d. Helium pumps - for gas mixing and helium recovery

e. Navigation equipment and techniques

f. Hookah pumps.

8. A submersible decompression chamber capable of being coupled with a surface decompression chamber must be provided.

9. It is recommended that a Sealab task group be established composed of 25 to 35 personnel, which will be the central group involved in future R&D work in the man-in-the-sea program, and that this group be established at some existing naval shore activity.

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Life and work under pressure

Robert Sténuit

Life and work

In July 1964 two divers made history by successfully living for two days 432 feet below the surface of the sea. This was an important step towards throwing open to exploitation the submerged continental shelves which stretch down to a depth of 1000 feet. What were the events leading up to this dive, and what has happened since?

Robert Sténuit is diving adviser and development engineer with Ocean Systems Inc. He works with the experimental diving group of this company at Linde's Bio-Research Laboratory in the United States when not in his native Belgium. His adventures in deep diving, particularly the dive mentioned above, will be published soon in his book 'The Deepest Days' (Hodder and Stoughton)

Alexander the Great is said to have submerged in a diving bell. In spite of this early start the science of diving did not experience any great leap forward until the Second World War when the Scuba (or *s*elf-contained *u*nder-water *b*reathing *a*pparatus) was developed. Before this the diver wore what amounted to a small copper diving bell on his head with a flexible rubberized suit to protect the rest of his body, but the scuba meant that divers could now carry their own atmospheres upon their backs. However, this new emancipation from the surface pump did not overcome the basic physiological limits imposed by the great pressures exerted on the body in the depths of the sea.

At pressures of five atmospheres or more air becomes increasingly toxic, and the mixture of gases which supports life on the surface produces adverse effects such as oxygen poisoning and nitrogen narcosis upon the diver. These ill-effects can only be avoided by reducing the partial pressure of oxygen in the mixture and replacing the nitrogen with a light inert gas such as helium. But this aspect of breathing mixtures for deep diving is only part of the problem; during the dive the gases are forced under the extreme pressure into solution in the blood and, unless special precautions are taken as the diver returns to the surface, they will bubble out of solution as the pressure becomes reduced. These precautions include a slow ascent, with decompression stops at various depths: a one hour long dive at 200 feet requires about four hours of decompression.

The only way a diver can avoid the costly inefficiency of such long periods of decompression is by saturation diving. At a given depth the various tissues of a diver's body will absorb only a certain volume of inert gas, and once this saturation level has been reached no further gas will enter into solution within his body. This means that a two month stay under pressure requires no more decompression time than a dive of two days, while the ratio of time spent working on the bottom to that in following the decompression schedule is far superior for the longer stay. Without this new concept of living and working under pressure, any organized exploitation or full-time colonization of the continental shelves of the world, as is now envisaged, would be unthinkable.

Man's early efforts

We know nothing about the capabilities of Alexander's diving bell; the earliest known picture, which may well owe more to an artist's imagination than anything else, appears in a French manuscript of 1250 and depicts a glass barrel lit by two candles with the monarch sitting inside. Sir Francis Bacon refers to the Macedonian diving bell in his *Novum Organum* published in 1620, and throughout the 17th century "a machine or reservoir, of air to which labourers upon wrecks might resort whenever they required to take breath" was widely used for salvage. Unfortunately all these bells suffered from the fact that no effort was made to renew their air or, for that matter, to counteract the increase in pressure with depth. Consequently their operational depth and the time for which they could be used on the sea floor were never very great.

The first undersea dwelling to show any real progress towards solving these limiting problems was that of Sir Edmund Halley, FRS. His diving bell, built in 1690 and perfected in 1716, received 'fresh air' in weighted drums sent down alongside, while its divers could venture forth wearing wooden helmets connected by leather air pipes to the bell. Even Halley did not make use of a suggestion made a few years earlier by the inventor Denis Papin, that force pumps or bellows should be used to keep the water level down and replenish the fouled air. In fact John Smeaton in 1788 was the first to do this; from his machine evolved present day bells, working caissons and also the small head-covering bell fitted with three glass portholes which Augustus Siebe introduced in 1819,

under pressure

Date	Project Sponsor	Name of Project	Depth	Duration	Location	Type of Dwelling	Aquanauts	Gas
Early 9/62	Dr E. Link	Man in Sea	200 ft	26 hours	Villefranche Mediterranean	Link Cylinder (3ft × 11ft) Aluminium	R. Sténuit	3% Oxygen 97% Helium
Mid 9/62	*Cmdt J-Y. Cousteau* OFRS	*Conshelf 1*	*30 ft*	*7 days*	Marseille France Mediterranean	Diogene Horizontal cylinder (8 ft × 16 ft)	A. Falco C. Wesly	Air (No narcosis and no decompression required)
6–7/63	Cmdt J-Y. Cousteau OFRS	Conshelf 2	34 ft	1 month	Shaab-Rumi Reef, Red Sea	Star House Four 8-ft diameter cylinders horizontally assembled in a starlike pattern	Prof. Vaissiere C. Wesly A. Falco P. Guilbert P. Vanoni	Air " " " "
			85 ft	7 days	Shaab-Rumi, Reef Red Sea	Deep house Vertical cylinder (7½ ft × 16 ft)	A. Portelantine R. Kientey	Air/Helium
6–7/64	Dr E. Link	Man in Sea	432 ft	49 hours	Berry Islands (Bahamas)	SPID (Submersible Portable Inflatable Dwelling). A rubber tent (7 ft × 4 ft)	R. Sténuit J. Lindbergh	4% Oxygen 91% Helium 5% Nitrogen
7/64	Dr G. Bond (USN)	Sea lab I	192 ft	11 days	Argos Tower (Bermuda)	Sealab I—cigar-shaped steel horizon*tal capsule* 35 ft long by 12 ft	R. Thompson R. A. Barth L. Anderson *S. Manning* (All USN)	16% Nitrogen 4% Oxygen 80% Helium
1964 ?	USSR Group	?	45 ft	4 weeks	Black Sea	?	?	?
8/65	*Ocean Systems Inc.* Dr E. Link	Man in Sea	650 ft (simulated dive)	48 hours	Tonawanda, NY, Linde Labs.	Dry chamber	R. Christiansen A. Noble	1·86% Oxygen 4% Nitrogen 94·14% Helium
9-10/65	Dr G. Bond, USN (ONR-SPO)	Sealab II	210 ft	15 days and 30 day periods	La Jolla, California	Sealab II—steel cylinder 57 ft × 12 ft with four compartments	Three successive teams of 10, headed by Col. Scott Carpenter	4% Oxygen 11% Nitrogen 85% Helium
10/65	Cmdt J-Y. Cousteau OFRS	Conshelf 3	330 ft	3 weeks	Villefranche Mediterranean	Steel sphere 40 ft—two stories resting on ballasted float	Team of six, headed by A. Laban	Oxygen Nitrogen Helium

Fig 1 HALLEY'S DIVING BELL, the 1716 version of the house under the sea (above, left). Fresh air was sent down in weighted drums to replace the spent atmosphere while the divers could go outside wearing wooden helmets connected to the bell by leather air pipes. This and other bells were severely limited both in depth and the time which they could remain submerged. Such early efforts contrast sharply with those of present-day groups which aim to place the entire area of the continental shelf (down to 1000 feet) within man's reach

Table 1 WHO'S WHO on the ocean floor (1965). In this table the author presents a summary of the most important events in the progress towards the conquest of "inner space". Apart from biological research, these programmes demand considerable technological advances. *Nevertheless, the justification* in economic, military and scientific terms for this expanding effort is obvious in view of the wealth which at present lies outside man's reach in the continental shelves of the world and which is still used today, with a spring loaded valve on the side and a full dress, by thousands of 'hard hat' divers all over the world.

Developments of the kind described above established the value of working on the sea bed and laid foundations for living under pressure, but complementary lines of thought were also developing. These derive from two concepts, the 'lock-out submarine' which divers could leave or re-enter via an airlock which could be pressurized to ambient pressure, and the true undersea dwelling with an open door at the bottom.

Bishop Wilkins first introduced the idea of the 'lock-out submarine' (with leather bellows as airlocks) in his *Mathematical Magic* in 1648. He even envisaged that "several colonies may thus inhabit (under-water) having their children born and bred without the knowledge of land . . ." In the late 19th century, Simon Lake, an American engineer, built several such submarines which had compressed air and water ballasts. *Argonaut Junior*, completed in 1894, was made of wood and could roll on its wooden wheels along sandy sea beds. In shallow waters after increasing the pressure inside the vehicle, Lake could open a hatch in its bottom and reach out to fish up oysters or to walk out to do salvage work. He anticipated that later submarine supply stations would be built on the sea bottom.

The idea of actually living under the sea surrounded by all comforts of terrestrial life was first patented by a Frenchman, L. de Rigaud. In 1899 he introduced plans for a highly impractical, 80 feet high, egg-shaped steel structure containing six stories, which stood on four legs planted firmly on the sea bed. Its great size made it more like a hotel than a home but interestingly his design seems to have included four air-locks by which workers could leave and return.

Later ideas for under-water living, although more practical, came to nothing, even though techniques of deep diving improved considerably. The building of the first Submerged Decompression Chamber (SDC) by Sir Robert Davis is particularly noteworthy since it provides a convenient and safe underwater elevator for divers. They can enter the pressurized chamber deep in the sea, and be brought to the surface under pressure. Still in the chamber, or in a larger pressurized room connected to it, the diver can then follow decompression schedules on board ship in a dry atmosphere in great comfort and within easy reach of medical assistance.

In the past decade, three groups have successfully taken a direct interest in promoting and demonstrating man's ability to live and work under pressure on the continental shelf. Edwin A. Link's 'Man in Sea Project' was the first to start in 1956, to be followed the next year by the U.S. Navy's 'Sealab' experiments originated by Dr George Bond. In late 1962 Commandant Jacques-Yves Cousteau and his group, the OFRS (Office Français de Recherche Sous-marine), began operation 'Conshelf', first with shallow but prolonged stays in the sea and recently penetrating to more significant depths. All three programmes are moving successfully towards placing most areas of the continental shelf within man's grasp, but since I have personally been associated with Edwin Link's project I will attempt to illustrate some of the problems and dangers of life under pressure by reference to his work and subsequent developments from it.

Living in the Link cylinder . . .

Edwin A. Link officially launched the Man in Sea Project when, in 1956, he submitted to a committee of the Smithsonian Institution in Washington an outline of his goal—"to put man in the sea, safely, deep and long enough to enable him to do useful work"—and showed for the first time the blueprints of his diving capsule, the Link cylinder. The principle of such a submersible cylinder was not new, but the wide use he planned for his invention and the ways he solved numerous practical problems related to working and living deep in the sea were.

Before the first phase of the project was completed a great deal of preparation and animal experimentation was necessary, so that the cylinder was not ready for its first long manned dive for another six years. In early September 1962, I descended in the cylinder 200 feet down into the Bay of Villefranche in the Mediterranean. My home and base for the next 24 hours was an aluminium cylinder 11 feet high, 37 inches in diameter and divided into two compartments by airlock hatches. I was able to leave the cylinder and work at will outside within a radius of 50 feet and at depths of 190 to 243 feet, and I returned

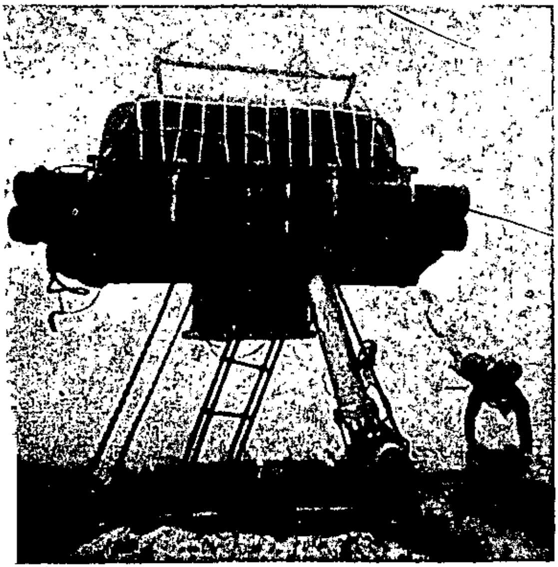


Fig 2 RUBBER TENT (SPID) lies on the bottom of the sea at a depth of 70 feet. This was the final rehearsal before the record-breaking dive at 432 feet made by Jon Lindbergh and the author. Oxygen, helium and gas mixtures in the cylinders make the tent an autonomous habitation during the long dive

Fig 3 THREE MAIN UNITS for phase two of the Man in Sea Project lie on the stern deck of Edwin Link's research ship *Sea Diver* (right). In the centre is the deck decompression chamber with the Link cylinder in position to be mated with it. On the left of the cylinder is the SPID, with its ballast tray on the other side of the cylinder. This project was to prove that deep diving can be safely performed with a minimum of equipment and limited support personnel working from a small ship. First the SPID was hoisted over the side (centre, right). After inflating with a mixture of oxygen and helium, the ballast tray was loaded with lead to send the rubber under-water house to the bottom. Then the Link cylinder went overboard (far right). The two divers climbed in, locked the hatches and then descended to the SPID using the cylinder as an elevator. After their stay in the sea, the divers re-entered the cylinder, ascended and then decompressed in comfort inside the chamber on deck to it only for rests, food, warmth, and to sleep (in a sitting position). My breathing mixture consisted of 3-4 per cent oxygen in helium. After 26 hours at 200 feet the cylinder was taken back on deck of R.V. *Sea Diver*, Edwin Link's specially designed ship. The pressure inside the cylinder was still 7 atmospheres and I stayed inside the cylinder, now lying horizontally, to be decompressed—a process which took 67 hours.

This first long dive established that the purpose for which the cylinder had been designed could be fulfilled in practice. The same vessel had been an underwater elevator, a shelter, an SDC and a decompression chamber on deck. The helium oxygen mixture had produced no ill-effects during the saturation dive and I found the chamber, although cramped, suitable as a refuge during the period concerned. Now we were ready to move on to the second part of the experiment —to penetrate deeper into the sea and stay living and working there longer.

. . . and the SPID

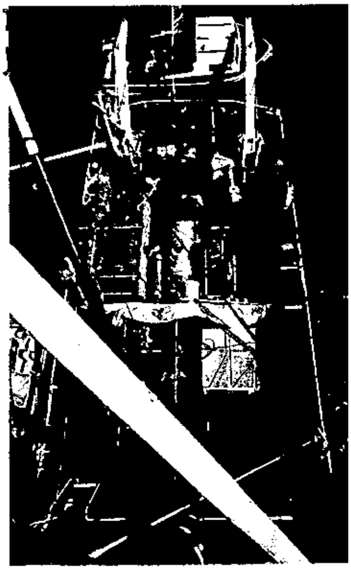
For the preparation of the second part of the project, considerable support came from the National Geographic Society, while both Professor Christian Lambertsen of the University of Pennsylvania and the U.S. Navy, especially Dr Bond and the Experimental Diving Unit in Washington, provided valuable active support by carrying out extensive experimental 'dry dives' to depths progressively increasing to 400 feet.

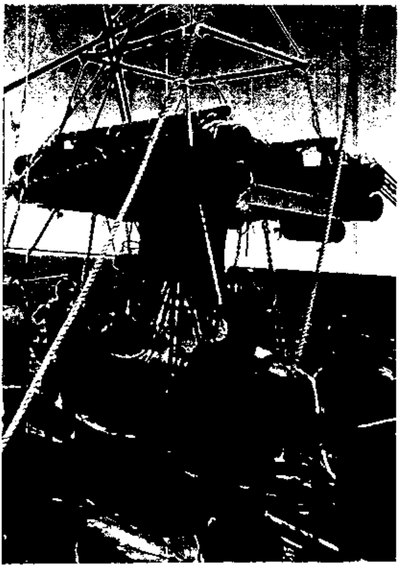
Living at such great depths produces new technical problems as well as physiological problems. Helium largely solves the physiological ones such as narcosis and adequate ventilation of the lungs, but this gas also causes additional problems of its own. Its thermal conductance, six times greater than nitrogen, causes such a considerable loss of heat from the diver that conventional insulated diving suits provide insufficient protection against the cold water, and the temperature inside any underwater dwelling must be kept around 82 to 85 degrees. Helium is also very expensive; the gas must be recirculated over and over again in a closed-circuit breathing apparatus, which calls for elimination of carbon dioxide, addition of oxygen and very careful monitoring. Permanent gas analysis under a pressure of 14 atmospheres required unprecedented high pressure units consisting of a polarographic oxygen sensor and an electrochemical carbon dioxide sensor in protective housings. Finally, because helium is such a light gas, it severely distorts the human voice and any phone equipment must incorporate a frequencies-filtering speech "unscrambler."

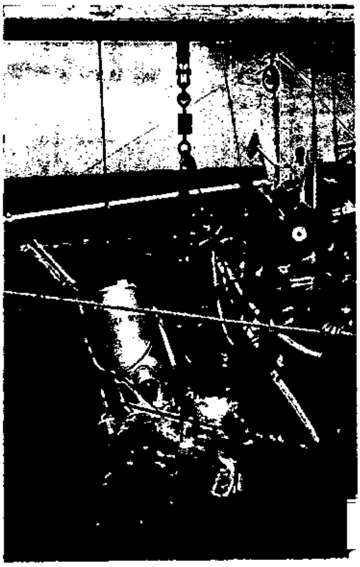
Numerous preliminary tests were carried out on board *Sea Diver* in Washington D.C., in Key West and Miami and off the Bahamas under the medical supervision of Dr J. McInnis. Then in July 1964, the important dive in the second phase of Link's Man in Sea Project began. Two divers, Jon Lindbergh and myself, went down in the Link cylinder to a depth of 432 feet. On arrival at the bottom we pressurized our 'elevator', opened both hatches and swam to the SPID (submersible portable inflatable dwelling), a rubber tent anchored on the bottom.

The tent, about seven feet long with a diameter of four feet, was completely autonomous except for part of its power. We used it as our base for two days and nights, swimming out freely to work in the surrounding sea for many hours. During the experiment we were breathing a mixture of approximately 4% of oxygen in helium with some 5% of residual nitrogen. After our stay, we returned once more to the Link Cylinder, secured the hatches and were hoisted back on board still under the pressure we had experienced during the experiment. The cylinder was then attached to a roomier, more comfortable, deck decompression chamber. The return to normal atmospheric conditions took 96 hours of decompression.

This dive was and still is the longest dive ever made at such a depth. In July 1965 British Navy divers went deeper, to 600 feet, using an SDC as their base, but they worked outside for only one hour. Our dive established decompression schedules for deep saturation dives previously carried out only in the laboratory and above all, as far as we are concerned in this article, showed the feasability of living and working at these previously unattained depths. The Project also showed that a small team of undersea researchers can operate safely and efficiently from an underwater dwelling, supplied by a small ship, at limited costs and with limited support personnel. On the more commercial side, the rubber SPID proved to be quite up to its task as well as having all the







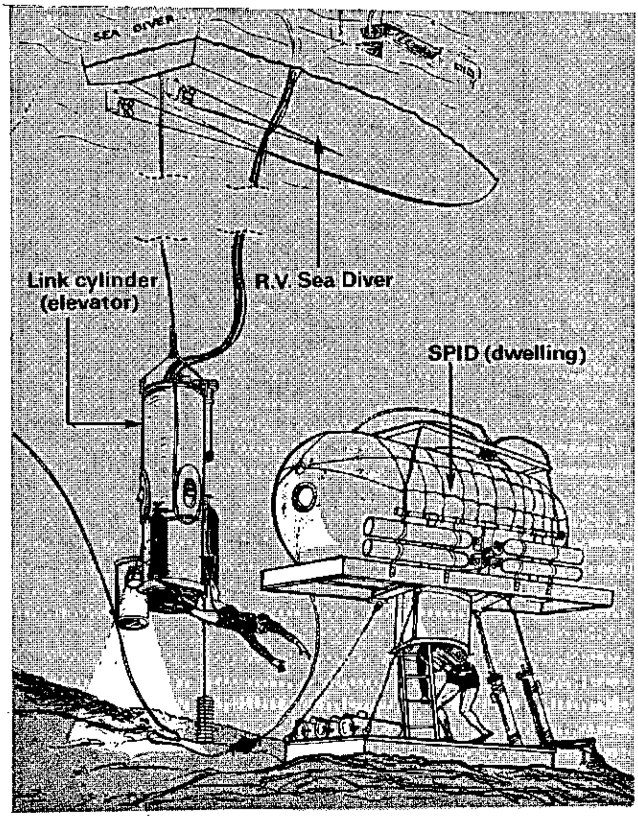


Fig 4 PROJECT MAN IN SEA as seen by an artist. The two divers are leaving their elevator, the Link cylinder, and entering their underwater dwelling, the SPID, which contains an appropriate mixture of oxygen and helium. Above them can be seen the bottom of the surface support vessel, *Sea Diver*. Jon Lindbergh and the author made this record-breaking dive in 1964

benefits of being cheap, easily carried, stored and maintained.

Opening up the continental shelf

At the beginning of 1965, the Man in Sea Project of Edwin Link was taken over by Ocean Systems, Inc., a company which aims to make available the whole of the continental shelf (depth up to 1000 feet). This will obviously call for new gas mixtures, equipment and diving capsules.

Already certain methods of attack have been devised. For example, a much improved SDC has been designed to take divers down, and provide them with a base. A separate compartment, kept at atmospheric pressure, will permit non-diving scientists or technicians, watching through portholes or closed circuit television, to supervise or direct the work of the divers. For long stays, several autonomous dwellings and workshops will be installed on the bottom while for repeated short trips men will remain between calls in a deck compression chamber at full pressure, using the SDC simply as a convenient elevator.

These principles have all been shown to work in the Man in Sea Project although the full commercial and scientific exploration of their possibilities means a greater investment in equipment. A fourth system, which I should just like to mention, involves a principle mentioned in the earlier historical section—the lock-out submarine. Ocean Systems is presently building such a submarine from which divers can exit or return to decompress in a chamber actually inside the submarine, the rest of the vessel being kept at atmospheric pressure. This system avoids the possible interference of rough weather and of course has obvious military applications.

Tomorrow's possible solutions

The recent Sealab 2 experiment off the Californian coast used a dolphin in various support roles for the divers. Because these animals can move from the surface down to several hundred feet without experiencing any discomfort, they can be used to carry messages either from the surface or between divers working on the sea floor. Their ability to learn such tasks—the intelligence of the dolphin is becoming almost legendary—will make them useful companions in undersea exploits. Once their language of whistles and grunts has been decoded it may even be possible to use sound to control their movements or call for their assistance. At present the prospects of using these and similar animals must be an unknown quantity, but studies of their physiology and that of other aquatic mammals may well open new approaches to the problem of decompression sickness.

Drugs too may offer some prospects of overcoming this basic limitation to moving quickly to the surface from great depths. The volume of inert gas dissolved during a dive in the body of a diver increases in proportion to its partial pressure in the breathing mixture, and its rate of elimination during decompression accelerates in proportion to the difference between its partial pressure in the blood and in the breathed gas mixtures. Thus, ideally in order to shorten the decompression time, a very high partial pressure of oxygen and a low partial pressure of inert gas in the breathing mixture, should be maintained both on the bottom and during decompression. Unfortunately, as I mentioned earlier, oxygen under high pressures has a toxic effect on the central nervous system, and epileptic-like convulsions will strike a diver who breathes oxygen under partial pressures higher than about 1.8 atmospheres (pure oxygen) or 2·3 atmospheres (oxygen in mixtures). This limits the use of oxygen closed circuit breathing apparatuses to a depth of 25 feet. However, recent experiments on laboratory animals have shown that injecting certain drugs in the bloodstream can improve considerably the ability of rats to resist such disastrous effects. For example, the rats have tolerated pure oxygen for two hours at a simulated depth of 135 feet. If a similar treatment could be applied safely to men, a very significant reduction in decompression time could be achieved.

Perhaps the ultimate answer will be to side-step these problems completely by doing away with the gas mixture system and using a physiologically neutral saline solution saturated with oxygen. This sounds fantastic, but Dr Johannes Kylstra of the Netherlands (presently working in the United Sates) has suceeded in keeping alive mice and dogs immersed in such a solution for periods of over 45 minutes. The dogs have survived and returned to breathing air without ill-effects. Man could conceivably breathe a similar fluid when submerged and the most recent work of Kylstra indicates that such a system would very possibly meet the respiratory requirements of a man working in the depths of the sea. What is certain is that man once freed from inert gas would be freed also from narcosis and from decompression problems; he would be able to dive safely to depths presently far out of reach, being limited only by the ultimate mechanical effects of pressure on his body.

If such dreams ever mature then undersea dwellings and life under pressure of the kind I have discussed here will become nothing more than another out-dated chapter in the history of diving. Undoubtedly the flooding of the lungs will involve tremendous psychological barriers, although in a future age where the use of mechanical replacements for vital organs has become commonplace, or at least acceptable, the climate of opinion for such extreme steps may well exist.

In the meantime, the advances started by the three major groups presently working at getting man in the sea will continue. The early experiments have shown up some of the areas where, apart from the medical considerations, considerable technological advances are needed. Power tools that will widen or multiply man's working capability are needed together with underwater vehicles for carrying personnel, equipment and materials, with heated diving suits, rebreathing apparatuses, automated physiological monitoring equipment and devices for the control of the atmosphere (a proposition made more and more delicate because of the narrower margins of tolerance by the body for both oxygen and carbon dioxide as the pressure increases). Communication equipment too is badly needed both for unscrambling speech and for underwater communications generally. Nevertheless the justification in economic, military and scientific terms for such developments is obvious when one considers the wealth which at present lies outside man's reach in the regions of the continental shelves of the world.

FURTHER READING—*see outside back*

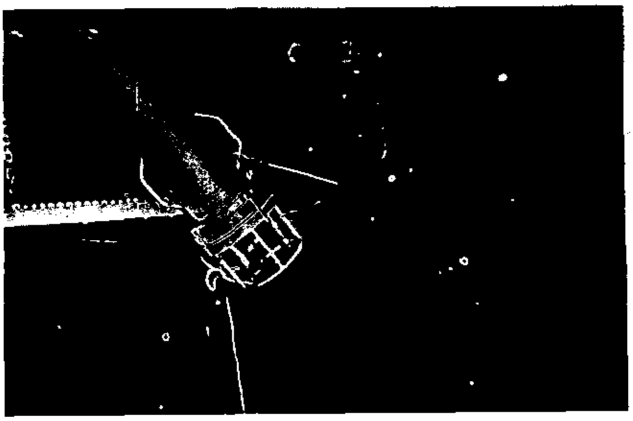
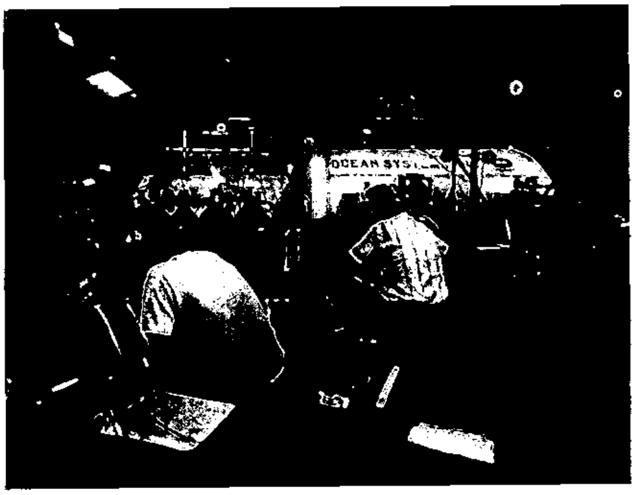


Fig 5 **WORK AND REST**, 432 feet below the surface of the sea. Jon Lindbergh works on the ballast tray of the SPID breathing through the recirculating hookah developed by Dr Link to conserve the supplies of helium (above). The author rests in the underwater 'home' after three hours work in the surrounding water (right). The two divers were watched constantly on closed circuit television

Fig 6 **DIVING RESEARCH** at Ocean Systems under Dr J. B. MacInnis develops and experiments with new decompression tables and gases for deep diving. In a recent experiment, two volunteer divers stayed for 48 hours at a pressure equivalent to a depth of 650 feet. During part of the experiment, they breathed a mixture in which the helium was replaced by neon. The overall results indicate neither gas has any measurable narcotic potency at these pressures and no adverse biological changes result from exposure to them



PROLONGED EXPOSURE OF ANIMALS TO PRESSURIZED NORMAL AND SYNTHETIC ATMOSPHERES

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SUMMARY PAGE

THE PROBLEM

To expose experimental animals, including primates, to natural and synthetic atmospheres under conditions of pressure equivalent to 200 feet of sea water, for periods up to two weeks; and subsequently to conduct adequate decompression of these animals before their removal from the experimental chamber.

FINDINGS

Results of this study confirm that survival of these experimental animals in a selected atmosphere of helium and oxygen can be predicted. Although these animals cannot survive a high pressure of air for more than thirty-five hours, an equivalent exposure to a selected synthetic breathing gas mixture is tolerated for a period of two weeks without physiological deterioration.

APPLICATION

The information gained in this investigation is of value in planning extention of the experimental design to include human subjects. Final application of the data derived from human experiments may be utilized in planning atmosphere and environmental control for operational exercises involving prolonged deep diving procedures; extensive underwater construction concepts; deep salvage operations; or in oceanographic and marine biological research on the continental shelves of the world.

ADMINISTRATIVE INFORMATION

This investigation was undertaken as a part of Bureau of Medicine and Surgery Research Task MR005.14-3100, under Subtask (3)—Effect of Prolonged Exposure to High Ambient Pressures of Synthetic Gas Mixtures. The present report is No. 2 on this Subtask and was approved on 26 January 1962.

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ABSTRACT

In order to explore the problem of mammalian survival under high ambient pressures of synthetic atmospheres, it was elected to expose several species of experimental animals to a selected artificial atmosphere at a simulated depth of 200 feet of sea water for a period of fourteen days. In a progressive series of experiments, colonies of rats, guinea pigs, and finally, squirrel monkeys, were so exposed. Temperature, humidity, carbon dioxide and ammonia levels were controlled with increasing success, as the experiments proceeded. Feeding and water supplies were automatically supplied to the isolated experimental animals. Although early deficiencies in experimental design posed problems, all animals in the series survived with no demonstrable physiological lesions in excess of endemic findings of control animals. In the final experiment, in which primates were utilized, there was no evidence of immediate or delayed adverse physiological effects.

The results of this series of animal exposures to high pressures of synthetic atmospheres indicate that: (1) In the case of the experimental animals employed, i.e., rats, guinea pigs, and squirrel monkeys, survival in a nitrogen-free atmosphere can be predicted with assurance; and (2) Although these animals can survive only brief periods in an environment of compressed air at 200 feet simulated depth, exposure to an equivalent total pressure of a selected synthetic mixture is tolerated for a period of fourteen days without physiological deterioration.

In a second series of experiments described in this report, an effort was made to establish limits of adequate decompression for a completely saturated, equilibrated, large experimental animal. For this purpose, goats were selected as ideal animal subjects. After equilibration at exposure depth of two hundred feet equivalent of sea water, random-mixed pairs of animals were decompressed on ratios which varied with respect to absolute bottom-pressure versus absolute decompression stages ambient. From these experiments, it is believed that a safe decompression ratio for gas-saturated humans can be established. It is finally concluded that human experiments may now be pursued with safety, on an increasing scale.

TABLE OF CONTENTS

PROLONGED EXPOSURE OF ANIMALS TO PRESSURIZED NORMAL, AND ARTIFICIAL ATMOSPHERES

INTRODUCTION

This report presents the results of a series of prolonged exposures of various mammals to normal air and to synthetic atmospheres at a pressure of 200 feet of sea water. The experimental objective was to provide a respirable atmosphere adequate to maintain normal physiologic functions in the exposed animals for 12-14 days, then to reduce the pressure in suitable stages so that decompression sickness might not occur.

Provision of a suitable atmosphere for man would make possible long-term exposure for work in underwater stations, and return to the surface following work periods in stations at intermediate depths selected to avoid decompression sickness.

Several authors (1, 2, 3, 4, 5, 6) have presented evidence that increased oxygen tension, rather than barometric pressure itself, is responsible for the morbidity and mortality occurring under conditions of prolonged exposure to high pressure air. Smith et al, (6), in 1932 found that albino rats exposed to optimal conditions of temperature and humidity on air with a pressure of four atmospheres (99 feet equivalent sea water depth) developed some cases of oxygen poisoning on the third day, and 13% mortality occurred on the fourth day. However, animals that survived on air for 40 days at this pressure level were resistant to oxygen toxicity on a subsequent exposure. All rats dying during exposure to high oxygen pressure (635 mm Hg) showed evidence of hyperemia and edema of lungs.

Barach (7) reported in 1935 that mice breathing an atmosphere of 79% helium and 21% oxygen at one atmosphere pressure for ten weeks suffered no harmful effects. This challenging experimental finding has not had the influence on respiratory research that might have been expected. To our knowledge, no subsequent reports have been published concerning prolonged exposure of animals to helium-oxygen mixtures at high pressures. There is, however, one such report of exposure of men for 12 hour periods, at pressures of 2-2.6 atmospheres, by Duffner and Snider, in 1950, (11). In our experiments, with helium-oxygen mixtures, the oxygen tension was maintained equivalent to air at one atmosphere, (160 mm Hg) to avoid risk of pulmonary damage, and a variety of mammals other than man served as subjects.

Decompression studies, following exposures to increased pressures, were carried out on goats, since, of all laboratory animals generally studied, goats compare most closely to man for decompression requirements. A considerable body of information is available concerning a wide range of pressure exposure for goats to air atmospheres (8, 9, 10). As mentioned, human exposures to helium-oxygen atmospheres for periods of 12 hours have been carried out previously and decompression requirements determined for these subject groups (11). Our overall objective was to expand this research and determine the viability of various animals in long-continued exposure to simulated depths of 200 feet of water, while breathing synthetic gas mixtures.

GENERAL METHODS AND PROCEDURE

In our series of experiments albino rats were first exposed to normal air at a pressure of seven atmospheres absolute to establish mortality and histopathological change under this condition. In the second experiment, albino rats and guinea pigs were exposed to a pressure of seven atmospheres absolute, breathing a nitrogen-oxygen atmosphere with pO_2 maintained at 160 mm Hg to determine whether pulmonary changes seen on the air exposure might in this manner be averted. In the third experiment, a similar exposure at seven atmospheres absolute was carried out with pO_2 maintained at 160 mm Hg, but with helium substituted for nitrogen as the inert component in the synthetic gas mixture breathed by the animals.

In the fourth experiment, squirrel monkeys were substituted for rats and guinea pigs in the helium-oxygen exposure to determine whether primates would respond in a more sensitive manner under these conditions.

In the fifth experiment, three pairs of goats were exposed successively to a helium-oxygen atmosphere in which the pO_2 was maintained at 160 mm Hg. Following a 72 hour exposure to insure equilibration of tissues to the synthetic atmosphere, the animals were surfaced in stages with stops of 36 hours at 84 and 26 feet respectively to determine whether decompression sickness could be avoided. In each of these experiments, decompression was accomplished in timed stages. A section devoted to the study of decompression is presented later in this paper.

Details of the above outlined experiments are described in the following sections of this report, (a) through (d), including the specific method used for animal maintenance and for atmosphere control.

(a.) Chronic Exposure of Albino Rats to High Pressure

Method:

In this representative experiment of our series, twenty-four young male rats (Wistar strain) were segregated, two in a cage, with ample supplies of food and water. They were allowed to acclimatize in a standard U. S. Navy recompression chamber, of 350 cubic feet capacity, for a period of four days and then were subjected to pressurized air (in a transition period of five minutes) to a simulated depth of 200 feet of sea water. The chamber was ventilated at a constant pressure for four to six minutes each hour to avoid excess carbon dioxide accumulation in the atmosphere. Every half-hour observations were made of chamber temperature, pressure, relative humidity, and the condition of the animals. Death of animals was ascertained by absence of visible respiratory movements. When all animals appeared to be dead, the chamber was "brought to the surface" within a period of seven minutes, and deaths were verified by observations of body temperature and absence of respiration. Three animals lived to within 30 minutes of the time the chamber was surfaced and these were autopsied immediately.

Temperature as recorded by thermograph was relatively constant throughout the experimental period, after the initial rise due to compression, and ranged from 76°F to 80°F. Relative humidity determined by wet-dry bulb thermometer averaged 96%.

Results:

The animals appeared lethargic after 15 hours at 200 feet. At this time hyperpnea was observed in most animals, as well as cyanosis of the ears and nose. The first death was recorded at 28 hours of pressure exposure; 50% mortality was attained at 30 hours; and all animals were dead at the conclusion of the 35th hour. Gross examination of the thoracic cavities of three longest surviving animals revealed numerous petechiae with marked diffuse hyperemia, and large, well delineated areas of necrotizing pneumonitis. In addition, bilateral pleural effusions were found. Each side of the chest was observed to contain clear, straw colored fluid in excess of one ml. The heart and great vessels were observed to be grossly normal. No evidence of froth or air bubbles was observed in them. Histopathological studies revealed interstitial hemorrhage in the myocardium, intra-alveolar hemorrhage, pneumonia, edema of the lungs (see Figure 1) and interstitial hemorrhage of kidneys.

Figure 1—Rat Lung: Animal was exposed to compressed air (200 feet) until death supervened (approximately 34.5 hours). Note excessive pulmonary edema and pneumonitis.
H&E x 350

(b.) Chronic Exposure of Albino Rats and Guinea Pigs to High Pressure 97% Nitrogen — 3% Oxygen.

Method:

As representative of a series using a reduced 0_2, twenty-four adult male rats (Wistar strain) and four guinea pigs were exposed to a simulated depth of 200 feet of sea water in a pressure chamber while breathing a 97% nitrogen — 3% oxygen mixture for 14 days. At a total pressure of 7 atmospheres absolute, or 5320 mm Hg, the oxygen content of the gas in the chamber remained at 160 mm Hg, or 3% of the total pressure. This becomes 21% physiologically effective oxygen at this depth (3% x 7 atmospheres). Carbon dioxide produced by the animals was absorbed by means of 40 pounds of granular soda lime spread in thin layers in shallow trays. Twenty pounds of silica gel was used for water vapor absorption. Two electric fans were operated continuously to provide circulation of the chamber atmosphere. Self-maintaining cages provided supplies of food and water for a period of one week. Cage-litter mixed 10:1 with boric acid powder was used in screen-covered litter trays beneath the cages to reduce ammonia formation from excreta. On the 8th day, soda lime, litter, food and water were replenished by a diver who entered the inner chamber after equalizing the outer chamber with nitrogen from pressurized cylinders. Carbon dioxide and oxygen content of the chamber atmosphere were analyzed by Scholander Micro-Gas Analyzer and Beckman Model-C Oxygen Analyzer. Oxygen was added to the chamber from pressurized cylinders as required to maintain concentration at 3% (160 mm Hg). Nitrogen was added to the chamber from pressurized cylinders to maintain pressure constant at 200 feet.

Decompression was carried out over a 24-hour period with stops at 5, 4, 3, and 2 atmospheres absolute pressure,—see graph, Figure 2.

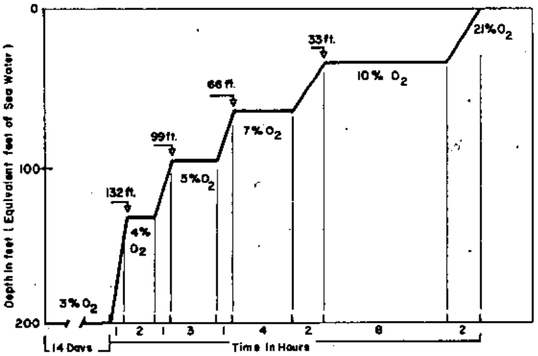

Figure 2—Decompression of rats and guinea pigs from 14 days exposure on 97% helium and 3% oxygen at atmospheric pressure.

Oxygen concentration was maintained at an effective pressure of 21% (160 mm Hg) during the decompression period.

Animals were sacrificed immediately after the chamber "surfaced," and at 10 and 30 days after surfacing. Blood was withdrawn for biochemical determinations from the left ventricles of sacrificed animals while the heart was still actively contracting. These determinations included whole blood pH, CO_2 content, oxygen content, blood urea nitrogen (BUN), blood sugar, hemoglobin, and plasma sodium and potassium. Methods used for these analyses are described in experiment (d), Page 7.

Results:

One rat died on the third day from unknown cause. All other animals survived the 14 day duration of the experiment. Analyses of carbon dioxide in the chamber atmosphere showed an effective concentration of less than 0.5% during the exposure period. Oxygen concentration was maintained at 160 ± 10 mm Hg. Blood biochemical studies, Table I, upon surfacing and ten days after surfacing, showed no significant difference from control animals. Histopathological studies on six animals (four rats and two guinea pigs), (Figures 3, 4, 5) sacrificed upon surfacing, showed four to have focal pulmonary atelectasis, three with focal pneumonia, (Figure 3) and three with adrenal changes characterized by decreased lipid material in cortex and zona fasciculata. One of four animals sacrificed ten days after surfacing showed focal bronchopneumonia, (Figure 4). No histopathological abnormalities were demonstrated in three rats sacrificed 30 days after surfacing.

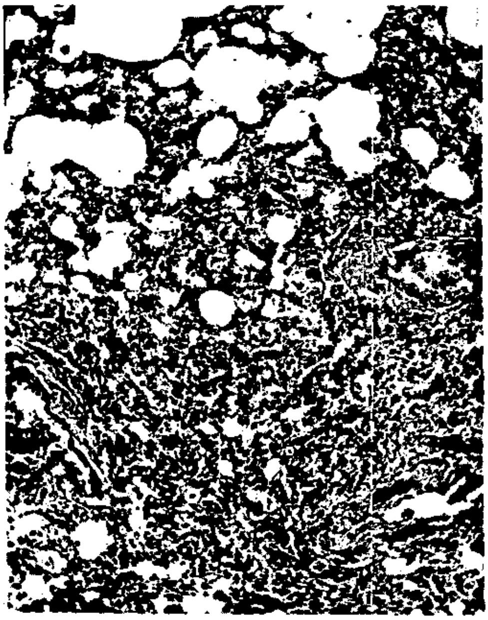

Figure 3—Rat Lung: Animal was exposed in 97% N_2—3% O_2 at 200 feet for two weeks and sacrificed *two hours after surfacing. Note focal zones of* atelectasis and pneumonitis.
H&E x 130

Figure 4—Rat Lung: Animal was exposed in 97% N_2—3% O_2 at 200 feet for two weeks and sacrificed ten days after surfacing. The alveolar walls remained thickened by the endemic pneumonitis but the atelectasis is diminished.
H&E x 130

Figure 5—Rat Brain (Hippocampus): Animal was exposed in 97% N_2—3% O_2 at 200 feet for two *weeks and sacrificed two hours after surfacing. Note* loss of neurons (arrows) from a hippocampal band.
Nissl x 90

Ten rats lost an average of 55 grams weight during the exposure period, while four rats showed no weight change. Six rats gained an average of 11 grams in weight. The four guinea pigs lost an average of 54 grams in weight. In this connection, it is probably significant that aspergillus mold appeared on the commercial rat biscuits at the end of the first week of exposure, after which the rats did not feed as actively as before. Furthermore, difficulty was encountered with the guinea pig feeders not dropping feed effectively so that adequate supplies of feed were not always available. These factors may have influenced uniform weight loss in the animals. Chamber temperature varied between 78°F, averaging 85°F. Relative humidity determined by dry-wet bulb readings ranged from 72% to 96%, averaging 87%.

The rats appeared sluggish and several animals dragged their hind legs intermittently during the exposure, (Figure 5). The guinea pigs were normally active and alert throughout.

Table I—Blood Studies on Animals Exposed to 97% Nitrogen —3% Oxygen at Seven Atmospheres for Fourteen Days

MEAN VALUES

	Immediate		10 Days Survival		Controls	
	Rats	G. Pigs	Rats	G. Pigs	Rats	G. Pigs
pH	7.37	7.41	7.39	7.41	7.38	7.40
$C0_2$ Content (Vol. %)	49.2	52.1	48.6	51.8	50.8	52.5
0_2 Content (Vol. %)	11.6	12.4	11.8	12.4	12.1	12.8
Blood Sugar (mgm %)	134.	141	96	115	105	115
BUN (Blood Urea Nitrogen) (mgm %)	9.7	10.5	11.3	14.1	11.0	10.4
Hemoglobin (gm %)	14.9	14.7	14.4	15.1	14.8	15.4
Plasma Na (MEq/L)	152	150	148	147	148	152
Plasma (MEq/L)	5.3	7.5	5.6	7.5	5.8	6.0
	N=4	N=2	N=4	N=2	N=4	N=4

(c.) Chronic Exposure of Albino Rats to a High Pressure of 97% Helium—3% Oxygen

In view of a mortality of 100% attained in the 35th hour of compression when albino rats were exposed to air at seven atmospheres pressure, and focal pulmonary atelectasis and pneumonia when exposed to normal $p0_2$ but high pN_2 in experiment (b), an attempt was made to provide a synthetic atmosphere which might make such a pressure exposure possible without significant morbidity and mortality in the experimental animals.

Helium, being a less dense gas than nitrogen, and without apparent narcotic effect in the range of observed pressure exposure (15), should make possible normal alveolar ventilation at seven atmospheres pressure, if we are to assume that inadequate ventilation is a factor in the mortality of animals when air is breathed at this pressure. In addition, the capacity of maintaining $p0_2$ of the mixture at a value equivalent to that in air at one atmosphere (160 ± 10 mm Hg) should eliminate the possibility of pulmonary damage resulting from long exposures to high $p0_2$.

Method:

Twenty-four male rats (Wistar strain) ranging from 280-440 grams in weight were placed four to a cage with ample supplies of food and water for eight days. These cages were placed in the outer compartment of our compression chamber to acclimatize to this environment for four days. At the end of this period, the inner chamber was purged with helium and the air mixture was exhausted through a low drain valve until the oxygen content sampled 3% on a Beckman Model-C Oxygen Analyzer, calibrated with helium-oxygen mixtures analyzed on the Scholander Micro-Gas Analyzer. Pressure was then built up to 16 feet simulated depth by addition of helium and oxygen until the oxygen analysis of sampled chamber atmosphere was 14% (160 mm Hg at this pressure). The outer lock containing the animals was then purged with an 80% helium—20% oxygen mixture before pressurization to 16 feet on 100% helium. Upon equalization of inner and outer chamber locks, the animals were taken into the inner lock, which was then pressurized to 200 feet with 100% helium. Oxygen sampled from the inner chamber lock analyzed 3% on the Beckman Oxygen Analyzer, the equivalent of 160 mm Hg at seven atmospheres pressure. These measures insured removal of the chamber air and its replacement with the final helium-oxygen mixture desired.

Carbon dioxide absorption was accomplished by means of 46 pounds of Baralyme placed on screens high and low in the chamber. Water vapor was absorbed by 25 pounds of activated alumina in pans on the deck of the chamber. Two electric fans were operated continuously to circulate gas in the chamber and insure thorough mixing of gas added from cylinders. Commercial animal litter mixed 10:1 with boric acid powder was used in litter trays to suppress ammonia formation from excreta.

The chamber atmosphere was sampled every 6-8 hours by withdrawing gas from a copper tube, placed at cage level between the rows of cages, into an evacuated rubber anesthesia gas bag. Oxygen was analyzed by the Beckman Model-C Oxygen Analyzer calibrated with helium-oxygen mixtures previously analyzed by Scholander Micro-Gas Analyzer. The latter instrument was also used to analyze oxygen and carbon dioxide content of the chamber. Ammonia concentration was monitored by Draeger analysis tubes. Oxygen was added to the chamber from cylinders via a manifold to maintain a pO_2 of 160 mm Hg. Pressure was maintained at 200 feet by addition of 100% helium to the chamber, as required.

Replenishment of water, food, Baralyme, and cage litter trays was carried out on the eighth day of exposure by entering the outer lock pressurized with helium after initial purge with 80% helium—20% oxygen mixture. The diver was breathing a mixture of 80% helium—20% oxygen from a mask, supplied by a demand valve attached to the gas supply cylinder in the chamber lock.

Exposure of animals continued for fourteen days at seven atmospheres. Conservative decompression was carried out exactly as described in Section (b), page 3, (see Figure 1), to avoid risk of superimposing decompression sickness upon effects of pressure exposure. An oxygen pressure of 160 mm Hg was maintained. This was accomplished by slowly raising this value just before leaving one level so that it would equal 160 mm Hg upon arriving at the next decompression stop.

Some animals were sacrificed immediately following arrival of the chamber at one atmosphere and others at 8, 14, 30, and 200 days after surfacing. Blood for biochemical determinations was drawn from the left ventricle of animals sacrificed while the heart was still actively contracting. Methods used for these analyses are described in experiment (d).

Results:

All animals survived and were normally active during the exposure period. With few exceptions the animals lost weight. The weight loss averaged 46 grams per animal. Three weeks after surfacing, the 10 animals which had not been sacrificed had gained an average of 63 grams. As in the previous experiment, development of aspergillus mold on the rat food was noted and may have been a significant factor in the weight loss of the animals.

Carbon dioxide analysis of chamber atmosphere showed an effective concentration of less than 0.5% during the exposure. The pO_2 was maintained at 160 ± 10 mm Hg during the exposure period. Temperature in the chamber ranged from 75°F - 83°F. Humidity by wet-bulb thermometers registered between 83 - 94%. No ammonia was detected by Draeger analysis tubes or odor of chamber atmosphere until decreasing chamber pressure during decompression flooded litter trays from drinking water bottles. Blood analysis carried out upon surfacing, and subsequent sacrifices included pH, CO_2 content, hemoglobin, hemotocrit, blood sugar, and blood urea nitrogen. Although our population was small, determinations on exposed animals did not vary importantly from those of control animals. See Table II.

Histological examinations of these animals were performed. No abnormalities were found in the two animals sacrificed immediately after surfacing (Figure 6). All thirteen animals sacrificed from eight days to seven

Table II—Blood Studies on Albino Rats Exposed to 97% Helium—3% Oxygen at Seven Atmospheres for 14 Days (Mean Values)

	HeO_2 Run—Rats		
	Immediate	1 week	Controls
pH	7.38	7.39	7.39
CO_2 Content (Vol. %)	50.2	50.4	48.8
Hemoglobin (gm %)	14.7	15.2	14.8
Hematocrit	44	45	46
Blood Sugar (mgm %)	96	103	105
Blood Urea Nitrogen (mgm %)	15.0	13.4	12.9
	N=6	4	6

months after surfacing were normal except for two animals in which some fresh intra-alveolar hemorrhage was noted, (Figure 7). Due to the recent nature of this hemorrhage and its proximity to zones of endemic pneumonitis, it was felt that these findings were unrelated to the pressure exposure.

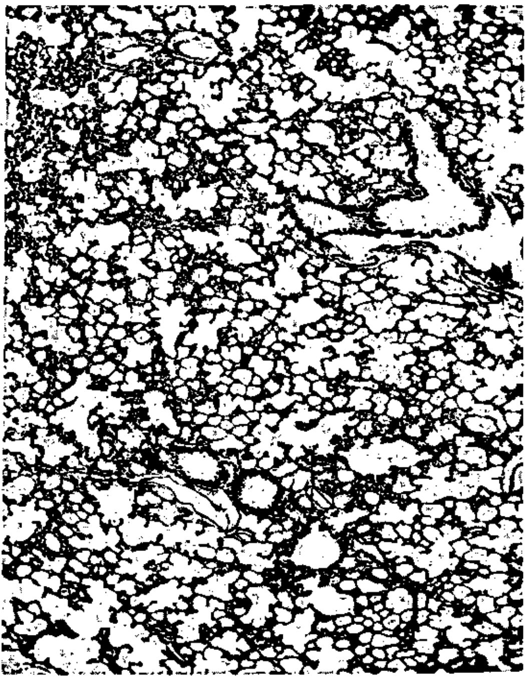

Figure 6—Rat Lung: Animal exposed in 97% He —3% O_2 at 200 feet for two weeks and sacrificed immediately after surfacing. Note that the lung is well aerated without evidence of atelectasis.
H&E x 55

Figure 7—Rat Lung: Animal exposed in 97% He —3% O_2 for two weeks and sacrificed ten days after surfacing. Note intense zone of fresh intra-alveolar hemorrhage. This is occasionally noted adjacent to zones of endemic pneumonitis.
H&E x 90

(d.) Chronic Exposure of Squirrel Monkeys to High Pressure Atmosphere of 97% helium—3% oxygen.

Method:

In anticipation of future experimental work in which human subjects might be utilized, it was felt desirable that small primates be exposed to the experimental conditions previously described.

Three squirrel monkeys weighing 425-435 grams were allowed to acclimatize to the environment of our compression chamber for four days in a self-maintained cage. At the end of this time they were pressurized to seven atmospheres, (200 feet equivalent depth of sea water) in the chamber by addition of helium from pressure cylinders. The oxygen concentration at this pressure was equivalent to 21%, though diluted to 3% (160 ± 10 mm Hg) of the total gas pressure of 5320 mm Hg. At the beginning, no attempt was made to purge the air completely from the chamber. Through frequent additions of helium to maintain chamber pressure, the pN_2 was continuously reduced during the exposure period. The partial pressure of oxygen was maintained at 160±10 mm Hg during the exposure by the addition of oxygen to the chamber from pressurized cylinders. Carbon dioxide removal was carried out by operation of a Desomatic Carbon Dioxide Removal Unit containing four canisters of soda lime of 9.4 lbs. each. One canister of silica gel in that unit was used to remove water vapor from the chamber atmosphere. An additional 10 lbs. of silica gel was spread in a thin layer in two shallow trays. Two electric fans operated continuously to circulate gas in the chamber and insure mixing of the chamber atmosphere. Oxygen concentration was maintained at 160 ± 10 mm Hg during the exposure. Measurements of 0.1% carbon dioxide concentration (0.7% effective concentration) were obtained after periods of 12 hours without use of the $C0_2$ removal unit. Operation of the Desomatic Unit for 30 minutes at 70 cfm capacity reduced the sampled atmosphere analysis to 0% $C0_2$. Chamber temperature ranged from 82°-90°F with an average of 85°F. The animals ate well and were normally active during the exposure period. Weight was maintained and an average gain of 15 grams per animal occurred during the exposure.

Carbon dioxide content of the chamber atmosphere was analyzed by high level Kitigawa carbon dioxide analysis tubes twice daily. Gas samples were withdrawn from the chamber by a sampling tube placed near the animal cage. Oxygen concentration of chamber atmosphere was analyzed with Beckman & Scholander apparatus, exactly as described in the two previous tests.

The monkeys were fed a commercial monkey biscuit ration daily by timed release of a solenoid-activated feed hopper. Additional rations of bananas, white grapes, and apples were placed in the cage at the beginning of the exposure, and on the seventh day, when water bottles, feed and litter were renewed. This housekeeping was performed by a diver breathing 80% helium—20% oxygen, with the outer lock of the chamber pressurized with helium to equalize with the inner lock.

Commercial animal litter mixed 10:0 with boric acid powder was used in the litter tray to decrease ammonia formation by urea-splitting bacteria in excreta. Fifty mgm of veterinary type aureomycin powder was added to each 1000 cc water bottle to limit intestinal infections encountered in monkeys of this kind.

Decompression was begun after the 12th day of exposure by reduction of the chamber pressure from 7 to 3.5 atmospheres (84 feet equivalent depth of sea water). The partial pressure of oxygen was maintained at 160 ± 10 mm Hg by increasing the oxygen concentration from 3% to 6% before reduction of pressure. After a 24 hour stop at 3.5 atmospheres, pressure was decreased to 1.75 atmospheres (26 feet) where the oxygen concentration was maintained at 12%. After 24 hours at 1.75 atmospheres, the oxygen concentration was increased to 17% before the chamber pressure was reduced to one atmosphere. Before one hour had elapsed after reaching the surface, two monkeys were sacrificed. Prior to sacrificing, 12 mgm of pentobarbital was injected peritoneally, the monkeys were weighed, and left heart blood was drawn into a heparinized glycerin-coated syringe under direct visualization of the heart through the opened thoracic cage. The third exposed monkey was maintained in the animal suite for a period of two weeks to observe changes, if any, following recovery in normal air atmosphere. Two control monkeys had been maintained in a similar cage in the outer chamber lock, throughout the experiment, where conditions of heat and humidity were comparable to those experienced by the three monkeys exposed to pressure. One of these controls was sacrificed at the same time as the initial two exposed to pressure, and the other at the end of the two weeks.

The $C0_2$ content and 0_2 content of heparinized anaerobically sampled, whole blood were measured in duplicate within one hour after withdrawal by the manometric method of Van Slyke and Neill (16). The *pH* determinations were made on the whole blood at 37.5°C with the Sanz glass electrode and the Metrohm E322 compensator by the method of Gambino and Arends (17). Plasma CO_2 content was calculated from whole blood CO_2 by means of the nomogram of Sendroy, Dillon and Van Slyke (18). Plasma CO_2 tension was calculated by means of the Henderson-Hasselbalch equation from the observations of CO_2 content, pH, oxygen content and saturation using the pK^1 and solubility factors, corrected to body temperature, of Severinghaus. Values of 6.10 for pK^1 at 37°C and 0.031 for solubility of CO_2 were used.

Blood urea and urea nitrogen content were measured by the method of Gentzkow (20). Sodium and potassium measurements were done with the Baird flame photometer. Blood chlorides were measured by the method of Schoales and Schoales (21). Blood sugar was measured by Nelson's adaptation of the Somogyi method (22). Carbonic anhydrase determinations were performed by the method of Altschule and Lewis (23).

Histopathological evaluation of the monkeys, as in experiment (c), included all vital organs as well as eyes, gonads, bone marrow and long bones. Radiographs of long bones were done on both experimental and control animals to check the possible existence of bony lesions attributable to decompression effects.

Results:

No significant differences were noted in blood biochemical values for the experimental animals compared to the unexposed animals as shown in Table III. Long bone radiographs of exposed and control animals revealed no evidence of bone pathology.

Histopathological studies were performed on the control animals as on all exposed animals. These revealed a focal pneumonitis scattered throughout all lobes of the lungs of one animal, (see Figure 8). Small nests of encysted nematodes were present, though not necessarily associated with zones of pneumonitis. Histopathological examination of all other organs of these two control animals were considered normal.

Two of the exposed animals revealed presence of encysted pulmonary nematodes and focal microscopic pneumonitis (Figure 9). There was no evidence of atelectasis or emphysema, and the bronchi appeared normal.

Figure 8—Monkey Lung: "Normal" control. Note encysted nematodes (arrows). These organisms and an accompanying focal pneumonitis are edemic in this species.

H&E x 130

Figure 9—Monkey Lung: Animal exposed in 97% He—3% O_2 at 200 feet for two weeks and sacrificed immediately after surfacing. Only the endemic nematodes (arrow) with their accompanying pneumonitis are noted.

H&E x 55

In one of the three exposed animals a slight hypertrophy of the zona fasciculata of the adrenal cortex was noted (Figure 10—compare with Figure 11 showing normal adrenal). With these exceptions, all other organs of the three exposed experimental animals showed no evidence of pathology. Examination of the central and peripheral nervous system in paraffin and celloidin sections revealed no abnormalities in any of these animals (Figure 12, 13, 14, 15). Histological studies aimed at detecting abnormalities in lysosomes, mitochrondia, and

Figure 10—Monkey Adrenal Gland: Animal exposed in 97% He—3% 0_2 at 200 feet for two weeks and sacrificed immediately after surfacing. This hypertrophy of the zona fasiculata was noted in only one of the three exposed monkeys.
H&E x 50

Figure 11—Monkey Adrenal Gland: This adrenal from a normal control animal may be compared with the case of hypertrophy (Figure 10).
H&E x 50

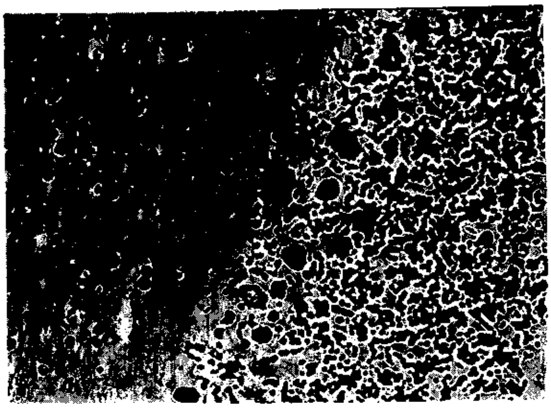

Figure 12—Monkey Cerebellum: Animal exposed in 97% He—3% 0_2 at 200 feet for two weeks and sacrificed immediately on surfacing. No abnormalities are noted.
Nissl x 230

Figure 13—Monkey Hippocampus: Same animal as Figure 12. No abnormalities are seen.
Nissl x 50

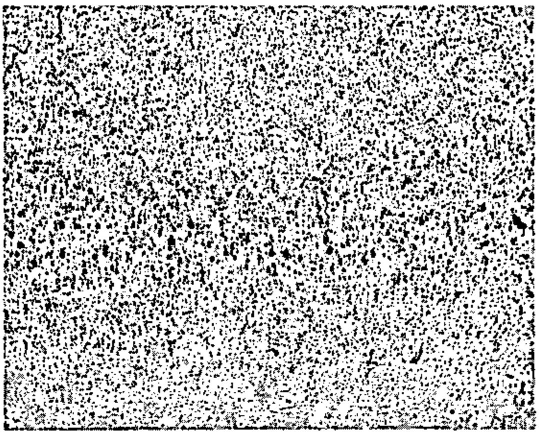

Figure 14—Monkey Neocortex: Same animal as Figure 12. No abnormalities are seen.

Nissl x 50

Figure 15—Monkey Cerebral Cortex: Normal control animal.

Nissl x 55

Golgi apparatus of neurons revealed no abnormalities. Recent studies (30, 31, 32) have indicated that alterations in these intracytoplasmic organelles are a useful index of early neuronal necrobiosis. It was considered that the pulmonary pathology seen in the experimental animals was indistinguishable from the inflammatory pulmonary lesions endemic in this species.

Table III—Chronic Exposure of Squirrel Monkeys to an Atmosphere of 97% Helium—3% Oxygen at Seven Atmospheres Pressure for 12 Days

	Blood Studies				
	Exposed Animals			Control Animals	
	M_1	M_2	M_3	M_4	M_5
pH	7.39	7.40	7.38	7.40	7.41
CO_2 Content (Vol. %)	46.8	48.3	46.4	47.2	46.8
O_2 Content (Vol. %)	16.9	14.5	16.8	15.5	15.1
(pCO_2) p (mm Hg)	41	42	41	41	40
(CO_2 Content) p (Vol. %)	54.7	56.3	54	55.3	56.1
O_2 Capacity (Vol. %)	18.0	17.0	16.3	17.3	18.9
Hemoglobin (gm %)	13.4	12.7	12.9	12.9	14.1
Blood Urea Nitrogen (mgm%)	12.7	15.4	16.0	15.96	18.1
Blood Urea (mgm %)	28.4	33.7	34.1	34.2	38.7
Sugar (mgm %)	97	112	79	86	110
Plasma Sodium (MEq/L)	154	153	156	152	151
Plasma Potassium (MEq/L)	2.8	2.6	2.6	2.7	2.8
Plasma Chloride (MEq/L)	110	120	113	116	123
Carbonic Anhydrase Warburg (Units)	3.61	3.54	3.64	3.6	3.52

DECOMPRESSION STUDIES ON GOATS

Experiment No. 1:

Our earlier experiments, as reported here, were concerned with the feasibility of using an artificial atmosphere of oxygen and helium under pressures as great as 200 feet of water. A further problem was to determine decompression requirements in a minimal number of stages after prolonged exposure to severe atmospheric pressures. For this study a series of experiments was performed on goats given saturation exposures of 72 hours in 97% helium—3% oxygen.

Method:

Two goats, a male weighing 37 lbs. and a female weighing 70 lbs., were exposed to pressure equivalent to that of a 200-foot depth of sea water. This was accomplished in the pressure chamber previously described, by adding helium gas from pressurized cylinders, as in the experiments with albino rats, guinea pigs, and squirrel monkeys.

Carbon dioxide absorption was provided for by spreading 45 lbs. of lithium hydroxide and 24 lbs. of Baralyme pellets in shallow trays with continuous fan circulation of the atmosphere to insure contact with this absorbent material. In addition, 15 lbs. of boric acid powder were added to retard ammonia formation from urea-splitting bacteria acting on excreta. Hay and pulverized commercial goat feed were provided. Water requirements would be satisfied from an 8-gallon open water container, see Figure 16.

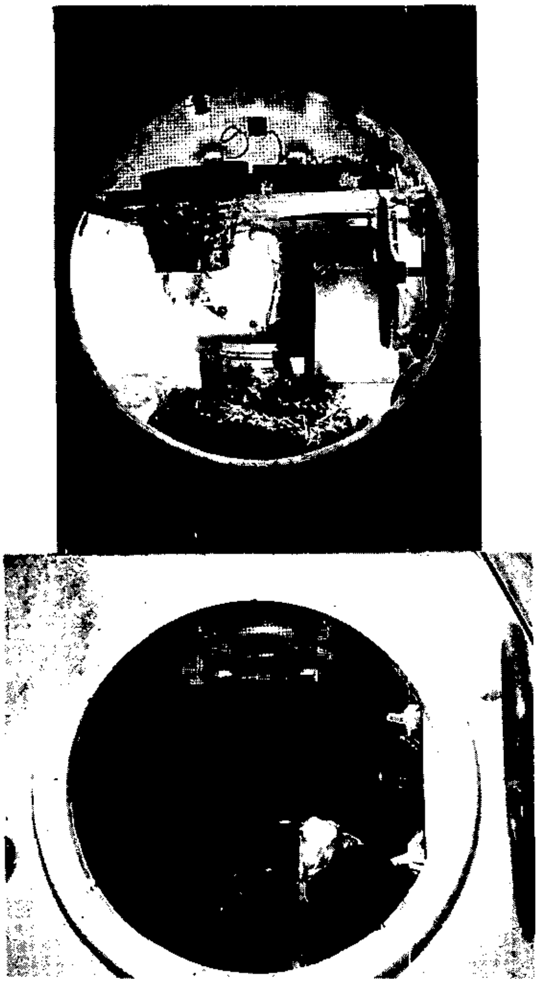

Figure 16—Interior view of compression chamber showing feeding arrangements for goats.

As needed, oxygen was added to the chamber from pressurized bottles to maintain a 3% level (160±10 mm Hg). The oxygen content of the atmosphere was monitored by a Beckman Model-C Oxygen Analyzer, calibrated in a helium background. Oxygen and CO_2 content of the chamber atmosphere were also analyzed by Scholander Micro-Gas Analyzer. Ammonia determinations were made by Kitigawa Ammonia Analysis Tubes. Pressure of the atmosphere in the chamber was maintained by addition of helium gas to the chamber from pressurized bottles.

A two-stop 72-hour decompression schedule was followed, (Figure 17).

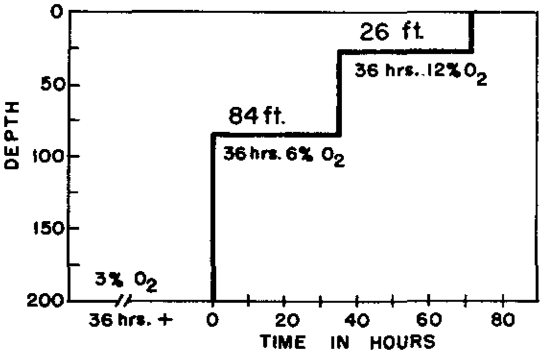

Figure 17—Stages of goats following 72 hours exposure to helium-oxygen atmosphere at 200 feet equivalent depth of sea water.

(1) After keeping the goats for 72 hours at 200 feet, the chamber pressure was reduced to 84 feet in ten minutes. More oxygen was released into the chamber during the ascent so that upon arrival at 84 feet (3.5 atmospheres absolute) the oxygen concentration, measured by the Beckman Analyzer, was raised to 6% (21% effective).

(2) After 36 hours at 84 feet, the chamber pressure was reduced to 26 feet over a period of 30 minutes and oxygen was added during the ascent so that the chamber atmosphere contained 12% oxygen (1.75 atm.) which is 21% effective pressure.

(3) After 36 hours at 26 feet, the chamber was brought to the surface in five minutes.

Results:

The two goats fed actively and moved about in the chamber throughout the exposure period and subsequent decompression stages. On the third day, before decompression to 84 feet was begun, Scholander analysis gave 0.358% CO_2 for an effective concentration of 2.5%. After 30 hours at 84 feet, the CO_2 analysis on Scholander was 0.14% (0.49% effective). After four hours at 26-foot stop, the ammonia reading by Kitigawa apparatus was 10 ppm. After 11 hours at 26 feet, the CO_2 reading on Scholander was 0.178% (0.311% effective). Ammonia read 30 ppm and CO_2 was 0.24% (0.42% effective) after 34 hours at 26 feet. The animals were observed for 18 hours after surfacing, and showed no evidence of decompression sickness, and none was found during or following decompression to the surface.

Experiment No. 2:

Method:

Two goats, both females, weighing 120 lbs. and 35 lbs. respectively, were pressurized to 200 feet in the chamber by addition of helium. Carbon dioxide absorption in this experiment was attempted by means of a scrubber tank containing 15 lbs. of lithium hydroxide in 20 gallons of water, though which the chamber atmosphere was bubbled. A refrigeration-type compressor of 1-CFM capacity removed gas from the chamber, forced it through a diffuser pipe at the bottom of the tank, and then passed the scrubbed gas back into the chamber. Electric fans in the chamber operated continuously to insure atmosphere mixing. Analysis of oxygen and carbon dioxide was accomplished as in the former experiment with goats.

Results:

Because of insufficient compressor output, difficulty was encountered in CO_2 removal, so that in 17 hours the chamber atmosphere, analyzed by Scholander Micro-Gas Analyzer, was 0.732% (5.1% effective). In spite of continuous scrubber operation and regeneration of solution, the CO_2 percentage rose to 0.9 (6.3% effective) as shown by Kitigawa analysis. A 2-CFM compressor was then substituted and a stainless steel pipe (½" I.D.) replaced the diffuser pipe which had become sealed over with lithium carbonate deposit. A greater volume of gas scrubbing was achieved, but CO_2 concentration in the chamber was only slowly decreased in the third 24-hour exposure period from 4.5% effective to 2.1% effective.

After 72 hours at 200 feet, the chamber pressure was reduced to 84 feet in 15 minutes. In the next ten minutes, the large goat became restless, chewed at her left front and left hind legs, and refused to bear weight on the left hind leg. Chamber pressure was reduced to 74 feet in two minutes to determine if signs of decompression sickness were accentuated. These were clearly demonstrated and pressure was promptly increased in the chamber by addition of helium. At 90 feet, the goat again supported herself on all four legs and appeared free of symptoms. The chamber pressure was then returned to the 200-foot level.

A three-stop 72-hour decompression schedule was followed. After three hours at 200 feet, the pressure was reduced to 100 feet over a 20 minute period, and a stop was made at this depth for 24 hours. No recurrence of signs of decompression sickness occurred in either of the two goats during this period. Oxygen concentration was maintained at 21% effective by addition of oxygen to the chamber before and during reduction of pressure. Carbon dioxide remained between 1.6 and 1.8% effective at 100 feet. Following the 24-hour stop at 100 feet, the chamber pressure was reduced to 43 feet in a transition period of 15 minutes. No evidence of decompression sickness occurred in the following 24 hours spent at this stop. Carbon dioxide percentage remained at 1.38 to 1.85% by Kitigawa analysis during this period. The chamber was then brought up to a 10-foot pressure level within ten minutes and this pressure was maintained for 24 hours. No immediate evidence of decompression sickness occurred in the animals on reaching this third stop level. After 10 hours at the 10-foot stop, ammonia concentration by Kitigawa analysis was 30 ppm. After 24 hours at the 10-foot stop, the chamber was brought to the surface in two minutes. No evidence of decompression sickness was observed then or during the following 24-hour period at the surface. The goats weighted 110 lbs. and 38 lbs. respectively, after the six days of exposure to the chamber habitation routine.

Experiment No. 3:

In our third goat experiment, we intended deliberately to produce decompression sickness in one or both of the experimental animals. Despite the safety of ratios, (as documented by Hempelmann et al (26)), which were employed in the previous experiment, we could not be completely sure that the unexpected "bends" described in the previous experiment might not have resulted from a close choice in decompression ratio selection, rather than the obvious CO_2 problem. Accordingly, we elected to expose a pair of goats, under ideal atmosphere control, to a much more strenuous decompression regimen. In short, we proposed to decompress these animals quite rapidly from the two hundred foot saturation level to a shallower depth which would ultimately produce decompression sickness, however shallow that depth might be.

As the following history will show, the saturated animals were decompressed on a ratio which is unacceptably dangerous by present applicable standards. Nevertheless, no "bends" resulted. It was decided to make a "stop" at forty feet, since the safety of the 2:1 ratio would here be more than adequately demonstrated, and the experimental animals would be spared the probability of massive decompression sickness and resultant fatality.

Method:

Two adult female goats weighing 76 and 86 lbs. respectively, with maintenance arrangements as previously described, were pressurized to the 200-foot level in the pressure chamber by addition of helium from pressurized cylinders. This pressure was maintained for 72 hours. Oxygen was maintained at 3% by additions to the chamber atmosphere from a high pressure source. Analyses of oxygen and CO_2 concentrations in the chamber atmosphere were carried out with Beckman Model-C Oxygen Analyzer, Scholander Micro-Gas Analyzer, and Kitigawa CO_2 analysis tubes. Carbon dioxide absorption was accomplished by forcing the chamber atmosphere through two pressure tanks connected in series, each containing 10 lbs. of lithium hydroxide in 20 gallons of water. A refrigeration-type compressor with 2 cu. ft./min. output was used for this purpose. Chamber temperature was to be maintained at 80-89°F by control of room temperature. Sixteen lbs. of baralyme pellets were spread in shallow trays for auxiliary CO_2 absorption. Two electric fans were operated continuously to insure circulation of the chamber atmosphere.

At the completion of a 72 hour exposure period the chamber pressure was vented off to an equivalent depth of 84 feet in 17 minutes. Oxygen concentration was maintained at 21% effective during ascent and at stops, by addition of oxygen as required from pressurized cylinders. After this rapid change from 7 to 3.5 atmospheres pressure, the goats were observed for a 10 minute period to determine if signs of decompression sickness were evident. The chamber pressure was then reduced to 70 feet in 3 minutes and the animals observed at this depth for 5 minutes The chamber pressure was further reduced by increments of 10 feet for observation periods of 5 minutes at each step until the 40 foot level was reached. At this depth the animals were observed for signs of decompression sickness for a 24 hour period, after which the chamber pressure was reduced to zero feet in a transition period of 20 minutes and at surface level the animals were observed for a 12 hour period.

Results:

Both goats were active, moved about the chamber, and fed throughout the exposure period and subsequent stages of decompression. After 18 hours exposure, the CO_2 content of the chamber analyzed 0.246% (1.72% effective) on the Scholander apparatus. After 40 hours exposure CO_2 measured 0.2% (1.4% effective), and after 68 hours exposure 0.04% (0.28% effective). Temperature in the chamber ranged between 86°-87°F. No odor of ammonia was detected in samples of chamber atmosphere during the exposure and subsequent decompression. However, upon surfacing a measurement of 10 ppm was obtained in the chamber by the Kitigawa analyzer.

No evidence of decompression sickness was observed in either animal during reduction of chamber pressure to the 40 foot stop, during the 24 hour stay at this stop, nor during the 12 hour period of observation at the surface. The animals gained 3 and 2 lbs. in weight respectively during the total experimental period of about 97 hours.

DISCUSSION AND CONCLUSIONS

Our experiment with rats subjected to normal air under pressure equal to seven atmospheres gave pronounced early deleterious results. These could have been predicted, since previous studies of mammalian survival under conditions of high ambient pressure of air have shown a significant morbidity and mortality. Smith et al, (6), exposed rats to air at four atmospheres absolute for periods up to seventy-two days and found a total morbidity of fifty per cent, resulting from pulmonary edema and hemorrhagic changes. The irritant level for prolonged inhalation of oxygen has been found to be the same for man as for lower animals (428 mm Hg), and 100% oxygen appears to be toxic after a period of inhalation of about 12 hours, (12). Excessive $p0_2$, i.e., above 600 mm Hg (6), density of respired gas, and narcotic effect of nitrogen, are all three considered to be factors in the development of pulmonary edema and hemorrhages demonstrated upon autopsy of animals dying within 30 minutes prior to surfacing the chamber.

It remained to be determined whether exposure to a synthetic atmosphere in which oxygen tension is controlled at 160 mm Hg, would permit survival and freedom from pulmonary pathology in animals exposed to the pressure equivalent of 200 feet of sea water. The possibility existed that a density increase equal to seven times that of normal atmospheric air, together with respiratory depression due to the narcotic action of nitrogen, might impair carbon dioxide elimination by decreasing alveolar ventilation sufficiently to be in part responsible for pulmonary tissue changes, (13), (15). Our next experiment gave further information on this problem.

Four guinea pigs and 24 rats (minus one) survived a 14-day exposure to 3% oxygen in nitrogen at seven atmospheres of pressure. Most of the animals lost weight. The rats were not normally active. Focal pulmonary atelectasis and pneumonia were demonstrated in four rats and two guinea pigs which were sacrificed immediately upon completion of the exposure. Sacrifices ten days after surfacing showed one case of focal bronchopneumonia. Although effective oxygen and carbon dioxide concentrations were maintained at values comparable to those in ambient air, the density of the atmosphere was increased by a factor of seven. Increased resistance to airway flow in the lungs, coupled with diminished ventilation due to depression of the respiratory center by high pN_2, may have been factors in the development of pulmonary atelectasis, (13), (14), (15). Chronic carbon dioxide retention due to decreased pulmonary ventilation was not in evidence, as whole blood pH and $C0_2$ content were within normal limits upon surfacing. The 24 hour period of gradual decompression may have permitted recovery to near normal values upon surfacing. Maintenance of $p0_2$ at 160 ± 10 mm Hg would appear to be the important factor in survival of animals when compared to 100% mortality of animals exposed to air at seven atmospheres, as reported in the previous experiment, since atmospheric density and pN_2 would have been comparable. However, it is important that the animals were lethargic and demonstrated intermittent paresis of the hind quarters during this type of exposure.

We found that a relatively nitrogen-free atmosphere containing 21% effective oxygen in helium permitted survival of white rats for 14 days at seven atmospheres pressure. Throughout this period approximately normal activity and feeding were observed. The exposed rats were sacrificed for examination over a period of seven months. These animals had been active; however, they lost weight, and subsequent to exposure were found to have an average loss of 46 grams. Formation of mold on animal food may have been a significant factor in this development.

Maintenance of pO_2 at 160 ± 10 mm Hg was considered to be an important factor in reduction of pulmonary damage and mortality in this experiment. Since density of the helium-oxygen mixture at seven atmospheres is comparable to air at 1.7 atmospheres absolute, alveolar ventilation was not considered to be significantly affected by the slight density increase. Narcosis resulting in respiratory depression, such as occurs with air breathing at a pressure of seven atmospheres, was avoided by use of helium. Thus, the focal pneumonia and pulmonary atelectasis evident in animals exposed to N_2O_2 in our experiments may have resulted from inadequate alveolar ventilation with a more dense mixture, since density alone was varied with the HeO_2 mixture, the pO_2 being controlled in both experiments at 160 ± 10 mm Hg (13), (15).

As the next step in our study, squirrel monkeys were exposed to the helium-oxygen atmosphere for a prolonged period to determine whether primates were able to maintain normal physiologic functions in an atmosphere which had proved adequate for rats and guinea pigs. The known susceptibility of squirrel monkeys to pulmonary parasites and infections presented a severe test situation. Though histopathological studies revealed encysted pulmonary nematodes and focal pneumonitis in both control and exposed animals, they were normally active and ate well during the exposure period in the compression chamber. Another consideration was the possibility of central nervous system and long bone pathology subsequent to the prolonged exposure and decompression to atmospheric level. However, no abnormalities of these systems were detectable by histopathological and X-ray techniques. The well-known absence of narcotic effects in man from breathing helium-oxygen mixtures at sea levels or in diving, taken into consideration with our experimental results, and more specifically these on monkeys, points to the conclusion that proper combinations of helium and oxygen may constitute a suitable artificial atmosphere for man at pressures greater than sea level.

Our three consecutive experiments on goats, each lasting six days and involving animals of different sexes, ages, and weights, using two animals at a time, in general, fulfilled expectations in reference to our hypothesis concerning safe decompression requirements.

In the first of this series, a 2:1 ratio of absolute exposure pressure to absolute pressure of the decompression stop, as proposed by Boycott, Damant and Haldane (8), was used to decompress the animals for the first two stops. Decompression to the surface from 26 feet was accomplished on a 1.75:1 ratio. The 72-hour exposure period was considered to be greatly in excess of that required for complete saturation with the helium-oxygen atmosphere to which these animals were exposed. Sutton et al, (9), have reported that five to six hours would appear to be adequate time for saturation to air at the exposure depth. Helium saturation time is reported by Behnke (15) to be somewhat less than air for man. Inasmuch as we were concerned over decompression problems of such "slow" tissues as the bony cortex and the crystalline lens of the eye, we felt justified in prolonging the exposure beyond the saturation levels established in the literature. Elevation of the CO_2 concentration in the chamber atmosphere to 2.5% before decompression commenced was a source of some concern, as increased susceptibility to decompression sickness occurs in the presence of increased carbon dioxide concentration in the inspired atmosphere (25). In this experiment, no evidence of decompression sickness was observed. Uneventful ascent to subsequent stages took place after carbon dioxide concentration of the atmosphere was reduced to less than 0.5% effective.

Stage decompression at depths of 84 and 26 feet, in each of which 36 hours were spent, provided freedom from decompression sickness for two goats previously exposed to a simulated depth of 200 feet in a chamber while breathing 97% helium—3% oxygen. A 2:1 ratio of absolute exposure depth to absolute depth of the stop was tested for an artificial atmosphere exposure of sufficient duration to allow complete saturation of the test animals.

In the second goat experiment, development of decompression sickness in one animal on coming from 200 feet to the 84 foot stop may have been related to the high CO_2 concentration existing in the previous 24 hours before ascent. This clear-cut case of decompression sickness in an experimental animal offered opportunity to determine whether a saturated subject, developing decompression sickness at a "stop" could safely be treated by return to saturation depth, a "soak" of several hours to permit bubble resolution, and decompression on a more conservative ratio. Accordingly, in this case, recompresion to 200 feet for 3 hours was done in an attempt to bring about reduction in size and possible resolution of gas bubbles in tissues producing signs of decompression sickness. Subsequent decompression was carried out on a more conservative 1.75:1 ratio of stops, except for the last stop before surfacing which was 1.3:1. No recurrence of signs of decompression sickness was in evidence.

The use of a 2:1 ratio of exposure pressure to that of decompression stops did not prove adequate to prevent decompression sickness in one of two goats exposed to 97% helium—3% oxygen for 72 hours at seven atmospheres. However, development of excessive carbon dioxide concentration in the chamber atmosphere may have contributed to this failure. Treatment of the observed decompression sickness in the larger goat was accomplished by returning the animals to previous saturation depth for a three-hour period, following which they were decompressed on a more conservative ratio. In this instance, at least, the described rationale of treatment was effective.

In the third goat experiment it is evident that, for both animals, we safely exceeded the 2:1 ratio. Decompression from 200 feet to 40 feet gives a ratio of absolute pressures of 3.16:1 (231:73), while that from 40 feet to the surface is 2.21:1 (73:33). Approximately one hour elapsed between leaving 200 feet and arriving at 40 feet, during which the animals were observed at decreasing 10 foot levels for evidence of decompression sickness. In this time significant d saturation of well perfused tissues would occur. However, poorly perfused tissues would still contain inert gas tension quite close to that at the exposure depth. Such a state of supersaturation occurring upon reduction of pressure did not cause signs of decompression sickness. The maintenance of relatively low CO_2 concentration in the chamber may well have been a factor for success in use of a 3.16:1 ratio at depth, when a 2:1 ratio failed to prevent decompression sickness in one animal in our second experiment in which atmosphere CO_2 was excessive.

SUMMARY

Using four species of animals, a series of respiration experiments was made in a pressure chamber operated at a level of seven atmospheres. The gases used were: normal air, 97% nitrogen with 3% oxygen; and 97% helium with 3% oxygen. Pressure periods of 72 hours, and of 12 to 14 days, were employed. The requirements for successful decompression were examined. White rats exposed to normal air at the pressure of 200 feet of sea water became lethargic in 15 hours and all were dead in 35 hours. Although the oxygen tension was controlled to 160 ± 10 mm Hg., focal pneumonia and pulmonary atelectasis were demonstrated in albino rats and guinea pigs exposed to the 97% nitrogen—3% oxygen atmosphere. Rats exposed to 97% helium—3% oxygen atmosphere for 14 days were normally active and survived the exposure without significant functional or anatomical changes. The fourfold greater density of the nitrogen-oxygen gas, as compared to the helium-oxygen atmosphere, is considered to be a limiting factor to normal alveolar ventilation, predisposing to the development of pulmonary atelectasis and pneumonia.

Squirrel monkeys were similarly exposed to a synthetic atmosphere of 97% helium—3% oxygen at 200 feet equivalent depth for 14 days. Their blood chemistry and histopathological studies did not differ from those made on our two control monkeys that were breathing atmospheric air and were living in the unpressurized section of the chamber during the period of the experiment.

Decompression studies carried out on goats exposed to a helium-oxygen atmosphere at 200 feet for 72 hours showed that 36 hour stops at 84 and 26 feet, respectively, were adequate to prevent decompression sickness. One animal was an exception, but accidental excessive carbon dioxide in the atmosphere of that experiment is considered to have facilitated development of decompression sickness. Treatment by return to saturation depth, a short "soak" phase, and decompression on a more conservative schedule proved effective in this case. Subsequent experimentation demonstrated that after 72 hours the pressures could be reduced from 200 to 40 feet, by making short stops with appropriate adjustments of oxygen tension over a period of about one hour. A stay at 40 feet for 24 hours proved adequate to prevent decompression sickness in the two goats similarly exposed.

It may be concluded that a helium-oxygen atmosphere with oxygen tension controlled at 160 ± 10 mm Hg should be satisfactory for 14 days exposure of men at the equivalent pressure of 200 feet of sea water. On the basis of established similarity of decompression requirements for goats and men, decompression stages of 36 hours at 84 and 26 feet, respectively, should provide adequate decompression for saturating exposures at seven atmospheres.

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UNDERWATER PERFORMANCE

Articles selected by Arthur J. Bachrach, Ph.D.
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18

UNDERWATER PERFORMANCE

Arthur J. Bachrach

It is patent that selection of a group of articles requires a certain amount of verve and nerve, for one is bound to omit works that others consider important, and conversely, to include some that others would not select. With this brief *apologia*, let me state that the primary criterion for selecting the documents in this section was that, in some manner, the work contributed importantly to the thinking of other investigators in the field.

On one selection I must make special comment: the paper by BACHRACH that appeared in the 2nd edition of Bennett and Elliott's *The Physiology and Medicine of Diving* (1975), is included because, as far as I can tell, it is the only critique published on the *methods* of conducting research in underwater performance, and as such, sets the stage for assessment of such research, particularly the problem of standardizing procedures and test materials as well as subject populations.

The success of divers in performing work under difficult conditions has been impressive, and it would be important to refine working modes to understand more fully the interaction of physiologic and performance variables, such as energy costs of work performed. To be sure, recent years have demonstrated that cognitive aspects of performance are critical variables, with loss of accurate judgment listed frequently as a factor in diving accidents and as a component of problems associated with progressive hypothermia. Environmental conditions, such as cold, degraded visibility, and swift currents, can markedly affect diver performance, as can equipment and problems of gas density. A basic study of stress-degrading cognition is that of WELTMAN and EGSTROM (1966).

Perhaps the biggest research problem in underwater performance as it relates to the field is that of extrapolation. Most of the work on underwater performance has been in hyperbaric chambers, with few studies in open ocean. The reason is obvious. Control of important variables is difficult to achieve in an open sea experiment, but it is very likely to be those variables that make performance possible or not; therefore, extrapolation from a dry, temperature-controlled, monitored, land-based chamber to a cold, dark, turbid, wet environment must be done with exceeding care. Two classic papers included in this collection illustrate this difficulty. KIESSLING and MAAG (1960) placed subjects in a dry chamber to study manual dexterity--an experiment described by BADDELEY (1966), the other paper in this section, as "probably the only reasonably detailed study of manual dexterity at pressure . . ." Baddeley studied manual dexterity both in a dry chamber and the open sea, with varying results.

These studies illustrate another feature of research in underwater performance: the need for standardization or equivalency of tests used. Many interesting experiments were on-the-spot creations, such as one study in which investigators handed divers a deck of playing cards on the surface and asked them to sort out the cards on the bottom--a test of possible nitrogen narcosis that might have, at most, surface validity. Kiessling and Maag also studied choice reaction time in their 1962 experiment, using a panel of two lights, red on the left, green on the right, with two hand switches. Another early classic is reported by SHILLING and WILLGRUBE (1937) in which reaction time--in this instance an electric light bulb was used--was measured. BEHNKE, THOMSON, and MOTLEY (1935) conducted another classic study 2 years earlier.

Two other papers contributed importantly to research literature in underwater performance: one, a classic published in 1906 by HILL and GREENWOOD, is among the earliest studies of increased barometric pressure and its effect on humans; the other reported the carefully developed experiments of CASE and HALDANE (1941), the particular series in this collection reproduced from a fundamental 1941 work.

In addition to marked influence on other research groups, these papers illustrate problems in standardized methodologies used in various studies, a problem to which I have alluded earlier. This problem is not unique to the underwater world. The very nature of the research, dealing with complex variables of physiology and performance in a stress environment, makes experimental control and design an exquisitely complicated endeavor, especially when the investigator leaves the comfort of a land-based chamber to drop his experimental techniques into the water. Nonetheless, there has been an interest in developing some approach to standardization so that different investigators in different laboratories and field research situations might better compare data emerging from their research.

Perhaps the most ambitious approach to standardized testing for underwater performance is represented by the "abilities approach" used by REILLY and CAMERON (1968). This testing was the forerunner of SINDBAD (Systematic Investigations of Diver Behavior at Depth), a study in which factor analysis of basic tasks and their performance was attempted. Later applications reported in 1974 by Bain and Berghage of the Navy Experimental Diving Unit and in 1978 by Fletcher at the University of Pennsylvania demonstrated that this approach had merit.

One problem with the SINDBAD technique was the large number of tasks used to assess specific abilities--a total of 26 tests in the battery. The direct application of tests, such as hidden figures, to the underwater environment was also a problem.

Another seminal paper reproduced here is one in which BOWEN (1968) studied the effects of cold on diver performance.

All of the studies reported in this series deal with the individual diver working on a designated task with his own skills: a one-to-one hand task event, to oversimplify the situation. Work modes are changing because task performance is required at greater depths under more difficult operational conditions.

With development of remote operating vehicles, manned submersibles, and related systems, such as the 1-ATA diving system JIM on the scene, a crucial question is comparability of manipulators and machines in completing a task when assessed against human divers working in an underwater mode. One basic study in this area was presented by Pesch, Hill, and Klepser in 1971, in which scuba divers and submersible manipulator controllers were compared on the same tasks.

Once again, these are a sampling of many papers on underwater performance. We hope they may be considered as representative of the type of key document of value for the research community.

UNDERWATER PERFORMANCE

A. J. BACHRACH

The articles included in this section are reprinted by permission of their original publishers, as follows:

Bachrach, A. J.: Underwater performance, in Bennett P. B., Elliott D. H. (eds): *The physiology and medicine of diving and compressed air work.* 2nd ed. London, Baillière Tindall, 1975, pp 264–284. (abstract)

Baddeley A. D.: Influence of depth on the manual dexterity of free divers: a comparison between open sea and pressure chamber testing. *J Appl Psychol* 1966; 50:81–85. Copyright 1966, American Psychological Assoc.

Bain E. C., Berghage T. E.: *Evaluation of SINDBAD tests.* US Navy Experimental Diving Unit, Rep No. NEDU 4-74. 1974. 68 pp.

Bowen H. M.: Diver performance and the effects of cold. *Human Factors* 1968; 10(5):445–463. Copyright 1968, The Human Factors Society, Inc.

Fletcher D. E., Lambertsen C. J., Gelfand R., Clark J. M., Peterson R. E.: Perceptual, memory, cognitive and psychomotor functions, in Lambertsen C. J., Gelfand R., Clark J. M. (eds): *Work capability and physiological effects in He-O_2 excursions to pressures of 400-800-1200-1600 feet of sea water.* Philadelphia, Inst for Environmental Medicine, Univ of Pennsylvania Med Ctr, 1978, pp. E10-1 to E10-58.

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Reilly R. E., Cameron B. J.: *An integrated measurement system for the study of human performance in the underwater environment.* Contract N00014-67-C-0410. Work Unit No. NR 196-074. Falls Church, VA, Biotechnology Inc, 1968, 88 p.

Weltman G., Egstrom G. H.: Perceptual narrowing in novice divers. *Human Factors* 1966; 8:499–506. Copyright 1966, The Human Factors Society, Inc.

The following articles are referenced in this section but appear in the sections indicated in parentheses:

Behnke A. R., Thomson R. M., Motley E. P.: The psychologic effects from breathing air at 4 atmospheres pressure. *Am J Physiol* 1935; 112:554–558. (Inert Gas Narcosis)

Case E. M., Haldane J. B. S. Human physiology under high pressure. *J Hyg* 1941; 41:225–249. (Hydrogen-Oxygen Diving)

Kiessling R. J., Maag C. H.: *Performance impairment as a function of nitrogen narcosis.* Res Rep 3-60 US Navy Exper Div Unit, US Nav Weapons Plant, Washington DC, 1960, 25 pp. (Inert Gas Narcosis)

Shilling C. W., Willgrube W. W.: Quantitative study of mental and neuromuscular reactions as influenced by increased air pressure. *US Nav Med Bull* 1937; 35:373–380. (Inert Gas Narcosis)

ABSTRACT

Bachrach, A. J.

Underwater Performance

In: Bennett, P.B. and D.H. Elliott. The physiology and medicine of diving and compressed air work. Second Edition, p. 264-284.
Baillière & Tindall, London, 1975.

Performance studies have produced contradictory results because of the lack of standardization of tests, and the difficulties of using the same tests on the surface and under water. Using performance under ideal diving conditions as a base line for evaluation is more desirable than using performance on land or in a hyperbaric chamber. Performance is affected by breathing mixture, pressure, and diver condition. The four main categories of performance to be tested are (1) cognitive, (2) perceptual-sensory, (3) psychomotor, and (4) physical proficiency. The Systemic Investigation of Diver Behavior at Depth (SINDBAD), designed at the Navy Experimental Diving Unit for wet or dry chamber dives, consists of 26 tests ranging from very simple to very complex. Factor analysis results showed that each measure was unique, and that the expected redundancy did not occur. Another approach to performance evaluation is the physiological one, which involves monitoring by telemetry such factors as heart rate, oxygen consumption, etc. Many types of stress can interact--both to potentiate and to mitigate each other. Other factors which greatly affect performance are equipment, training, practice effects, and adaptation. Subject variability and task variability must also be considered.
(MFW/UMS)

Journal of Applied Psychology, 1966, vol. 50, no. 1, pp. 81-85.

Journal of Applied Psychology
1966, Vol. 50, No. 1, 81-85

INFLUENCE OF DEPTH ON THE MANUAL DEXTERITY OF FREE DIVERS:

A COMPARISON BETWEEN OPEN SEA AND PRESSURE CHAMBER TESTING

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Using a compression chamber, Kiessling and Maag (1962) showed a decline in manual dexterity at a pressure simulating 100 ft. of water. Impairment was slight (7.9%) and was assumed to be of little practical importance. The present study examines this conclusion by testing divers in the water. The manual dexterity and tactile sensitivity of 12 free divers were tested above the surface, and at 10 and 100 ft. below the surface. The dexterity test took 28% longer at 10 ft. and 49% longer at 100 ft. than on the surface, the differences between all conditions being significant ($p < .005$). Tactile sensitivity did not change. Replication in a dry pressure chamber showed an impairment of less than 6%, which though reliable ($p < .05$) was significantly smaller than that shown in the open sea ($p < .05$). Conclusions are (a) the impairment of manual dexterity at depth is considerable when tested under water. (b) it is unwise to generalize from pressure chamber experiments to under water performance.

The growing military and commercial importance of the self-contained or free diver is focussing attention not only on the classical problems of survival underwater, but also on the less dramatic, but in the long run equally important question of the limits of performance underwater. Most diving of commercial and military importance is carried out at relatively shallow depths where, given reasonable precautions, the problem of survival is not very great, but where the diver's efficiency may well be impaired. In such circumstances it may be costly and even dangerous to expect too much of a diver. The present study attempts to take one simple but important capacity, manual dexterity, and see how this is affected by depth.

There is a considerable body of evidence that human performance is impaired under pressure. At depths of 100 feet and probably less, a diver begins to suffer from "nitrogen narcosis" or in Cousteau's phrase, from "the rapture of the depths" (Barnard, Hempleman, & Trotter, 1962; Cousteau, 1953; Kiessling & Maag, 1962). However, in most of this work the prime interest was physiological, and in much of the earlier work the psychological studies were not adequately controlled. Probably the only reasonably detailed study of manual dexterity at pressure is that of Kiessling and Maag (1962), who found a significant impairment in speed of performance on the Purdue Pegboard, a task which involves placing pegs in holes and mounting a metal collar and washer on each peg. While the subjects were consistently slower, the amount of impairment was small (7.90%) in comparison to the other two tasks they studied, namely, reaction time (20.85%) and a conceptual reasoning test (33.46%). On the basis of this they conclude that "If the individual merely has to perform a simple manual task, the pressure level may be quite high without severe impairment [p. 94]." However this, like most other experiments on nitrogen narcosis, was performed in a pressure chamber and not in the water. From the point of view of ease of administration and control of extraneous variables a pressure chamber has enormous advantages, but it does raise the question of how validly such results can be generalized to the actual diving situation.

When a diver enters the water, he is immediately faced with a number of additional

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[1] The author would like to thank J. Chilton of Cyprus Port Unit Royal Engineers, D. Jones of the Royal Engineers Diving School and all the Royal Engineers divers who acted as subjects. The author is also grateful to the Medical Research Council who gave financial assistance.

limitations and stresses. His equipment may hamper movement, his vision is likely to be restricted by the refractive properties of his face mask (Barnard, 1961), and in addition he must cope with his relative weightlessness. Combined with this, he is more likely to be influenced by such stresses as cold, isolation, and anxiety about his safety. It seems possible that such stresses may interact with the effect of nitrogen narcosis to produce either increased or decreased impairment (Broadbent, 1963). In view of this, it seems advisable that results obtained in a pressure chamber should be validated under water before they are applied to practical diving. The following experiment studies the manual dexterity of divers above the surface, at 5–12 feet below the surface, and at a depth of 100 feet. It further attempts to observe tactile sensitivity in the three conditions so as to obtain some indication of whether any impairment is due to increased finger numbness, or is of more central origin.

EXPERIMENT I

Method

Materials—manual dexterity. The basic apparatus was a screwplate comprising a 6 × 12-inch plate of $\frac{1}{16}$-inch brass. It had 32 $\frac{1}{4}$-inch holes regularly arranged in two 4-inch squares. One side of the plate was painted white, the two groups of holes being separated by a $\frac{1}{2}$-inch strip of unpainted metal. Each hole in the left-hand group contained a $\frac{1}{4}$-inch cheese-head 2 BA brass screw backed by a hexagonal brass nut. The *S* was required to transfer the 16 nuts and bolts from one set of holes to the other as rapidly as possible using his fingers, and was scored in terms of time taken and number of loose nuts, that is, nuts which could be tightened a quarter turn or more.

Tactile sensitivity. This was measured using a modified version of the V test which was found by Mackworth (1955, 1956) to be sensitive to finger numbness induced by cold. The present test consisted of two 12-inch perspex rulers bolted together in the middle and at one end, and separated at the other end by a $\frac{1}{4}$-inch block of tufnol. The *S* was required to run the index finger of his preferred hand along the two edges till he reached the point at which the gap between them was just discriminable.

Design. Performance was studied above the surface, and underwater at depths of 5–12 feet and 100 feet. There were 12 *S*s, 11 army divers of the Royal Engineers and 1 amateur diver. Each *S* carried out all three conditions, 2 *S*s being allocated to each of the six possible orders of presentation.

Procedure. In all conditions, *S* carried out both the screwplate and the V test. During the V test *S* averted his face and his finger was placed on the ruler by *E*. In each condition, six readings were taken, three with *S* starting at a point before the two edges diverged and three starting well above the point of divergence, with *S* always moving towards the point of divergence. The order in which these two blocks of readings were taken was varied at random and the actual distance of the starting point from the point of convergence was also varied. Half of the *S*s began with the screwplate test, while the remainder began with the V test. All *S*s performed both tests seated on a low canvas chair. In the two underwater conditions the chair was on the seabed and a belt carrying approximately 30 pounds of lead weights was laid across *S*'s lap to increase his stability.

The *S*s were timed with a stopwatch on the surface in all conditions. In the 10-feet condition *S* was observed by a surface swimmer (E^1) using a face mask and snorkel, who signaled the beginning and end of the screwplate test to an *E* on the surface (E^2). In the 100-feet condition, E^1 timed *S* using the second hand of a pressurized diving watch, and also used a pre-arranged code of pulls on his lifeline to signal the beginning and end of a run to E^2 who timed the run by stopwatch. E^1 noted the results of both the screwplate and V tests on a formica board using a soft pencil. All *S*s tested at 100 feet were first allowed 5 minutes to acclimatize to the narcotic effect of CO_2 which has been shown by Rashbass (1955) to influence performance for only the first few minutes at pressure. In all conditions, *S*s were given their score on the screwplate test immediately.

All the tests were carried out in Famagusta Bay, Cyprus, the deep water tests from the deck of a Royal Engineers Z craft in calm, fine August weather. Underwater visibility was relatively good (80–90 feet), giving ample illumination in all conditions (approximately 300 foot-candles).

TABLE 1

SPEED AND ACCURACY ON THE SCREWPLATE TEST AS A FUNCTION OF DEPTH

	Depth in feet		
	0	10	100
M time	184.75	237.17	276.0
SD	29.39	47.30	69.00
Total nuts loose	9	18	19
Range	0–3	0–5	0–5

Results

Manual dexterity. (*a*) Speed—Table 1 shows the mean time to complete the screwplate test at each depth, and the total num ber of loose nuts. In the 100-feet condition there was good agreement between timing on the surface and timing at the bottom, except for a relatively constant lag of 2 to 3 seconds presumably due to the signaling system. The bottom times, which were shorter, were used for the analysis.

All 12 *Ss* took longer at 10 feet than on the surface and 11 of the 12 took longer at 100 feet than at 10 feet. When conditions were compared using a Wilcoxon test, both these differences proved highly significant ($p < .005$ two-tailed). (*b*) Accuracy—It can also be seen from Table 1 that *Ss* left relatively few nuts loose in all conditions (8.1%), but that there is a tendency for the number loose to increase with depth. A more detailed analysis of the data using Jonckheere's distribution-free concordance test against ordered alternatives (Jonckheere, 1954) supports this conclusion ($p < .01$, two-tailed).

None of the comparisons between individual conditions was significant, probably because so few loose nuts occurred, leading to a large number of zeros and ties. Of the 12 *Ss* tested however, 5 were more accurate on the surface than at 10 feet and none was less accurate, and 7 were more accurate at 10 feet than at 100 feet while 3 were less accurate. This implies a systematic decrease in accuracy with depth rather than a simple difference between performance above and below the surface as Table 1 might suggest.

(*c*) Efficiency and Experience—The *Ss* differed widely in amount of diving experience, ranging from 7 years to less than a week, with a median of about 18 months. While there was a significant positive correlation between speed at the screwplate test on the surface and length of diving experience (Tau = +.50, $p < .025$ two-tailed), there was no relationship between experience and performance either at 10 feet (Tau = +.165, $p > .1$) or at 100 feet (Tau = +.21, $p > .1$).

(*d*) Practice Effects—Improvements in performance over the three successive tests were relatively small, and were not statistically significant.

Tactile sensitivity. The V test was scored in terms of the size of the smallest just-discriminable gap between the two edges of the rulers. This was recorded in terms of the distance in centimeters from the closed end of the rulers and was later transformed into size of gap in millimeters. The median just discriminable gap for ascending and descending runs in each condition is shown in Table 2. The most striking feature of this table is the tendency for all 12 *Ss* to select a smaller gap when starting at the wide end of the V. There is, however, no significant change in tactile sensitivity with depth. While there appears to be a tendency for the ascending threshold to increase with depth, this is not significant on Jonckheere's test (1954) and does not occur with the descending threshold. A comparison between tactile thresholds taken before the screwplate test and those obtained after showed no difference. Within the limits of this relatively crude test, it seems unlikely then that the impairment in manual dexterity at depth was due to finger numbness.

TABLE 2

MEDIAN AND RANGE OF JUST-DISCRIMINABLE GAP (MILLIMETERS) ON THE V TEST AS A FUNCTION OF DEPTH

	Depth in feet		
	0	10	100
Ascending runs	1.1 (.7–3.5)	1.8 (.9–3.4)	1.85 (.7–3.5)
Descending runs	.9 (.7–1.3)	.8 (.5–1.4)	.8 (.5–1.5)
M	1.00	1.30	1.325

Discussion

These results suggest that manual dexterity is impaired by depth to a much greater extent than the 7.9% shown by Kiessling and Maag. This implies that results obtained in a dry pressure chamber can not validly be generalized to performance under water. However, the present experiment used a different test of manual dexterity and a different population of divers from the Kiessling and Maag study. Experiment I was therefore repeated in a dry pressure chamber. If the large effect of depth was indeed due to testing under water, then this second experiment should show only a small effect such as was shown by Kiessling and Maag.

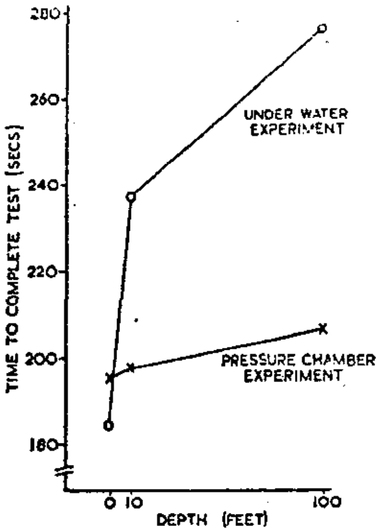

FIG. 1. Time to complete the screwplate test as a function of depth for the pressure chamber experiment and the underwater experiment.

EXPERIMENT II

Procedure. The manual dexterity of 16 Army divers from the Royal Engineers and 2 civilian divers was studied using the previously described screwplate test. They were tested in a pressure chamber at pressures equivalent to 0, 10, and 100 feet of seawater. Three *Ss* were tested in each of the six possible orders. They were timed with a stopwatch by two *Es*, one inside the pressure chamber and one outside. Agreement between the two time scores was in all cases very close.

Results. (*a*) Speed—Figure 1 shows the mean time to complete the screwplate test at each pressure. The results of Experiment I are included for comparison. The influence of pressure is clearly much less than in Experiment I, with *Ss* taking only 5.5% longer at the equivalent of 100 feet than they do on the surface. A Wilcoxon test showed this difference to be significant however ($p < .05$, two-tailed), though the difference between the 10-feet and 100-feet conditions was not significant ($.05 > p > .01$, one-tailed).

(*b*) Accuracy—This was consistently higher than in Experiment I; only eight loose nuts occurred, three each at 0 and 100 feet and two at 10 feet.

(*c*) Efficiency and Experience—Of the 18 *Ss*, 5 were inexperienced trainee divers. The performance of these *Ss* did not differ substantially from the mean in any condition, and was in fact marginally less affected by pressure (3.3% as against 5.5%).

(*d*) Practice Effects—A marked practice effect occurs between the first trial (mean 206.7 seconds) and the two subsequent trials (mean 194.6 and 195.1 seconds, respectively). This effect is shown by all but 3 of the 18 *Ss* and is thus highly significant ($p < .01$ two-tailed, Sign Test.). The practice effect is of approximately the same magnitude as the effect of pressure, about 10 seconds. In Experiment I it was presumably masked by the much larger effects of depth.

Comparison with Experiment I. (*a*) Speed—In both experiments *Ss* worked at approximately the same rate on the surface, suggesting that the groups were comparable. The crucial question is whether the effect of increasing pressure is greater when *Ss* perform under water. This was tested by calculating a percentage impairment score for each *S* using the formula $[H - T]/S$, where H = Performance time in the 100 feet condition, T = time at 10 feet and S = time taken on the surface. The mean impairment score for *Ss* tested in the water was 19.8% and was significantly greater than the impairment shown by *Ss* tested in the pressure chamber ($t = 2.38$ $p < .05$, two-tailed), who showed a mean decrement of only 4.6%.

(*b*) Accuracy—Experiment II *Ss* tended to be more accurate in all conditions, but data were too sparse to allow any very meaningful comparison.

Discussion

Experiment II shows that the influence of pressure on manual dexterity is much smaller when the experiment is performed in a dry pressure chamber than when the diver is tested under water. In Experiment II, the only difference between conditions was that due to pressure. In Experiment I, however several other factors were probably operative.

Immediately a diver enters the water, he is faced with several handicaps. His equipment is likely to prove slightly cumbersome the tunneling of vision accompanying the visual magnification induced by his face mask may prove a handicap (Barnard, 1961), but the greatest difficulty is probably due to his relative weightlessness. Thus, even though well weighed down with lead, Ss tended to be unstable and their gross movements to be slow and clumsy. The difficulties raised by weightlessness may be amplified in shallow water by turbulence on any but calm days. This almost certainly reduced stability and impaired the performance of some Ss when tested in the 10-feet condition. All these factors may contribute to the impairment of performance at 10 feet.

At 100 feet, although the diver is unlikely to be affected by turbulence, he has the additional problem of nitrogen narcosis. If this were a simple effect, Experiment II would suggest a further impairment of about 5%. The fact that it is much greater implies an interaction between the general stress of performing a task under water and the effect of pressure. Whether the actual degree of nitrogen narcosis is increased by the presence of anxiety and other stresses under water or whether the test just becomes more difficult and thus more sensitive when performed under water, is not at present clear. If, however, the interaction is due to the increased sensitivity of the task under water, it seems possible that tasks may be differentially affected by the under water physical handicaps imposed on the diver. If so, it may be extremely misleading to generalize from the relative difficulty of different tasks in a pressure chamber to their difficulty at an equivalent pressure under water.

The practical implications of these results are first, that the manual dexterity of a diver is considerably impaired whenever he must work under water, and further deteriorates at a depth of 100 feet. The implications of this for the design of diving equipment and the assignment of jobs to the diver are obvious. Secondly, they suggest that it is unwise to generalise from experiments performed in a pressure chamber to the actual performance of a diver under water.

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EVALUATION OF SINDBAD TESTS

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ABSTRACT

This paper presents the baseline results and analysis of the SINDBAD (Systematic Investigation of Diver Behavior At Depth) data gathered at the U. S. Navy Experimental Diving Unit. Fourteen of the tests in the SINDBAD battery were administered in a dry hyperbaric chamber at one atmosphere absolute pressure to twenty-seven U. S. Navy first class divers. Eight additional tests from the same battery were taken by sixteen of the same divers under similar conditions. Factor analysis of the results revealed that each test was measuring a unique ability. The normative data was gathered on each test for use in comparative studies in both wet and dry hyperbaric environments.

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INTRODUCTION

Purpose

The purpose of this study is twofold: (1) to evaluate the adequacy of the various tests in the SINDBAD performance test battery and (2) to establish normative dry baseline data on Navy First Class Divers. No evaluation of the tests in the SINDBAD test system has ever been conducted. Although most of the tests in the system are well established, the transfer of these tests from paper and pencil administration to the SINDBAD presentation style may have altered their validity and reliability. It is also possible that there is a great deal of redundancy among the 26 tests in the SINDBAD test battery. Therefore, one of the goals of this evaluation program is test consolidation. This test consolidation is to be done mathematically by the use of Factor Analysis.

The gathering of the normative dry baseline data was designed to obtain performance statistics on the Navy diver population. These statistics are to be used in evaluating the test instructions and the range of item difficulty. The baseline scores are also to be used as a reference point for comparative studies done during immersion and at various depths with various gas mixtures.

Background

There has never been a systematic attempt to study the effects of the undersea environment on a broad spectrum of human performance There have been several studies of man's performance in hyperbaric environments which have focused on specific aspects of human behavior

Recent attempts have been made to integrate these diverse studies into a consolidated picture of man's underwater performance capability. (Egstrom, G.H., Weltman, G., Cuccaro, W.J. and Willis, M.A., 1973; and Vaughan, 1974.) The results of this work, although instructive, have done little more than point up the large gaps that exist in our knowledge. We still do not have an adequate description of the relationship between the pressure environment and man's primary mental and perceptual motor abilities.

In 1966, the Experimental Diving Unit surveyed the various tests that were being utilized in various diving laboratories around the world. Based upon this survey, a decision was made to develop an integrated human performance testing system. A system that would include measures of all of the primary mental and perceptual motor abilities that had been thus far defined. In the system definition phase of the program, the contractors, BioTechnology, Inc. and the Experimental Diving Unit, settled on a set of potential primary abilities and related performance measures that seemed to be applicable to present and anticipated diver activities. Through a subcontract with Edwin Fleishman (American Institute for Research), a number of tests were identified for each ability factor. From the list of altermative tests identified for each selected ability factor, the particular measure to be included in the system was selected. Selection involved the application of three basic criteria. There were:

(1) Methodological considerations (e.g., factorial purity, range of ability levels covered, sensitivity);

(2) Engineering constraints; and

(3) Practical considerations

In Table 1 are listed the selected factors and their associated tests. A full description and an example of each of these tests can be found in the paper by Reilly and Cameron (1968). For a detailed listing of alternative perceptual motor tests for the same factors, see Fleishman (1954). For the same detailed listing for cognitive factors, see Zavala (1967).

METHOD

Subjects

Twenty seven subjects were used in the evaluation of the SINDBAD test system. They ranged in age from 26 to 41 years with a median age of 31.6 years. All the subjects were U. S. Navy first class divers stationed at the Experimental Diving Unit. Their pay grades ranged from E-4 to E-8.

A comparison of the Navy General Classification Test Scores for this sample, with those of the average Navy first class diver, reveals no significant difference on the GCT (General Classification Test), MECH (Mechanical), and CLER (Clerical) subtests. However, the experimental group performed significantly lower ($P < .05$) on the Air (Arithmetic) subtest.

Tests

A description of each of the tests used in this study along with the underlying theoretical factor is given below:

#1 Factor: Flexibility of Closure

Test: Hidden Patterns

Description

Flexibility of Closure is the ability to keep one or more definite configurations in mind so as to make identification in spite of perceptual distractions. In the Hidden Patterns tests, stimuli are projected on the screen. The subjects attempt to recognize a figure that may or may not be hidden among other lines. The test contains many rows of patterns. In each pattern, the subject looks for a model figure which is shown at the top of the slide. If the model is embedded in the pattern, he touches the (+) key on the keyboard; if the model does not appear in the pattern, he touches the (-) key. Correct, incorrect, and total responses are accumulated on the experimenter's console. The test is scored as correct minus incorrect responses in a two-minute period.

#2 Factor: Length Estimation

Test: Shortest Road

Description

Length Estimation is the ability to judge distances. In the Shortest Road test, stimuli are projected on the screen. The subject examines two irregular lines that connect a pair of points to determine which of the two lines is shorter. The upper line of each stimulus is designated (+), the lower line is designated (-). The subject selects the shorter line and indicates his choice by touching the appropriate key on the keyboard.

Correct, incorrect, and total responses are accumulated on the experimenter's console. The test is scored as correct minus incorrect responses in a 30 second period.

#3 Factor: Perceptual Speed

Test: Number Comparison

Description

Perceptual Speed is the ability to compare one pattern with another under speeded conditions, and involves making rapid comparisons among items of visual information. In the Number Comparison tests, the subject inspects pairs of multi-digit numbers, projected on the screen, to determine whether the numbers in each pair are the same or different. He indicates "same" or "different" by touching, respectively, the (+) or (-) key on the keyboard. Correct, incorrect, and total responses are accumulated on the experimenter's console. The test is scored as correct minus incorrect responses in a 90-second period.

#4 Factor: Spatial Orientation

Test: Card Rotations

Description

Spatial Orientation is the ability to identify a particular kind of spatial pattern and not be distracted by patterns in a different spatial position. The Card Rotations test measures an individual's ability to detect differences in the spatial orientation of figures. The subject inspects drawings of irregularly shaped objects projected on the screen, and determines whether they are the same as or different from a reference object. He indicates "same" or "different" by touching, respectively, the (+) or (-) key on the keyboard. Correct, incorrect, and total responses are accumulated on the experimenter's console. The test is scored as correct minus incorrect responses in a 2-minute period.

#5 Factor: Finger Dexterity

Test: Key Insertion

Description

Finger Dexterity is the ability to make rapid, skillful, controlled movements of small objects where the fingers are primarily involved. The Key Insertion test employs a small shape-coded object containing a permanent magnet. Half of the object is square, the other half round. The square and round keys correspond to openings in a template which covers the keyboard. The subject's task is to insert the test object into nine templat openings working across rows. To execute the task, the subject uses one hand, and must insert, retrieve, and invert, then insert the test object in the next position, etc. Each insertion of the test object is monitored visually on the experimenter's console to ensure that the sequence is being performed properly. The test is scored automatically as the total insertions made in a 30-second period.

#6 Factor: Manual Dexterity

Test: Wrench and Cylinder

Description

Manual Dexterity is the ability to make skillful, controlled arm-hand manipulation of relatively large objects. The Wrench and Cylinder test employs specially constructed tools which are used in conjunction with the keyboard. The outer portion of the cylinder is a sleeve which, by means of internal threads, can be moved to expose one or the other end of the inner component. The ends of the inner component are shape coded (square and round) and magnetic. The subject uses the wrench to stabilize the inner component and rotates the outer sleeve to expose first one end, then the other. As each end is exposed, it is inserted into a correspondingly shaped opening on the keyboard. Each complete operation is thus registered and accumulated for scoring at the experimenter's console. The test is scored automatically as the total operations (keyboard registrations) performed in a 60-second period.

#7 Factor: Reaction Time

Test: Visual Reaction Time

Description

Reaction Time is the speed with which an individual can respond to a stimulus. In Visual Reaction Time, the subject inserts a magnetic stylus into an aperture on the keyboard, and when a window beneath the position lights up, withdraws the stylus as rapidly as possible. Response time accumulates on the experimenter's console Score is the mean of 10 trials.

#8 Factor: Time Interval Estimation

Test: Interval Reproduction

Description

Time Interval Estimation is the ability to judge intervals of elapsed time or to discriminate differences between two or more time intervals. In Interval Reproduction, the subject indicates his estimate of elapsed time intervals ranging from 10 seconds to as long as is practicable in the testing situation, recognizing that both long- and short-term interval reproduction depend on operationa requirements. Error score is the difference between the prescribed time interval and the subject-generated interval. Score is expresse as a percentage; the relationship between actual and estimated time.

#9 Factor: Wrist-Finger Speed
Test: Tapping

Description

Wrist Finger Speed is the ability to make pendular and/or rotary wrist movements which involve rapid, repetitive jabbing in which accuracy is not critical. In the Tapping test, the subject uses the magnetic stylus to tap as rapidly as possible, back and forth between the (+) and (-) keys on the keyboard. The number of responses accumulates on the experimenter's console. Score is the number of responses in one 30-second trial.

#10 Factor: Associative Memory
Test: Word-Number

Description

Associative Memory is the ability to remember bits of unrelated material. On the Word-Number test, columns of six words, each of which is paired with a two-digit number, are projected on the screen The subject's task is to memorize the numbers associated with the words. Later, the words by themselves, are presented in a different order, and the subject responds by indicating the appropriate numbers on the keyboard. Each response registers on the experimente console. Score is the number of items remembered correctly. There is no time limit on the recall phase of the test.

#11 Factor: Induction

Test: Letter Sets

Description

Induction is the ability to find general concepts that fit sets of data, and to form and test hypotheses. In the Letter Sets test, problems are projected on the screen. Each problem has five groups of letters with four letters in each group. Four groups are alike in some way, the fifth is different. The subject determines the rule that makes four group alike, and indicates the group of letters that does not conform to the rule by touching the appropriate key on the keyboard. Responses are registered on the xperimenter's console. Score is the number of correct responses in a 3-minute period.

#12 Factor: Number Facility

Test: Addition
Subtraction
Multiplication
Division

Description

Number Facility is the ease with which abstract symbols can be mentally manipulated. Addition, Subtraction, Multiplication, and Division tests measure how quickly and accurately an individual can mentally perform a basic computational operation. Arithmetic problems are projected on the screen. The subject solves each problem and indicates his answer by touching the appropriate digits on the keyboard. Subject responses register on the experimenter's console The tests are scored as the number of correct responses in a 2-minute period. The score is the sum of the scores for the four tests.

#13 Factor: Spatial Scanning
Test: Choosing a Path

Description

Spatial Scanning is the ability to visually explore a wide or complicated visual field. Items in the Choosing a Path test are projected on the screen. Each item consists of a network of lines as in an electrical-circuit diagram having many intermeshed wires with several sets of terminals. The subject visually traces the circuits and determines which one of five pairs of terminals completes a circuit through a circle at the top of the diagram. Th subject responds by touching the appropriate key on the keyboard. Responses register on the experimenter's console. The test is score as the number of items correct in a 3-minute period.

#14 Factor: Visualization
Test: Surface Development

Description

Visualization is the ability to understand relationships involved performing imaginary movements in three-dimensional space. In the Surface Development test, the subject tries to visualize how a two-dimensional pattern can be bent to form a three-dimension object. The subject inspects drawings projected on the screen, one of which represents a flat piece of metal which can be bent to form a three-dimensional object which is also shown. He indicates which edges on the pattern correspond to designated points on the object by touching the appropriate key on the keyboard. The score is the number of correct responses in a 3-minute period.

#15 Factor: Control Precision

Test: Position Control

Description

Control Precision is the ability to make sensitive, highly controlled positioning adjustments, primarily where larger muscle groups are involved. Adjustments are made in response to visual stimuli. In the test of Position Control, a target dot moves in a clockwise course around the face of the oscilloscope display. The subject controls a second dot which he attempts to keep superimposed on the target dot by moving the control stick with his dominant hand in a smooth clockwise circle. Performance is scored as the time integral of the absolute value of error voltage. The score is computed and shown on the experimenter's console. The score is the mean of three 60-second trials.

#16 Factor: Multi-limb Coordination

Test: Two-hand Tracking

Description

Multi-limb Coordination is the ability to coordinate the movements of two hands, two feet, or combinations of hands and feet simultaneously. Two-hand Tracking involves keeping a luminous dot centered on the face of the oscilloscope display by using left and right hand control sticks to control horizontal and vertical axes of motion respectively. Performance is scored as the time integral of the absolute value of error voltage. The score is the mean of three 60-second trials.

#17 Factor: Response Orientation
Test: Choice Reaction Time

Description

Response Orientation is the ability to choose and perform an appropriate movement from several alternatives. In Choice Reaction Time, the subject holds a magnetic stylus at the center of four apertures in a keyboard template which provides for a directional response--forward, backward, left, or right. The subject is shown a random sequence of four colors, one at a time, projected on the screen. To each color, he makes the appropriate directional response which has been learned through practice prior to actual testing. Time for each response made by the subject is totaled automatically on the experimenter's console. The test is scored as the mean response time for a series of 24 test stimuli.

#18 Factor: System Equalization
Test: Rate Control

Description

System Equalization is the ability to control one or more axes of motion in systems having zero-order dynamics, first-order dynamics, or second-order dynamics. In Rate Control, the subject uses the tracking control(s) to keep a dot centered on the oscilloscope (compensatory mode) or to keep a control dot superimposed on a target dot (pursuit mode). Performance is scored as the time integral of the absolute value of error voltage and is shown on the experimenter's console. The score is the mean of three 60-second trials.

#19 Factor: Vigilance
Test: Visual Signal Detection

Description

Vigilance is the ability to attend to one or more information scources or situations for relatively long periods to detect specified events which occur at random, or unpredicted intervals. In Visual Signal Detection, the subject observes the on-line digital display to detect numbers which appear at irregular intervals. Ten signals appear during a 6-minute period. The signals appear for .25 seconds at random intervals. The subject indicates his having seen the signal by touching the appropriate key on his keyboard. The score is the percentage of signals detected.

#20 Factor: Memory Span
Test: Visual Digit Span

Description

Memory Span is the ability to recall and reproduce a series of items after a single presentation of the series. The Visual Digit Span test involves recall and reproduction of a series of digits immediately after they have been presented and removed from view. The subject views series of digits of increasing length (from three to ten digits) shown one at a time, at 1-second intervals, on the optical (on-line) display. He then attempts to recall the sequence and reproduce it by touching the appropriate digits on the keyboard. Subject responses register on the experimenter's console. Score is the length of the longest series correctly reproduced. Maximum score is 10.

#21 Factor: Time Sharing

Test: Track and Monitor

Description

<u>Time Sharing</u> is the ability to divide attention among two or more information sources through temporal/spatial sampling. Time sharing is customarily measured by presenting the subject with two or more displays separated in a manner which prohibits their being viewed simultaneously. In the <u>Track and Monitor</u> test, the subject uses the control stick to keep a control dot superimposed on a target dot on the oscilloscope. At the same time, he monitors a keyboard light which illuminates at various intervals. The subject indicates he has detected the onset of the light by using the keyboard. Score is expressed as tracking error during four 60-second trials (t) by the formula:

$$t = \frac{(t_2 + t_3) - (t_1 + t_4)}{(t_1 + t_4)}$$

where trials 2 and 3 consist of tracking with time sharing.

#22 Factor: Visual Monitoring

Test: Terminal Digits

Description

<u>Visual Monitoring</u> is the ability to attend to a continuously changing visual information source and report system status on

request. In Terminal Digits, the subject observes numbers which change at a rate of one per second on the on-line display. At various times, the display goes blank, and the subject reports the last two digits shown before the display was interrupted by using his keyboard. Score is the percentage of correct reports in ten trials. Trials consist of random length intervals longer than 10 seconds, but less than 60 seconds duration.

TEST ADMINISTRATION

The tests were administered in two sections; each section having a total test time of approximately one hour. The first section included Tests #1 through #14 which were given in chronological order. The tests in the second section were presented in the following order: 17, 15, 16, 18, 21, 19, 20, 22 to make administration simpler for the experimenter. For those tests that used slide stiumuls material, the same slides were presented in the same order for all subjects. All of the 22 tests used in this initial evaluation were administered to each test subject twice. Although the first administration of the tests was considered an orientation, scores were recorded in an attempt to obtain equivalent form reliability coefficients. In the "Time Interval Reproduction" task, the same times and order of presentation were used for all individuals; they being: 10 seconds, 35 seconds, 15 seconds, 47 seconds, 60 seconds, 22 seconds, and 150 seconds (2 1/2 minutes). The "Key Insertion," "Wrench and Cylinder," and "Tapping" tests were timed with the clock starting with the subject's action needed for such tests is outlined in the discussion section of this paper.

The equivalent form reliability for the first 14 tests are given in Table 4. Because the first administration of the tests was designed to be an orientation to the SINDBAD test system, the reliability scores are somewhat in question. On the first administration of the tests, a number of questions arose and several of the tests had to be started over or repeated. The question whether or not the authors should have even attempted this statistic or bothered to include it in the report is one worth asking. The authors feel that even if these statistics are wrong, they are the best information that is presently available on the SINDBAD tests, and therefore, should be included. Future studies will confirm or refute these findings.

Table 5 presents the intercorrelations among the 22 tests that were given. The correlations among the last eight tests are based upon a sample of only 16 divers as are all the other statistics on these tests. The lack of any real high correlations in this matrix can be indicative of a couple different things. First of all, it could mean that each of the tests within the SINDBAD test battery is an independent measure of some underlying unique human ability. The tests included in the system were selected on a theoretical basis to do just that. The lack of high correlations among the tests is certainly an indication of test independence. Before we get too carried away with these results, however, the reader must keep in mind the low reliabilities in Table 5 and the large variances of Table 3. If the tests within the SINDBAD system are inprecise or unreliable, one would also expect to find a lack of correlation. Which interpretation one chooses is still open to question. This study has provided some hints concerning the structure of the SINDBAD system, but no clear cut position on its adequacy.

As a further interpretive aid, the data was subjected to a factor analysis. Two separate principal component factor analyses were conducted to determine the minimum number of factors that could explain the correlation matrix in Table 5. An important decision in any factor analysis is; how much of the matrix variance do you wish to account for? This decision depends a great deal upon what the factor analysis is being used for. In this study, we choose to account for all the variance in intercorrelation matrix. The authors wished to see if a single test would correlate with each individual factor. For those readers interested in a different interpretive strategy, the authors have included Figure 1 which shows the proportion of variance accounted for by each additional factor.

Tables 6 and 7 present the results of the factor analysis. The importance of these two tables is that each theoretical factor has one and only one test that correlates highly with each. This is certainly additional support for the position that the tests selected for the SINDBAD system are independent measures of separate unique underlying abilities. Although the results are indicative, they are far from conclusive. The real significance of these findings will have to wait for a second study.

DISCUSSION

Since the "Hidden Patterns," "Shortest Road," "Number Comparison," and "Card Rotations" tasks are all quite similar in format, they will be discussed together. All four tests have low reliability (.18-.34) and high standard deviations in comparison to their means. Even so, the factor analysis revealed high factor loadings for these four variables - all .90 or above. It is suspected that the low reliability is due to an inconsisten binary scoring mechanism in the SINDBAD machinery. This low reliability could probably be improved by changing the scoring format by by-passing the binary scorer. This would require manual recording of the responses. Because of the rapid rate of responses in these tests, a recorder would be necessary, as it would be impossible for the experimenter to handle the recording as well as the changing of the slides and monitoring of the clock.

The "Key Insertion" and the "Wrench and Cylinder" tasks have also been grouped together for discussion purposes because of their similarities. These tests are also plagued with relatively low reliabilities (.40 and .35, respectively). They both have high factor loadings (both in excess of .90), and more respectabl standard deviations. The low reliability can be accounted for by the length of the tests. That is, the difference between a score of 12 and 13 is presently a substantial difference in

formance, when in fact it may not be. It is suggested that
time of testing for these two tasks be increased to between
ce and three times as long. This would increase the range,
e the difference between consecutive scores less significant,
hopefully, increase reliability.

Reaction time is shown as a distinct factor with a high
tor loading (.94) and respectable reliability (.73). No changes
suggested for this task.

"Interval Reproduction" shows, again, a high factor purity
5), but with a mediocre reliability (.50). This is probably
erent in what is being tested. A more consistent measure
the results might be the median percentage error rather than
mean percentage error. Most of the results seem to have a
itive skew, and this should tend to compensate for the ceiling
ect of this test.

The "Tapping" test has very respectable results. The reli-
lity is high (.83), the factor loading is high (.90) and no
nificant skew in either direction. No alterations are proposed.

The "Word-Number" task shows only a moderately high factor
ding (.75), but a fairly high reliability (.72). The low
tor purity is quite likely due to the nature of the factor.
"Associative Memory" is required in most of the other tasks
small portions. No changes are recommended.

The "Letter Sets" tasks suffers from the same problems as
"Key Insertion" and "Wrench and Cylinder" tests. It has a
ll range and, consequently, a measurement difference of unity

is quite substantial. The factor loading on this test is high (.93), but the reliability is low (.49). Recommendations are to increase the testing time from 180 seconds to 300 seconds to broaden the range and increase consistency of testing.

The results from the arithmetic tests revealed high factor purity (.90) and quite high test-retest reliability (.93). No modifications are recommended.

The "Choose a Path" task revealed a high factor loading (.94) and a moderate reliability (.68). This test has a very substantial positive skew. An increase in the testing time would have little effect on this skew, but it would decrease the basement effect. It is recommended that the administration time be increased from 180 to 240 seconds in future testing.

The "Surface Development" task has a high reliability (.80) but a low factor purity (.41). This factor has loadings greater than .41 for two other tests. It is proposed to retain this test, despite the factorial impurities, as measurement of visualization with no changes in methodology.

The "Position Control," "Two-Hand Tracking," and "Rate Control" tracking tasks all had high factor purity (.96, .87, and .90 respectively). No reliability data is available on these test (as well as the rest of the tests discussed). The two-hand tracking, and especially rate control tasks, suffer from a basement effect. The scoring mechanism has an upper limit of 100. It is suggested that the times be shortened to 40 seconds from 60 seconds on these two tasks to avoid the testing basement.

The "Choice Reaction Time" task has the highest factor loading (.98). The only recommendation on this test is shorten the number of trials from 24 to 10. A cursury scanning of the data shows no substantial changes within the test over the 24 trials so this reduction should have very little effect.

The "Visual Signal Detection" task shows a factor loading of .87. The range is low and the test is affected by a ceiling. It is suggested the test time be increased from 6 to 15 minutes and to give a total of 25 to 50 signals in this time instead of 10.

The "Visual Digit Span" task has a factor loading of .86. The range is small (5-8). There is no obvious modification in the methodology that might increase the range short of biasing the results in favor of certain subjects.

The "Track and Monitor" task has a high factor loading (.91). It is suspected that the reliability is low on this task. The major problem area is that since there are no practice trials, the learning taking place during the task seems to be more of a major component than the time-sharing. Consequently, in several cases, the subjects performed poorer while not time-sharing. It is proposed to have several practice trials, (not time-sharing), to decrease the learning factor, before beginning to measure.

The "Terminal Digits" task has a high factor loading (.97). There is a severe ceiling problem in this test. Fifty percent of the subjects performed perfectly. To correct this, the subjects should be required, in the future, to recall the last 3 or even the last 4 digits presented.

The following is a summary of suggested changes in the methodology:

HIDDEN PATTERNS	1.	By pass binary scorer
SHORTEST ROAD	2.	Same as 1
NUMBER COMPARISON	3.	Same as 1
CARD ROTATIONS	4.	Same as 1
KEY INSERTION	5.	Increase testing time from 30 seconds to 60-90 second
WRENCH & CYLINDER	6.	Increase testing time from 60 seconds to 120-180 seconds
REACTION TIME	7.	No changes
INTERVAL REPRODUCTION	8.	Use median performance instead of mean
TAPPING	9.	No changes
WORD-NUMBER	10.	No changes
LETTER SETS	11.	Increase testing time from 180 seconds to 300 seconds
ARITHMETIC	12.	No changes
CHOOSE A PATH	13.	Increase testing time from 180 seconds to 240 seconds
SURFACE DEVELOPMENT	14.	No changes

POSITION CONTROL	15.	No changes
TWO-HAND TRACKING	16.	Decrease time of each trial from 60 seconds to 40 seconds
CHOICE REACTION TIME	17.	Decrease number of trials from 24 to 10
RATE CONTROL	18.	Same as 16
VISUAL SIGNAL DETECTION	19.	Increase testing time from 6 to 15 minutes and number of signals from 10 to 25 - 50
VISUAL DIGIT SPAN	20.	No changes
TRACK & MONITOR	21.	Allow subject practice trials
TERMINAL DIGITS	22.	Increase number of digits to be recalled from 2 to 3 or 4

CONCLUSIONS

The test data gathered and the structural analysis conducted tends to indicate that the twenty-two tests that were evaluated are separate, independent measures of underlying human abilities. Test administration and scoring procedures are still a crucial problem for the SINDBAD system. The instructions and testing times need to be re-evaluated using the changes suggested in this report. Alternative equipment for presenting and scoring the tests is needed. The optical scoring technique is far to sensitive for use in this type of environment. The potentials originally projected for the SINDBAD system are still present, but will require additional equipment changes and test alterations to be realized.

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TABLE 1

List of Factors and Tests Included in the SINDBAD Measurement System

	FACTOR	TEST
1.	Flexibility of Closure	Hidden Patterns
2.	Length Estimation	Shortest Road
3.	Perceptual Speed	Number Comparison
4.	Spatial Orientation	Card Rotations
5.	Finger Dexterity	Key Insertion
6.	Manual Dexterity	Wrench and Cylinder
7.	Reaction Time	Visual Reaction Time
8.	Time Interval Estimation	Interval Reproduction
9.	Wrist-Finger Speed	Tapping
10.	Associative Memory	Word-Number
11.	Induction	Letter Sets
12.	Number Facility	Addition Subtraction Multiplication Division
13.	Spatial Scanning	Choosing a Path
14.	Visualization	Surface Development
15.	Control Precision	Position Control
16.	Multi-limb Coordination	Two-hand Tracking
17.	Response Orientation	Choice Reaction Time
18.	System Equalization	Rate Control
19.	Vigilance	Visual Signal Detection
20.	Memory Span	Visual Digit Span
21.	Time Sharing	Track and Monitor
22.	Visual Monitoring	Terminal Digits
23.	Arm-Hand Steadiness	Arm Tremor
24.	Flexibility of Set	Binary Set Persistance
25.	Speed of Arm Movement	Horizontal Arc

TABLE 2

COMPARISON OF EXPERIMENTAL GROUP WITH THE GENERAL DIVER FIRST CLASS POPULATION

		GCT	ARI	MECH	CLER
Experimental Sample	Mean	56.81	50.00	56.42	48.23
	S.D.	7.43	6.49	5.80	8.94
	N	27	26	26	26
Average Navy 1st Class Diver	*Mean	54.85	53.30	56.45	50.26
	S.D.	8.10	7.82	6.62	8.11
	N	351	351	351	351
	t	1.31	2.46	.02	1.12
	p	N.S.	.05	N.S.	N.S.

*BERGHAGE (1972)

TABLE 3

SUMMARY TABLE OF SINDBAD RESULTS

TEST NO.	TEST NAME	FACTOR NAME	MEAN (X)	STD. DEV.	RANGE	MEDIAN	MODE
1	HIDDEN PATTERNS	FLEXIBILITY OF CLOSURE	28.3	14.7	9-66	23.1	9
2	SHORTEST ROAD	LENGTH ESTIMATION	7.15	3.77	1-16	6.2	7
3	NUMBER COMPARISON	PERCEPTUAL SPEED	12.6	5.25	7-27	11.8	8
4	CARD ROTATIONS	SPATIAL ORIENTATION	15.1	10.3	1-36	13.5	11
5	KEY INSERTION	FINGER DEXTERITY	17.6	3.09	12-23	17.3	18
6	WRENCH AND CYLINDER	MANUAL DEXTERITY	10.3	2.11	8-14	9.5	8
7	VISUAL REACTION TIME	REACTION TIME	.285	.036	.242-.394	.275	.258,.272
8	INTERVAL REPRODUCTION	TIME INTERVAL ESTIMATION	16.3	10.2	3.6-32.7	13.2	None
9	TAPPING	WRIST-FINGER SPEED	106.0	20.3	78-174	104	95, 106
10	WORD-NUMBER	ASSOCIATIVE MEMORY	8.93	4.73	0-18	8.6	9
11	LETTER SETS	INDUCTION	6.18	1.96	2-10	5.9	6
12	ARITHMETIC	NUMBER FACILITY	35.1	12.5	10-57	36.5	34,40,42,47
13	CHOOSE A PATH	SPATIAL SCANNING	3.93	3.09	0-14	3.1	6
14	SURFACE DEVELOPMENT	VISUALIZATION	11.3	5.35	2-23	11.2	14
15*	POSITION CONTROL	CONTROL PRECISION	43.8	16.7	28.3-99.7	40.0	None
16*	TWO-HAND TRACKING	MULTI-LIMB COORDINATION	97.1	17.3	63.8-132.9	102	None
17*	CHOICE REACTION TIME	RESPONSE ORIENTATION	1.09	.242	.65-1.54	1.08	None
18*	RATE CONTROL	SYSTEMS EQUALIZATION	99.8	26.7	57.3-141.4	99.5	None
19*	VISUAL SIGNAL DETECTION	VIGILANCE	80.0	8.94	60-90	75.7	80
20*	VISUAL DIGIT SPAN	MEMORY SPAN	6.19	.981	5-8	6.25	7
21*	TRACK AND MONITOR	TIME SHARING	.178	.508	-.355-2.00	.0835	None
22*	TERMINAL DIGITS	VISUAL MONITORING	89.4	13.4	60-100	95.0	100

* Based on N = 16, all others based on N = 27

TABLE 4

EQUIVALENT FORM RELIABILITY

Test No.	r	Test No.	r
1	.20	12	.93
2	.34	13	.68
3	.18	14	.80
4	.33	15	NA
5	.40	16	NA
6	.35	17	NA
7	.73	18	NA
8	.50	19	NA
9	.83	20	NA
10	.72	21	NA
11	.49	22	NA

TABLE 5

INTER-CORRELATION MATRIX

	FACTOR NAME	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
# 1	Flexibility of Closure	1.0																					
# 2	Length Estimation	-.17	1.0																				
# 3	Perceptual Speed	.11	.33	1.0																			
# 4	Spatial Orientation	.58	.14	.03	1.0																		
# 5	Finger Dexterity	.17	-.05	-.11	.31	1.0																	
# 6	Manual Dexterity	-.08	.08	.00	.09	.33	1.0																
# 7	Reaction Time	-.33	-.04	-.11	-.28	.16	.14	1.0															
# 8	Time Interval Estimation	-.11	-.11	-.21	-.16	-.40	-.23	.22	1.0														
# 9	Wrist-Finger Speed	.05	.04	.34	-.06	.33	.40	-.16	-.21	1.0													
#10	Associative Memory	.28	-.28	.14	.21	.10	-.29	-.35	.03	.21	1.0												
#11	Induction	-.18	.03	.00	.02	.13	-.08	.17	-.07	.04	.48	1.0											
#12	Number Facility	.02	.09	.29	.09	.12	-.18	-.15	.10	.10	.53	.53	1.0										
#13	Spatial Scanning	-.30	.18	-.03	-.15	.26	.09	.21	-.28	.28	.16	.26	.22	1.0									
#14	Visualization	.13	-.48	-.28	.17	.60	.19	.16	.16	.20	.17	.26	.22	.13	1.0								
#15	Control Precision	.28	-.11	-.27	.07	.33	-.22	-.06	-.09	.04	.32	.19	-.04	.09	.14	1.0							
#16	Multi-Limb Coordination	-.06	-.45	-.29	-.56	.01	-.13	.13	-.01	.20	-.10	-.38	-.17	.22	-.14	.19	1.0						
#17	Response Orientation	-.52	-.06	.14	-.48	.13	-.06	.42	-.26	-.06	-.34	.17	-.08	.26	.11	-.13	.18	1.0					
#18	Systems Equalization	-.22	.01	-.25	-.41	-.18	-.34	-.03	-.22	.11	.17	-.15	-.47	-.08	-.49	.37	.32	.10	1.0				
#19	Vigilance	.51	-.24	.21	.61	.03	-.10	-.35	.08	-.23	.17	-.18	.22	-.19	.35	.07	-.35	-.31	-.56	1.0			
#20	Memory Span	.33	-.26	-.23	.17	.02	.05	-.02	-.39	-.29	.02	.00	.03	-.08	.04	.38	.24	-.12	-.20	.46	1.0		
#21	Time Sharing	.02	.55	.20	.34	.22	.45	.18	-.42	-.15	-.13	.44	.09	-.19	.01	-.13	-.52	-.02	-.40	.08	.31	1.0	
#22	Visual Monitoring	.19	.49	.58	.48	-.10	-.03	-.20	.10	.05	.49	.43	.46	-.42	-.18	-.07	.34	.16	-.03	.06	-.24	.27	1.0

Correlations between Variables 1 - 14 based on N = 27
All other based on N = 16

TABLE 6

SINDBAD FACTOR ANALYSIS RESULTS

FACTOR NAMES

VARIABLES	SPATIAL ORIENTATION	REACTION TIME	INDUCTION	LENGTH ESTIMATION	WRIST-FINGER SPEED	TIME INTERVAL ESTIMATION	SPATIAL SCANNING	PERCEPTUAL SPEED	FINGER DEXTERITY	NUMBER FACILITY	FLEXIBILITY OF CLOSURE	ASSOCIATIVE MEMORY	MANUAL DEXTERITY	VISUALIZATION
1. HIDDEN PATTERNS	.30	-.16	-.10	-.11	.03	-.07	-.15	.06	.09	.01	-.90	-.07	.06	-.01
2. SHORTEST ROAD	.09	-.02	.02	.96	.01	-.04	.09	.16	-.07	.04	.09	.11	-.04	.01
3. NUMBER COMPARISON	.01	-.03	-.01	.18	.17	-.12	-.04	.94	-.11	.15	-.06	-.04	.01	.02
4. CARD ROTATIONS	.91	-.14	.03	.10	-.07	-.08	-.07	.00	.17	.03	-.29	-.06	-.06	-.01
5. KEY INSERTION	.14	.07	.02	.00	.14	-.24	.11	-.07	.92	.05	-.07	-.05	-.15	.06
6. WRENCH AND CYLINDER	.05	.06	-.04	.04	.20	-.10	.01	-.01	.15	-.08	.05	.10	-.95	-.01
7. VISUAL REACTION TIME	-.13	.94	.09	-.04	-.10	-.11	.08	-.03	.10	-.07	.14	.12	-.06	-.01
8. INTERVAL REPRODUCTION	-.07	-.11	-.03	-.05	-.07	.95	-.14	-.11	-.13	.07	.06	.00	.10	-.02
9. TAPPING	-.07	-.12	.01	.00	.90	-.08	.15	.20	.18	.02	-.03	-.10	-.23	-.01
10. WORD-NUMBER	.11	-.23	.34	-.22	.16	-.01	-.15	.07	.05	.31	-.12	-.75	.20	.01
11. LETTER SETS	.02	.10	.93	.01	.01	-.03	.12	-.02	.07	.25	.10	-.16	.03	-.02
12. ARITHMETIC	.03	-.08	.28	.04	.01	.08	.13	.17	.09	.90	-.01	-.17	.09	-.02
13. CHOOSE A PATH	-.07	.08	.11	.09	.14	-.14	.94	-.04	.12	.11	.13	.08	-.01	-.01
14. SURFACE DEVELOPMENT	.12	.12	.19	-.45	.13	.26	.08	-.14	.64	.15	-.07	.05	-.11	-.41

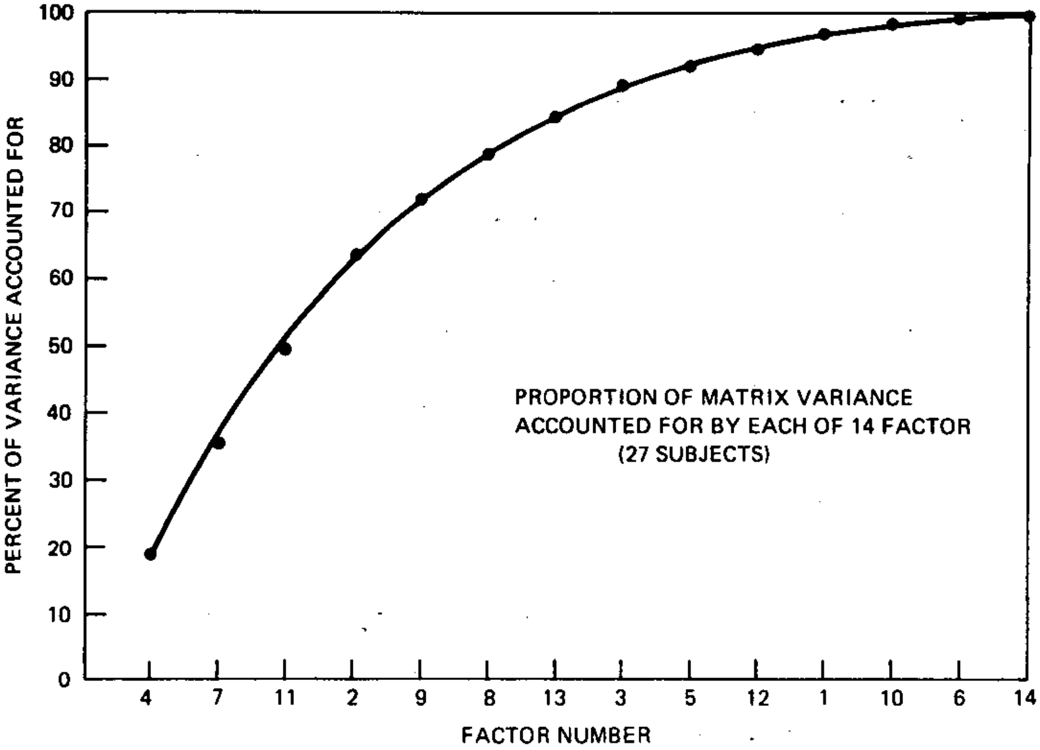
TABLE 7

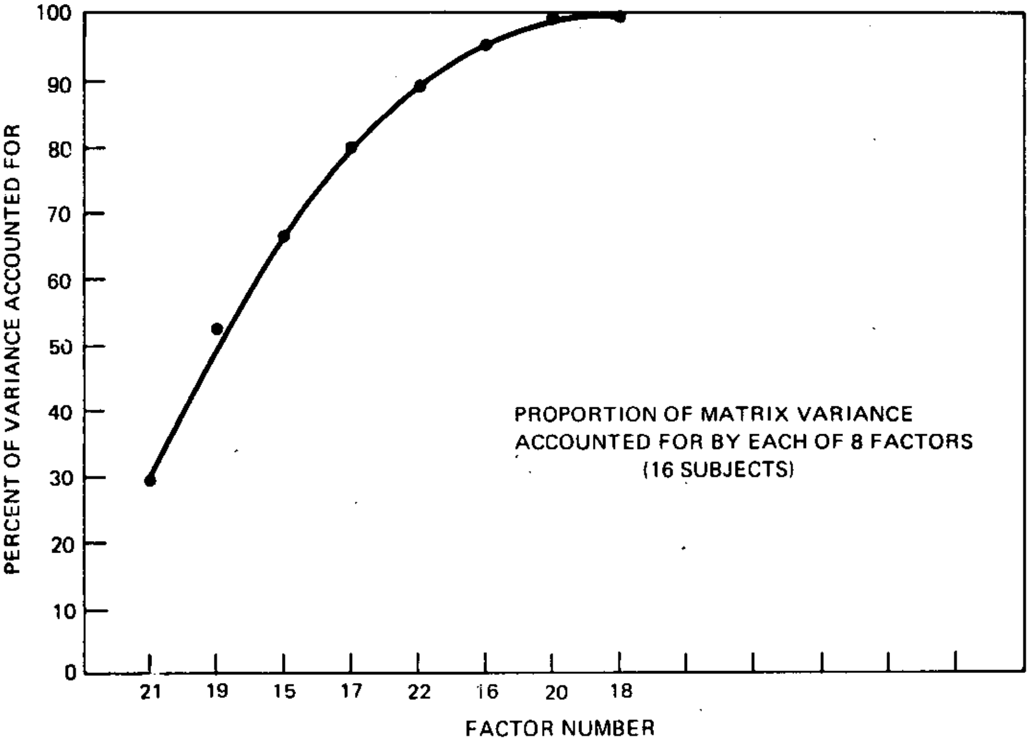
SINDBAD FACTOR ANALYSIS RESULTS

FACTOR NAMES

VARIABLES	TIME SHARING	VIGILANCE	CONTROL PRECISION	RESPONSE ORIENTATION	VISUAL MONITORING	MULTI-LIMB COORDINATION	MEMORY SPAN	SYSTEMS EQUALIZATION
15. POSITION CONTROL	.06	-.04	.96	-.07	-.02	.06	.17	-.18
16. TWO-HAND TRACKING	.30	.21	.08	.11	-.18	.87	.19	-.11
17. CHOICE REACTION TIME	.01	.12	-.06	.98	.08	.08	-.03	-.03
18. RATE CONTROL	.20	.28	.22	.04	.00	.10	-.08	-.90
19. VISUAL SIGNAL DETECTION	.05	-.87	.05	-.17	-.02	-.21	.26	.32
20. VISUAL DIGIT SPAN	-.24	-.27	.24	-.04	-.15	.20	.86	.09
21. TRACK AND MONITOR	-.91	.04	-.06	.00	.15	-.27	.21	.19
22. TERMINAL DIGITS	-.12	.02	-.02	.09	.97	-.14	-.10	.00

TABLE 8


PROPORTION OF MATRIX VARIANCE ACCOUNTED FOR BY EACH OF 14 FACTOR (27 SUBJECTS)


PROPORTION OF MATRIX VARIANCE ACCOUNTED FOR BY EACH OF 8 FACTORS (16 SUBJECTS)

APPENDIX A

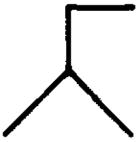
#1 Diver Task/Instructions

Determine whether the figure shown at the top center of the slide is present or absent within each of the remaining 10 figures. If the figure is present, touch the (+) key. If it is not present, touch the (-) key. The pattern must be in the orientation shown. It will not be turned or rotated in any way. Work from left to right, doing first the top row, then the bottom row.

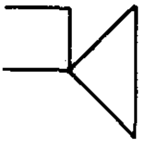
Work as rapidly as possible but make only one response to each pattern. If you feel that an error has been made, ignore it and continue doing the problems in order. This test is scored electronically and scoring requires that there be 10 and only 10 responses per slide all in order.

After responding to the final pattern on a slide, signal (*) for the next slide.

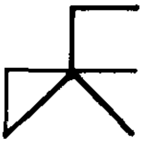
SAMPLE:



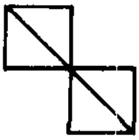
In the next row, when the model appears, it is shown by heavy lines:



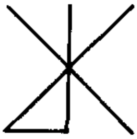
( )



(X)

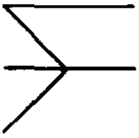


( )



( )

(X)



( )

( )

#2 Diver Task/Instructions

In each figure shown in the slide, determine which line is the shortest between the two points. Register your answers by touching (+) or (-), whichever one identifies the line selected as the shortest.

Do the problems in order: only one answer per problem - no corrections permitted. Signal (*) when slide is completed.

In this test, you are to examine two lines and determine the shorter and make a response with the magnetic stylus. In the problems, the high road is (+) and the low road is (-). The shorter road is darkened (wider).

I


II


#3 Diver Task/Instructions

Look at each pair of numbers. Compare them quickly but carefully. If they are exactly the same, touch (+). If they are different, touch (-). Give only one answer per problem; no corrections permitted. Work down the slide from top to bottom. When you are finished with a slide, signal (*).

SAMPLE:

659_____659	(+)	7343801_____7343801	(+)
73845_____73855	(-)	18824_____18824	(+)
1624_____1624	(+)	705216831_____795216831	(-)
438_____436	(-)	971_____971	(+)
4821459_____4814259	(-)	446014721_____446014721	(+)

#4 Diver Task/Instructions

On each side, compare the reference figure on the left, isolated by a vertical line, with each of the figures to the right of the line. If the figure on the right of the line has been formed by simply rotating the reference figure clockwise (or counterclockwise), touch (+). If the figure on the right has been formed by flipping the reference figure over on its back (and then possibly rotating it), touch (-).

Do the problems from left to right in order. Do not skip any items; make no corrections. Signal (*) when slide is completed.

SAMPLE:

The pluses and minuses indicate correct responses.

#5 Diver Task/Istructions

Set the finger dexterity template (template #1) in place on the keyboard and tighten the holding screws (finger-tight only).

Hold the test object in your dominant hand (hand used in writing, etc.). Use your other hand and the magnetic stylus to signal (*) that you are ready, then put the stylus aside. Use only one hand in doing the test. On signal, turn the square surface of the object downward and insert it into #1 on the keyboard. Without releasing the object, retrieve it, rotate it in your fingertips, and insert the circular side into #2. Continue working in this manner, row by row, until you have completed the board (...#7, #8, #9). Move from #9 back to #1 and continue the test until signaled to stop. Work as rapidly as possible.

#6 Diver Task/Instructions

Fasten the template in place on keyboard. Grasp the test object in one hand and the wrench in the other.

Use the wrench on the square end of the object to rotate the cylinder exposing the square end. Remove the wrench and insert the square into position #1 on keyboard. Retrieve, and use the wrench again, this time to expose the round end. Insert the round end in #2. Repeat this procedure, square in #3, round in #4, etc. until signaled to stop. (Figure 12 illustrate the test procedure). Work as rapidly as possible.

#7 Diver Task/Instructions

Insert your stylus into the position marked RT and observe the window directly beneath RT position. When the window lights up, withdraw the stylus as rapidly as possible. Return your stylus to the RT position and stand ready for the next trial. Repeat this procedure until the experimenter signals that the test is over.

#8 Diver Task/Instructions

Your task is to indicate when a certain period of time has gone by. Do this by inserting your stylus at #9 and holding it there until you think the prescribed time interval has elapsed. Then, remove the stylus. A timer runs while the stylus is inserted and thus a direct measure of your ability to judge elapsed time is obtained.

#9 Diver Task/Instructions

Grasp the magnetic stylus firmly between the thumb and first two fingers of your dominant hand (hand used for writing, etc.) as though throwing a dart. On signal, tap as rapidly as possible, back and forth between (+) and (-) keys. Continue tapping until you are signaled to stop.

#10 Diver Task/Instructions

Study the slides containing the work-number pairs. Learn to associate each word and number. Later, you will be shown only the words and asked to give the number. The amount of time for learning is prescribed by the experimenter. You will be advised of the total time available.

Upon presentation of the test slides which contain only the work of the word-number pair learned previously, tap out the corresponding numbers, working down the test in order from top to bottom. After registering each two-digit number, touch the (*) key. An answer sequence would thus be: 25(*); 14(*); 38(*); and so on.

SAMPLE LEARNING SLIDE:

Object	Number
Window	75
Desk	41
Carpet	19
Door	84
Glass	90

#11 Diver Task/Instructions

Each row of letter sets on a slide represents a separate problem. In each row, all but one set have a certain characteristic in common. For example, four sets may have their letters in alphabetical order, while the remaining one does not.

The task is to identify that set which does not agree with the others. There is only one such set in each problem. If it looks as though there is more than one possible answer, you have not discovered the correct rule. The rules are not based on the sound of groups of letters, the shape of letters, or whether the letter combinations form parts of words.

Working the problems in the order A, B, C, D, identify the answer by its number. For example, in row A, the answer may be #3; in row B, the answer may be #5, and so on.

Give only one answer per problem. Signal (*) when all problems on the slide have been completed.

#12 Diver Task/Instructions

Solve each arithmetic problem mentally. When you have the answer, enter it on the keyboard. For example, 18 x 9 = 162. The answer should be entered as 1, 6, 2, not 2, 6, 1.

Important: After each complete answer, signal (*) and then, continue with the next problem.

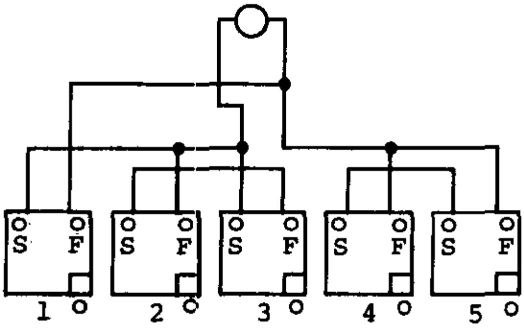
Signal (***) when you have completed a slide.

#13 Diver Task/Instructions

Examine the "wiring diagram" on the slide. Note that connections are made only at the dots, otherwise the lines cross without connecting.

Each box contains an "S" for "Start" and an "F" for "Finish." From one of the boxes, the line eleaves from S, goes through the circle at the top of the diagram, and returns to F in the same box it started from. This is true of only one box. The task is to identify that box, enter its number (1, 2, 3, 4, or 5) on the keyboard and signal (*) for next slide.

SAMPLE:

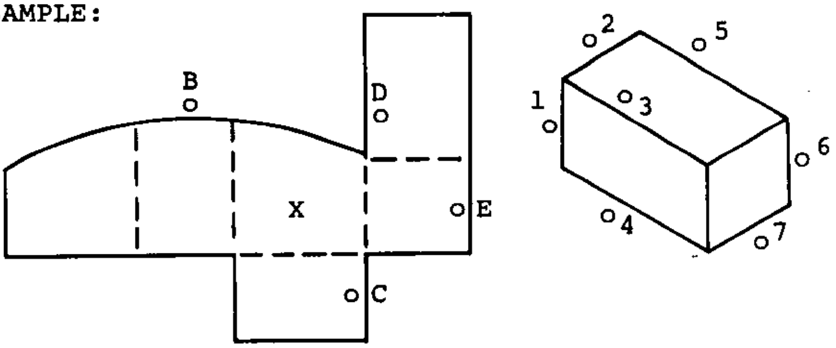


The first box is the one which has the line from S, through the circle, and back to F.

#14 Diver Task/Instructions

At the left of each slide is a flat figure containing dotted lines. Imagine that the pattern was made from thin metal and folded or bent along the dotted lines to form the object on the right. Your task is to tell where an edge in the left figure, marked by a letter, appears in the right figure, identified by a number. One surface has been marked "x" in both figures. It is the same surface in both figures. This helps to show how the pattern was folded. Sometimes two edges are folded together so that they both have the same letter in the right-hand figure. Start with edge "A" and identify its new location by entering the proper number on the keyboard. Enter only numerical answers. Do not enter any letters. Do the problems in order, A, B, C, etc. If you do not know an answer, guess at it, but do not skip any problems. Signal (*) when you have completed the slide.

SAMPLE:



A = 6, B = 2, C = 7, D = 4, E = 6

#15 Diver Task/Instructions

On the oscilloscope display, a target dot will move in a clockwise circle during the test. Keep the control dot superimposed on the target dot by moving the control stick in a smooth clockwise circle.

#16 Diver Task/Instructions

Use your left and right hand control sticks to control the horizontal and vertical axes respectively in keeping the dot centered on face of oscilloscope.

#17 Diver Task/Instructions

Attach the Response Orientation template to the keyboard. Hold the stylus at the center of the four openings on the templat When a colored slide appears, move the stylus rapidly to the position corresponding to that color. Slide the stylus forward, backward, and so on. Do not raise the stylus. Continue responding to a slide until the slide is removed, indicating that the correct response has been made.

This is primarily a test of response speed, but incorrect responses are also scored, so do not make unnecessary moves. The experimenter will give you practice trials to learn the response for each color.

#18 Diver Task/Instructions

In COMPENSATORY mode, keep the dot centered on oscilloscope using the manual tracking controls(s) selected by the experimenter.

In PURSUIT mode, keep the control dot superimposed on the target dot using the manual tracking control(s) selected by the experimenter.

#19 Diver Task/Instructions

Observe the digital display to detect numbers as they occur. Use your stylus on the keyboard to report each number detected. When a digit appears, respond as rapdily as possible.

The test may last for a relatively long time. The numbers that you are to detect will occur at irregular intervals; meanwhile, you must continue to watch the display.

#20 Diver Task/Instructions

View the series of digits on the optical (on-line) display. The display goes dark after the final digit in the sequence. Wait for the entire sequence to be presented before responding.

Reproduce the sequence (all the digits in the order that they were presented) by touching appropriate digits on the keyboard. Touch the (*) key at the end of your answer sequence.

#21 Diver Task/Instructions

With your dominant hand (hand you wirte with) on the control stick, keep the control dot superimpsoed on the target dot. As you track, visually scan back and forth between the oscilloscope and the "correct" (green) lamp on the keyboard. This lamp will be illuminated from time to time while you are tracking. Each time you detect the light, signal (*) the experimenter using the stylus in your other hand.

Continue tracking and reporting the light signals until advised that the test is over.

#22 Diver Task/Instructions

Observe the numbers that appear on the digital (on-line) display. The numbers will continue to change at a rate of one per second. At various times, the display will be interrupted and go blank. When it does, you are to report the last two digits shown before the display was interrupted. Use the magnetic stylus and keyboard to register your answers. Give the digits in the order they occurred.

As an example, the dispaly may have shown: 7, 9, 3, 6, 8, 2, 4, "OFF". You would recall the last two digits as "2" and "4", and respond on the keyboard: 2, 4,. When you have responded, the display will begin the cycle again. Continue working until you are signaled to stop.

#23 Diver Task/Instructions

With your arm fully extended, but without locking your elbow, hold the photocell stylus directly in front of the spot of light on the screen. The tip of the stylus should be no more than one inch away from the screen, but it should not touch the screen at any time. (The trial starts and ends upon signal from the experimenter.)

#24 Diver Task/Instructions

You will be shown a series of words whose letters have been rearranged. Your task is to mentally unscramble the letters to discover the word they represent. For example, N-T-K-I-H would be solved as the word "THINK".

To indicate your answers, spell out the word by using the number corresponding to each letter. For example: if you saw

D O L F
1 2 3 4 , you would answer with "FOLD" by touching 4, 2, 3, 1

with the stylus. Signal (*) when all problems on the slide have been completed.

#25 Diver Task/Instructions

The speed at which you can move your extended arm through the water (or through space, if dry) is measured in the following way:

> Hold the photocell stylus as you would hold a pencil. Let the cable fall outside your wrist (away from your body). Extend your arm fully but without locking your elbow and stand (or sit) so that the top of the stylus is about 6 to 8 inches outside the left edge of the screen, then swing your arm in an arc from left to right so that the stylus "looks at" the screen as it goes by.

A timer will start when the stylus crosses the edge of the screen and stops when the stylus moves off the screen on the opposite side. During the test, make the movement as rapidly as possible. Be careful not to strike the screen. The test is two moves left to right, and two moves right to left.

IMPORTANT: Keep the stylus pointed away from the screen except during arm movement in testing.

INDIVIDUAL TEST SCORES
Raw Data Sheet-Baseline

TEST No.	SUBJECT 01 Alger	SUBJECT 02 Ault	SUBJECT 03 Brewer	SUBJECT 04 Brown	SUBJECT 05 Goehring
1	34	31	21	19	66
2	04	14	12	02	07
3	16	14	08	07	12
4	13	32	15	11	23
5	19	18	19	16	20
6	08	12	14	09	08
7	.287	.272	.287	.339	.242
8	10.0	11.6	14.7	18.7	21.4
9	112	119	140	088	106
10	18	02	10	09	16
11	08	03	08	08	06
12	42	14	34	39	47
13	03	06	06	03	04
14	10	05	06	13	12
15			46.6		56.4
16			105.2		101.8
17			0.91		0.85
18			138.6		97.6
19			60		80
20			05		06
21			.209		.134
22			100		100

TEST No.	SUBJECT 06 Goodspeed	SUBJECT 07 Hink	SUBJECT 08 Lash	SUBJECT 09 Nordan	SUBJECT 10 O'Bryan
1	09	22	20	34	26
2	11	10	06	02	03
3	17	28	20	18	19
4	17	20	08	11	11
5	18	13	20	18	19
6	11	08	13	14	12
7	.294	.247	.329	.271	.342
8	32.2	14.1	12.3	25.8	11.4
9	089	117	174	114	092
10	08	16	11	10	09
11	07	07	08	02	08
12	47	40	49	19	28
13	06	02	09	00	04
14	12	05	21	15	19
15	37.1	42.0	45.6	34.1	47.7
16	89.1	67.5	110.3	108.2	86.6
17	1.30	0.90	1.17	0.76	1.54
18	72.2	141.4	74.0	92.9	105.6
19	80	80	80	90	80
20	05	05	06	07	06
21	.012	-.055	.120	-.043	.083
22	100	100	090	070	100

TEST No.	SUBJECT 11 Phillips	SUBJECT 12 Price	SUBJECT 13 Radecki	SUBJECT 14 Schlegel	SUBJECT 15 Templin
1	44	27	45	20	22
2	04	01	10	07	13
3	10	13	21	07	15
4	18	18	05	14	25
5	14	15	17	14	21
6	11	10	12	09	14
7	.254	.272	.252	.245	.314
8	14.1	19.6	05.8	38.0	03.2
9	095	103	132	095	096
10	06	09	04	11	08
11	04	07	04	11	08
12	14	10	24	42	40
13	00	04	01	01	02
14	07	11	06	14	14
15					28.7
16					63.8
17					1.15
18					63.8
19					80
20					07
21					2.000
22					100

TEST No.	SUBJECT 16 Thomas	SUBJECT 17 Travers	SUBJECT 18 Virgil	SUBJECT 19 Watkins	SUBJECT 20 Wetzel
1	09	09	22	19	32
2	16	07	05	06	09
3	12	08	12	07	16
4	01	02	01	03	28
5	13	16	12	18	21
6	08	10	08	10	08
7	.324	.250	.262	.394	.258
8	27.0	03.0	42.9	06.3	09.5
9	078	107	092	081	106
10	00	06	06	00	10
11	06	07	06	04	05
12	27	46	36	17	34
13	05	14	00	07	04
14	03	08	11	10	14
15		33.7		45.0	28.3
16		110.7		106.7	80.8
17		1.29		1.03	1.06
18		97.4		115.2	91.4
19		80		70	90
20		07		06	05
21		.000		.084	.073
22		070		060	090

TEST No.	SUBJECT 21 Langdon	SUBJECT 22 Jones	SUBJECT 23 Kennedy	SUBJECT 24 Gibson	SUBJECT 25 Fine
1	61	24	18	24	15
2	07	04	07	08	05
3	18	08	14	27	08
4	36	07	06	05	19
5	18	23	16	16	23
6	10	09	07	11	13
7	.305	.286	.296	.274	.276
8	11.1	26.1	06.7	13.3	10.5
9	098	126	093	110	103
10	05	09	14	12	04
11	04	07	06	06	04
12	43	38	35	55	34
13	03	06	00	05	02
14	13	23	02	06	14
15	34.6	36.5	45.7		
16	98.6	105.3	132.9		
17	1.10	1.29	1.40		
18	80.0	109.1	140.0		
19	90	70	70		
20	07	05	07		
21	.273	-.355	-.048		
22	100	080	100		

TEST No.	SUBJECT 26 Bunting	SUBJECT 27 Hesler
1	43	48
2	07	06
3	08	09
4	25	34
5	23	16
6	09	10
7	.268	.257
8	09.1	21.8
9	105	086
10	13	15
11	08	09
12	36	57
13	06	03
14	18	14
15	99.7	39.6
16	99.2	87.6
17	0.97	0.65
18	120.2	57.3
19	90	90
20	08	07
21	.214	.145
22	080	090

#1 FACTOR: FLEXIBILITY OF CLOSURE

TEST: HIDDEN PATTERNS

```
        DESCRIPTIVE  STATISTICS
           FOR VARIABLE  1

NUMBER OF OBSERVATIONS =             27.0

CENTRAL TENDENCY
     MEAN =                           28.296
     MEDIAN =                         23.063

DISPERSION
     STANDARD DEVIATION =             14.720
     COEFFICIENT OF VARIATION =       52.021
     RANGE =        9.00   TO      66.00

SKEWNESS
     BASED ON THE THIRD MOMENT =       0.921

KURTOSIS
     BASED ON THE FOURTH MOMENT =      0.151


 SCORE INTERVAL       MID POINT  FREQUENCY  PERCENT  CUMULATIVE  HISTOGRAM  X=  0.160
                                                      PERCENT

 9.000  -  14.000      11.500        3.     11.111    11.111    XXXXXXXXXXXXXXXXXX
14.000  -  19.000      16.500        4.     14.815    25.926    XXXXXXXXXXXXXXXXXXXXXXXXX
19.000  -  24.000      21.500        8.     29.630    55.556    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
24.000  -  29.000      26.500        2.      7.407    62.963    XXXXXXXXXXXX
29.000  -  34.000      31.500        4.     14.815    77.778    XXXXXXXXXXXXXXXXXXXXXXXXX
34.000  -  39.000      36.500        0.      0.0      77.778
39.000  -  44.000      41.500        2.      7.407    85.185    XXXXXXXXXXXX
44.000  -  49.000      46.500        2.      7.407    92.593    XXXXXXXXXXXX
49.000  -  54.000      51.500        0.      0.0      92.593
54.000  -  59.000      56.500        0.      0.0      92.593
59.000  -  64.000      61.500        1.      3.704    96.295    XXXXXX
64.000  -  69.000      66.500        1.      3.704   100.000    XXXXXX
```

#2 FACTOR: LENGTH ESTIMATION

TEST: SHORTEST ROAD

```
           DESCRIPTIVE  STATISTICS
              FCR VARIABLE  2

NUMBER OF CBSERVATICNS =              27.0

CENTRAL TENDENCY
     MEAN =                            7.148
     MEDIAN =                          6.750

DISPERSION
     STANDARD DEVIATICN =              3.769
     COEFFICIENT CF VARIATION =       52.732
     RANGE =       1.00   TO      16.00

SKEWNESS
     BASED ON THE THIRD MOMENT =       0.516

KURTCSIS
     BASED ON THE FOURTH MOMENT =     -0.448

 SCORE INTERVAL       MID POINT  FREQUENCY  PERCENT  CUMULATIVE  HISTOGRAM  X=  0.120
                                                      PERCENT

 0.500  -   1.500       1.000        1.       3.704     3.704    XXXXXXXX
 1.500  -   2.500       2.000        2.       7.407    11.111    XXXXXXXXXXXXXXXX
 2.500  -   3.500       3.00C        1.       3.704    14.815    XXXXXXXX
 3.500  -   4.500       4.000        3.      11.111    25.926    XXXXXXXXXXXXXXXXXXXXXXXXX
 4.500  -   5.500       5.00C        2.       7.407    33.333    XXXXXXXXXXXXXXXX
 5.500  -   6.500       6.00C        3.      11.111    44.444    XXXXXXXXXXXXXXXXXXXXXXXXX
 6.500  -   7.500       7.00C        6.      22.222    66.667    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 7.500  -   8.500       8.00C        1.       3.704    70.370    XXXXXXXX
 8.500  -   9.500       9.CCC        1.       3.704    74.074    XXXXXXXX
 9.500  -  10.500      10.000        2.       7.407    81.481    XXXXXXXXXXXXXXXX
10.500  -  11.500      11.00C        1.       3.704    85.185    XXXXXXXX
11.500  -  12.500      12.000        1.       3.704    88.889    XXXXXXXX
12.500  -  13.500      13.00C        1.       3.704    92.592    XXXXXXXX
13.500  -  14.500      14.000        1.       3.704    96.296    XXXXXXXX
14.500  -  15.500      15.00C        0.       0.0      96.296
15.500  -  16.500      16.000        1.       3.704   100.000    XXXXXXXX
```

#3 FACTOR: PERCEPTUAL SPEED

TEST: NUMBER COMPARISON

```
           DESCRIPTIVE  STATISTICS
              FOR VARIABLE  3

NUMBER OF OBSERVATIONS =            27.0

CENTRAL TENDENCY
     MEAN =                        12.593
     MEDIAN =                      11.500

DISPERSION
     STANDARD DEVIATION =           5.250
     COEFFICIENT OF VARIATION =    41:688
     RANGE =       7.00   TO      27.00

SKEWNESS
     BASED ON THE THIRD MOMENT =    0.806

KURTOSIS
     BASED ON THE FOURTH MOMENT =  -0.060


 SCORE INTERVAL       MID POINT  FREQUENCY  PERCENT  CUMULATIVE  HISTOGRAM  X=  0.200
                                                      PERCENT

  6.500  -   8.500      7.500       10.      37.037    37.037    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  8.500  -  10.500      9.500        2.       7.407    44.444    XXXXXXXXXX
 10.500  -  12.500     11.500        3.      11.111    55.556    XXXXXXXXXXXXXXX
 12.500  -  14.500     13.500        3.      11.111    66.667    XXXXXXXXXXXXXXX
 14.500  -  16.500     15.500        3.      11.111    77.778    XXXXXXXXXXXXXXX
 16.500  -  18.500     17.500        3.      11.111    88.889    XXXXXXXXXXXXXXX
 18.500  -  20.500     19.500        1.       3.704    92.592    XXXXX
 20.500  -  22.500     21.500        1.       3.704    96.296    XXXXX
 22.500  -  24.500     23.500        0.       0.0      96.296
 24.500  -  26.500     25.500        0.       0.0      96.296
 26.500  -  28.500     27.500        1.       3.704   100.000    XXXXX
```

#4 FACTOR: SPATIAL ORIENTATION

TEST: CARD ROTATIONS

```
                 DESCRIPTIVE  STATISTICS
                    FOR VARIABLE  4

NUMBER OF OBSERVATIONS =                27.0

CENTRAL TENDENCY
     MEAN =                             15.111
     MEDIAN =                           14.000

DISPERSION
     STANDARD DEVIATION =               10.263
     COEFFICIENT OF VARIATION =         67.918
     RANGE =        1.00   TO       36.00

SKEWNESS
     BASED ON THE THIRD MOMENT =         0.407

KURTOSIS
     BASED ON THE FOURTH MOMENT =       -0.942


 SCORE INTERVAL       MID POINT  FREQUENCY  PERCENT  CUMULATIVE  HISTOGRAM  X=  0.080
                                                        PERCENT

 0.500  -   3.500       2.000        4.      14.815     14.815    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 3.500  -   6.500       5.000        3.      11.111     25.925    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 6.500  -   9.500       8.000        2.       7.407     33.333    XXXXXXXXXXXXXXXXXXXXXXXXX
 9.500  -  12.500      11.000        3.      11.111     44.444    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
12.500  -  15.500      14.000        3.      11.111     55.556    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
15.500  -  18.500      17.000        3.      11.111     66.667    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
18.500  -  21.500      20.000        2.       7.407     74.074    XXXXXXXXXXXXXXXXXXXXXXXXX
21.500  -  24.500      23.000        1.       3.704     77.778    XXXXXXXXXXXX
24.500  -  27.500      26.000        2.       7.407     85.185    XXXXXXXXXXXXXXXXXXXXXXXXX
27.500  -  30.500      29.000        1.       3.704     88.889    XXXXXXXXXXXX
30.500  -  33.500      32.000        1.       3.704     92.592    XXXXXXXXXXXX
33.500  -  36.500      35.000        2.       7.407    100.000    XXXXXXXXXXXXXXXXXXXXXXXXX
```

#5 FACTOR: FINGER DEXTERITY

TEST: KEY INSERTIONS

```
            DESCRIPTIVE  STATISTICS
               FOR VARIABLE  5

NUMBER OF OBSERVATIONS =                   27.0

CENTRAL TENDENCY
     MEAN =                                17.630
     MEDIAN =                              17.800

DISPERSION
     STANDARD DEVIATION =                   3.090
     COEFFICIENT OF VARIATION =            17.529
     RANGE =        12.00  TO       23.00

SKEWNESS
     BASED ON THE THIRD MOMENT =            0.079

KURTOSIS
     BASED ON THE FOURTH MOMENT =         -0.896

 SCORE INTERVAL       MID POINT  FREQUENCY  PERCENT  CUMULATIVE  HISTOGRAM  X=  0.100
                                                      PERCENT

11.500  -  12.500     12.000        1.       3.704     3.704     XXXXXXXXXX
12.500  -  13.500     13.000        2.       7.407    11.111     XXXXXXXXXXXXXXXXXXXX
13.500  -  14.500     14.000        2.       7.407    18.519     XXXXXXXXXXXXXXXXXXXX
14.500  -  15.500     15.000        1.       3.704    22.222     XXXXXXXXXX
15.500  -  16.500     16.000        5.      18.519    40.741     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
16.500  -  17.500     17.000        1.       3.704    44.444     XXXXXXXXXX
17.500  -  18.500     18.000        5.      18.519    62.963     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
18.500  -  19.500     19.000        3.      11.111    74.074     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
19.500  -  20.500     20.000        2.       7.407    81.481     XXXXXXXXXXXXXXXXXXXX
20.500  -  21.500     21.000        2.       7.407    88.889     XXXXXXXXXXXXXXXXXXXX
21.500  -  22.500     22.000        0.       0.0      88.889
22.500  -  23.500     23.000        3.      11.111   100.000     XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

#6 FACTOR: MANUAL DEXTERITY

TEST: WRENCH AND CYLINDER

```
              DESCRIPTIVE  STATISTICS
                FOR VARIABLE  6

 NUMBER OF OBSERVATIONS =              27.0

 CENTRAL TENDENCY
      MEAN =                           10.296
      MEDIAN =                         10.000

 DISPERSION
      STANDARD DEVIATION =              2.109
      COEFFICIENT OF VARIATION =       20.482
      RANGE =       7.00   TO       14.00

 SKEWNESS
      BASED ON THE THIRD MOMENT =       0.357

 KURTOSIS
      BASED ON THE FOURTH MOMENT =     -1.139



 SCORE  INTERVAL      MID POINT  FREQUENCY  PERCENT  CUMULATIVE  HISTOGRAM  X=  0.140
                                                       PERCENT

  7.500  -   8.500     8.000        7.      25.926     25.926    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  8.500  -   9.500     9.000        4.      14.815     40.741    XXXXXXXXXXXXXXXXXXXXXXXXXXXX
  9.500  -  10.500    10.000        5.      18.519     59.259    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 10.500  -  11.500    11.000        3.      11.111     70.370    XXXXXXXXXXXXXXXXXXXXX
 11.500  -  12.500    12.000        3.      11.111     81.481    XXXXXXXXXXXXXXXXXXXXX
 12.500  -  13.500    13.000        2.       7.407     88.889    XXXXXXXXXXXXXX
 13.500  -  14.500    14.000        3.      11.111    100.000    XXXXXXXXXXXXXXXXXXXXX
```

#7 FACTOR: REACTION TIME

TEST: VISUAL REACTION TIME

```
              DESCRIPTIVE  STATISTICS
                FOR VARIABLE  7

NUMBER OF OBSERVATIONS =               27.0

CENTRAL TENDENCY
     MEAN =                             0.285
     MEDIAN =                           0.275

DISPERSION
     STANDARD DEVIATION =               0.036
     COEFFICIENT OF VARIATION =        12.729
     RANGE =        0.24  TO       0.39

SKEWNESS
     BASED ON THE THIRD MOMENT =        1.079

KURTOSIS
     BASED ON THE FOURTH MOMENT =       0.782

SCORE INTERVAL       MID POINT  FREQUENCY  PERCENT  CUMULATIVE  HISTOGRAM  X=  0.100
                                                     PERCENT

0.242  -   0.251       0.246        4.      14.815    14.815    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.251  -   0.260       0.255        4.      14.815    29.630    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.260  -   0.269       0.264        2.       7.407    37.037    XXXXXXXXXXXXXXXXXXXX
0.269  -   0.278       0.273        5.      18.519    55.555    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.278  -   0.287       0.282        2.       7.407    62.963    XXXXXXXXXXXXXXXXXXXX
0.287  -   0.296       0.291        2.       7.407    70.370    XXXXXXXXXXXXXXXXXXXX
0.296  -   0.305       0.300        2.       7.407    77.778    XXXXXXXXXXXXXXXXXXXX
0.305  -   0.314       0.309        1.       3.704    81.481    XXXXXXXXXX
0.314  -   0.323       0.318        0.       0.0      81.481
0.323  -   0.332       0.327        2.       7.407    88.889    XXXXXXXXXXXXXXXXXXXX
0.332  -   0.341       0.336        1.       3.704    92.592    XXXXXXXXXX
0.341  -   0.350       0.345        1.       3.704    96.296    XXXXXXXXXX
0.350  -   0.359       0.354        0.       0.0      96.296
0.359  -   0.368       0.363        0.       0.0      96.296
0.368  -   0.377       0.372        0.       0.0      96.296
0.377  -   0.386       0.381        0.       0.0      96.296
0.386  -   0.395       0.390        1.       3.704   100.000    XXXXXXXXXX
```

#8 FACTOR: TIME INTERVAL ESTIMATION

TEST: INTERVAL REPRODUCTION

```
          DESCRIPTIVE  STATISTICS
             FOR VARIABLE  8

NUMBER OF OBSERVATIONS =              27.0

CENTRAL  TENDENCY
     MEAN =                          163.037
     MEDIAN =                        132.500

DISPERSION
     STANDARD DEVIATION =            102.613
     COEFFICIENT OF VARIATION =       62.938
     RANGE =      30.00  TO     429.00

SKEWNESS
     BASED ON THE THIRD MOMENT =       0.931

KURTOSIS
     BASED ON THE FOURTH MOMENT =      0.071


  SCORE  INTERVAL       MID POINT  FREQUENCY  PERCENT  CUMULATIVE  HISTOGRAM  X=  0.160
                                                        PERCENT

 30.000  -   70.000      50.000        5.      18.519    18.519    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 70.000  -  110.000      90.000        4.      14.815    33.333    XXXXXXXXXXXXXXXXXXXXXXXXX
110.000  -  150.000     130.000        8.      29.630    62.963    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
150.000  -  190.000     170.000        1.       3.704    66.667    XXXXXX
190.000  -  230.000     210.000        3.      11.111    77.778    XXXXXXXXXXXXXXXXXX
230.000  -  270.000     250.000        3.      11.111    88.889    XXXXXXXXXXXXXXXXXX
270.000  -  310.000     290.000        0.       0.0      88.889
310.000  -  350.000     330.000        1.       3.704    92.593    XXXXXX
350.000  -  390.000     370.000        1.       3.704    96.296    XXXXXX
390.000  -  430.000     410.000        1.       3.704   100.000    XXXXXX
```

#9 FACTOR: WRIST–FINGER SPEED

TEST: TAPPING

```
          DESCRIPTIVE  STATISTICS
             FOR VARIABLE  9

NUMBER OF OBSERVATIONS =                27.0

CENTRAL TENDENCY
     MEAN =                           105.815
     MEDIAN =                         103.500

DISPERSION
     STANDARD DEVIATION =              20.258
     COEFFICIENT OF VARIATION =        19.145
     RANGE =       78.00  TO     174.00

SKEWNESS
     BASED ON THE THIRD MOMENT =        1.431

KURTOSIS
     BASED ON THE FOURTH MOMENT =       2.525


 SCORE INTERVAL        MID POINT  FREQUENCY  PERCENT  CUMULATIVE  HISTOGRAM  X=  0.120
                                                        PERCENT

  77.500  -   85.500    81.500       2.       7.407      7.407    XXXXXXXXXXXXXXXX
  85.500  -   93.500    89.500       6.      22.222     29.630    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  93.500  -  101.500    97.500       4.      14.815     44.444    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 101.500  -  109.500   105.500       6.      22.222     66.667    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 109.500  -  117.500   113.500       4.      14.815     81.481    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 117.500  -  125.500   121.500       1.       3.704     85.185    XXXXXXXX
 125.500  -  133.500   129.500       2.       7.407     92.593    XXXXXXXXXXXXXXXX
 133.500  -  141.500   137.500       1.       3.704     96.296    XXXXXXXX
 141.500  -  149.500   145.500       0.       0.0       96.296
 149.500  -  157.500   153.500       0.       0.0       96.296
 157.500  -  165.500   161.500       0.       0.0       96.296
 165.500  -  173.500   169.500       0.       0.0       96.296
 173.500  -  181.500   177.500       1.       3.704    100.000    XXXXXXXX
```

#10 FACTOR: ASSOCIATIVE MEMORY

TEST: WORD—NUMBER

```
                    DESCRIPTIVE  STATISTICS
                       FOR VARIABLE 10

NUMBER OF OBSERVATIONS =                 27.0

CENTRAL TENDENCY
     MEAN =                               8.926
     MEDIAN =                             8.625

DISPERSION
     STANDARD DEVIATION =                 4.731
     COEFFICIENT OF VARIATION =          52.999
     RANGE =        0.0   TO       18.00

SKEWNESS
     BASED ON THE THIRD MOMENT =         -0.071

KURTOSIS
     BASED ON THE FOURTH MOMENT =        -0.718


 SCORE INTERVAL      MID POINT  FREQUENCY  PERCENT  CUMULATIVE  HISTOGRAM  X=  0.080
                                                     PERCENT

 0.0    -   1.000      0.500        2.      7.407      7.407    XXXXXXXXXXXXXXXXXXXXXXXXX
 1.000  -   2.000      1.500        1.      3.704     11.111    XXXXXXXXXXXX
 2.000  -   3.000      2.500        0.      0.0       11.111
 3.000  -   4.000      3.500        2.      7.407     18.519    XXXXXXXXXXXXXXXXXXXXXXXXX
 4.000  -   5.000      4.500        1.      3.704     22.222    XXXXXXXXXXXX
 5.000  -   6.000      5.500        3.     11.111     33.333    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 6.000  -   7.000      6.500        0.      0.0       33.333
 7.000  -   8.000      7.500        2.      7.407     40.741    XXXXXXXXXXXXXXXXXXXXXXXXX
 8.000  -   9.000      8.500        4.     14.815     55.555    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 9.000  -  10.000      9.500        3.     11.111     66.667    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
10.000  -  11.000     10.500        2.      7.407     74.074    XXXXXXXXXXXXXXXXXXXXXXXXX
11.000  -  12.000     11.500        1.      3.704     77.778    XXXXXXXXXXXX
12.000  -  13.000     12.500        1.      3.704     81.481    XXXXXXXXXXXX
13.000  -  14.000     13.500        1.      3.704     85.185    XXXXXXXXXXXX
14.000  -  15.000     14.500        1.      3.704     88.889    XXXXXXXXXXXX
15.000  -  16.000     15.500        2.      7.407     96.296    XXXXXXXXXXXXXXXXXXXXXXXXX
16.000  -  17.000     16.500        0.      0.0       96.296
17.000  -  18.000     17.500        1.      3.704    100.000    XXXXXXXXXXXX
18.000  -  19.000     18.500        0.      0.0      100.000
```

#11 FACTOR: INDUCTION

TEST: LETTER SETS

```
            DESCRIPTIVE  STATISTICS
               FCR VARIABLE 11

NUMBER OF OBSERVATIONS =                27.0

CENTRAL TENDENCY
     MEAN =                               6.185
     MEDIAN =                             6.400

DISPERSION
     STANDARD DEVIATICN =                 1.962
     COEFFICIENT CF VARIATION =          31.719
     RANGE =        2.00   TO       10.00

SKEWNESS
     BASED ON THE THIRD MOMENT =         -0.220

KURTOSIS
     BASED ON THE FCURTH MOMENT =        -0.826


SCORE INTERVAL      MID POINT  FREQUENCY  PERCENT  CUMULATIVE  HISTOGRAM  X=  0.120
                                                     PERCENT

1.500  -   2.500     2.000        1.       3.704      3.704    XXXXXXXX
2.500  -   3.500     3.000        1.       3.704      7.407    XXXXXXXX
3.500  -   4.500     4.000        5.      18.519     25.926    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
4.500  -   5.500     5.000        2.       7.407     33.333    XXXXXXXXXXXXXXXX
5.500  -   6.500     6.000        5.      18.519     51.852    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6.500  -   7.500     7.000        5.      18.519     70.370    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
7.500  -   8.500     8.000        6.      22.222     92.593    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
8.500  -   9.500     9.000        1.       3.704     96.296    XXXXXXXX
9.500  -  10.500    10.000        1.       3.704    100.000    XXXXXXXX
```

#12 FACTOR: NUMBER FACILITY

TEST: ARITHMETIC

```
           DESCRIPTIVE  STATISTICS
              FOR VARIABLE 12

NUMBER OF OBSERVATIONS =              27.0

CENTRAL TENDENCY
     MEAN =                           35.074
     MEDIAN =                         36.500

DISPERSION
     STANDARD DEVIATION =             12.484
     COEFFICIENT OF VARIATION =       35.592
     RANGE =      10.00   TO      57.00

SKEWNESS
     BASED ON THE THIRD MOMENT =      -0.370

KURTOSIS
     BASED ON THE FOURTH MOMENT =     -0.749

 SCORE INTERVAL        MID POINT  FREQUENCY  PERCENT  CUMULATIVE  HISTOGRAM  X=  0.080
                                                        PERCENT

10.000  -   13.000      11.500        1.      3.704      3.704    XXXXXXXXXXXX
13.000  -   16.000      14.500        2.      7.407     11.111    XXXXXXXXXXXXXXXXXXXXXXXXX
16.000  -   19.000      17.500        2.      7.407     18.519    XXXXXXXXXXXXXXXXXXXXXXXXX
19.000  -   22.000      20.500        0.      0.0       18.519
22.000  -   25.000      23.500        1.      3.704     22.222    XXXXXXXXXXXX
25.000  -   28.000      26.500        2.      7.407     29.630    XXXXXXXXXXXXXXXXXXXXXXXXX
28.000  -   31.000      29.500        0.      0.0       29.630
31.000  -   34.000      32.500        3.     11.111     40.741    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
34.000  -   37.000      35.500        3.     11.111     51.852    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
37.000  -   40.000      38.500        4.     14.815     66.667    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
40.000  -   43.000      41.500        3.     11.111     77.778    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
43.000  -   46.000      44.500        1.      3.704     81.481    XXXXXXXXXXXX
46.000  -   49.000      47.500        3.     11.111     92.592    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
49.000  -   52.000      50.500        0.      0.0       92.592
52.000  -   55.000      53.500        1.      3.704     96.295    XXXXXXXXXXXX
55.000  -   58.000      56.500        1.      3.704    100.000    XXXXXXXXXXXX
```

#13 FACTOR: SPATIAL SCANNING

TEST: CHOOSE A PATH

```
               DESCRIPTIVE  STATISTICS
                 FCR VARIABLE 13

NUMBER OF CBSERVATIONS =                  27.0

CENTRAL TENDENCY
     MEAN =                                3.926
     MEDIAN =                              3.125

DISPERSICN
     STANDARD DEVIATICN =                  3.125
     COEFFICIENT CF VARIATION =           79.590
     RANGE =        0.0    TO       14.00

SKEWNESS
     BASED ON THE THIRD MOMENT =           1.108

KLRTOSIS
     BASED ON THE FCURTH MOMENT =          1.774

 SCORE INTERVAL       MID POINT  FREQUENCY  PERCENT  CUMULATIVE  HISTOGRAM  X=  0.120
                                                        PERCENT

  0.0    -    1.000       C.500         6.     22.222     22.222    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  1.000  -    2.000       1.500         3.     11.111     33.333    XXXXXXXXXXXXXXXXXXXXXXXX
  2.000  -    3.000       2.500         4.     14.815     48.148    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  3.000  -    4.000       3.500         4.     14.815     62.963    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  4.000  -    5.00C       4.500         2.      7.407     70.370    XXXXXXXXXXXXXXXX
  5.000  -    6.000       5.50C         5.     18.519     88.889    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  6.000  -    7.00C       6.500         1.      3.704     92.593    XXXXXXXX
  7.000  -    8.000       7.500         0.      0.0       92.593
  8.000  -    9.000       8.500         1.      3.704     96.296    XXXXXXXX
  9.000  -   10.000       9.5CC         C.      0.0       96.296
 10.000  -   11.000      1C.5CC         C.      0.0       96.296
 11.000  -   12.000      11.500         C.      0.0       96.296
 12.000  -   13.000      12.50C         C.      0.0       96.296
 13.000  -   14.000      13.500         1.      3.704    100.000    XXXXXXXX
 14.000  -   15.000      14.5CC         C.      0.0      100.000
```

#14 FACTOR: VISUALIZATION

TEST: SURFACE DEVELOPMENT

```
           DESCRIPTIVE  STATISTICS
              FOR VARIABLE 14

 NUMBER OF OBSERVATIONS =             27.0

 CENTRAL TENDENCY
      MEAN =                          11.333
      MEDIAN =                        11.750

 DISPERSION
      STANDARD DEVIATION =             5.349
      COEFFICIENT OF VARIATION =      47.200
      RANGE =         2.00  TO      23.00

 SKEWNESS
      BASED ON THE THIRD MOMENT =      0.221

 KURTOSIS
      BASED ON THE FOURTH MOMENT =    -0.663


  SCORE INTERVAL      MID POINT  FREQUENCY  PERCENT  CUMULATIVE  HISTOGRAM  X=  0.120
                                                       PERCENT

  1.500  -   3.500     2.500        2.       7.407      7.407    XXXXXXXXXXXXXXXX
  3.500  -   5.500     4.500        2.       7.407     14.815    XXXXXXXXXXXXXXXX
  5.500  -   7.500     6.500        4.      14.815     29.630    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  7.500  -   9.500     8.500        1.       3.704     33.333    XXXXXXXX
  9.500  -  11.500    10.500        4.      14.815     48.148    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 11.500  -  13.500    12.500        4.      14.815     62.963    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 13.500  -  15.500    14.500        6.      22.222     85.185    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 15.500  -  17.500    16.500        0.       0.0       85.185
 17.500  -  19.500    18.500        2.       7.407     92.593    XXXXXXXXXXXXXXXX
 19.500  -  21.500    20.500        1.       3.704     96.296    XXXXXXXX
 21.500  -  23.500    22.500        1.       3.704    100.000    XXXXXXXX
```

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Diver Performance and the Effects of Cold

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The capability of divers was tested by a test battery composed of tests of tactile sensitivity, grip strength, manual dexterity, tracking, assembly of a structure by groups, mental arithmetic, symbol processing, simple problem solving and memory. At a diving tower and a flooded quarry, test data were collected for performance on dry land (control) and at water temperatures between 44° and 72° F. A limited sample of post-dive urine temperatures and skin temperatures were recorded. Divers wore a complete 3/16" wet suit, except that, during the tests, the hands were bare. The results show: hand impairment—losses in tactile sensitivity, grip strength and manual movement; the losses were proportional to degree of cold and exposure time; the losses follow a similar course to skin temperature decrease and hence are considered due mainly to peripheral physiological attenuations; psychomotor impairment—losses in manual dexterity, tracking and group assembly were proportionate to water temperature; mental impairment—losses in mental capability occurred in those cases where the task required intense attention and involved considerable short-term memory; "blocking" effects occurred at the lower temperatures. The causes of the losses in capability are discussed in terms of peripheral and central impairments, in terms of "water" effects and "cold" effects, and in terms of a hypothesis that immersion in cold water serves to distract the diver. Some practical and theoretical implications of the study are reviewed.

INTRODUCTION

With the growth of diving for military, commercial and scientific purposes, there has developed a growing need for data on the work effectiveness of divers and for data to guide the design and development of man/machine diving systems. Now that life support systems can place a diver down to 600 feet or more for extended periods with safety, it has become important to discover what the diver is capable of doing and how and why he is handicapped in the underwater environment.

Some indications are that the diver is severely handicapped. Mosby (1967) gives his opinion that divers are only about 15% as work effective as men on dry land. There have been attempts to substitute robot systems for human divers. Interestingly, these attempts have not met with great success due, apparently, to the man's not being at the work site. Remote orientation of a TV camera, for example, can be very difficult to accomplish. However, many jobs are being done by divers and providing diving services is a flourishing industry. Nevertheless, many problems remain. There seems to be general agreement that the capability range of diving operations and their cost-effectiveness are undesirably low.

Previous reports (Bowen, Andersen & Promisel, 1966; Pauli and Clapper, 1967) describe diver performance as witnessed during the Sealab II experiment. A more recent paper (Bowen, 1968) analyzes the overall nature of the stresses and impediments imposed upon the diver. These and other reports make clear that a man enters a different and generally adverse environment when he submerges and that his performance capability is constrained, changed and/or depleted in varying degree, depending upon the particular man, the task he is attempting, his equipment and the particular state of the ocean and ocean floor about him.

For the studies described below, the parameter of cold was chosen as the major environmental stress. Nearly all water likely to be dived in for work purposes is cold; that is, it occasions a heat drain away from the body and acts as a heat sink. Typical continental shelf temperatures, where most diving takes place, are in the range of 45° to 55° F., and may average about 50° F., or less. Cold is, therefore, nearly always present, constituting a major adversary. Recently, various heated diving suits have been developed and used in practice. Frey (1967) has reviewed some aspects of the present state-of-the-art. In their current stage of development, heated suits cannot be considered as either thoroughly reliable or available for all diving tasks; furthermore, they pose various problems in terms of complexity, diver maneuverability and mobility, which must be traded off against keeping the diver warm. For purposes of future development, one would wish to know how warm a diver should be kept to assure any given level of work capability and/or psychological function, and to resolve such trade-offs as the benefit of heating the extremities only rather than the whole body.

While the effect of cold on divers was the primary orientation of the study, no less important was examination of divers' capability in warm water. Firstly, and from a methodological viewpoint, the effects of cold can be studied only against the baseline of diver performance in warm water, which, in turn, takes on additional meaning against the baseline of dry-land performance. Secondly, entry into water puts a man in a non-normal environment; one for which he did not evolve and to which he is not specifically adapted in a biological sense.

The primary physical characteristics of water that affect man and that differ from the terrestial environment are, as well as its thermal conditions, its buoyancy, its viscous resistance and its restriction of visibility. A diver is approximately neutrally buoyant (generally he is rigged to be somewhat negatively buoyant), and is consequently unstable in the water. He is not anchored naturally by gravity, and muscular exertion acts equally upon him and upon the object being acted acted upon. He cannot stay still without anchoring, and if he relaxes, he will tend to float about in a variety of postures. Thus, there is a continuous need to gain and maintain postural stability. Viscous resistance may be described as an "energy sink." Water is 82 times more viscous than air, so any movement requires more force, the amount being dependent upon the velocity and drag characteristics of the members in motion. Visibility is restricted by the presence of particulate matter which diffuses and absorbs light. At shallow depths in daytime, illumination is generally sufficient to make near objects easily visible; it is predominantly the visibility range that is changed.

There are a number of other factors that impose some "burden" upon the diver. Vision is restricted through the face mask (Weltman, Christianson and Egstrom, 1965) objects are enlarged and depth perception and perception of relative size are disturbed (Ross, 1965). Communication by speech, in our case, was not possible on the diver's part. (While speech communication systems exist, the fluency and intelligibility of spoken communication is never as good as on dry land, and, under many operational conditions may be very poor or impossible.) The personal equipment of the diver encumbers him; the suit restricts limb motions and flexion and the tank is an off-centered mass that disturbs the individual's normal stability whenever an accelerative body movement is made.

Among the many other factors that may burden the diver is the presence of hazard. Any dive introduces a level of risk greater than is normally encountered in everyday life. The diver must always be prepared to take quick emergency action, since any one of several contingencies may occur; some of them constitute immediate threats to survival, such as gas stoppage. In general, the diver is more immediately and personally responsible for his own survival than is normally the case. This confrontation with reality is inescapable and its potency has been used in clinical procedures. Wiener (1967), in discussing hydropsychotherapy, writes, "There is an autonomy and self-dependency in water that is unmatched on land, for one must assume responsibility for his own safety and survival." The inherent hazard for a human in water forces a man/environment relationship that differs from that on land. While intelligent adaptation to the situation is mandatory, yet the defense of the person is far more dependent on overt motor behaviors than on the more sophisticated intellectual responses which are the normal currency of problem resolution in contemporary society.

There are other rather special conditions that affect the diver. For instance, he may have to contend with dizziness and disorientation induced by entrance of cold water in the outer ear; and, on the social level, he must always be watchful of his companion diver ("buddy"), for whom he is responsible in an emergency.

These various aspects of the diving situation constitute a number of specific burdens upon the diver, as well as some general stress level. The purpose of the experiments to be described was to measure the effect of these various environmental factors on divers' performance under relatively mild conditions. Diving depth was shallow, visibility good and safety assured as far as possible. While the divers were subjected to cold and did in fact become unpleasantly chilled, they knew that the exposure was limited to approximately 30 minutes and that they could at any time choose to discontinue. Operational diving conditions would virtually always be more severe and the results of these studies can therefore be interpreted as conservative estimates of performance decrement.

PURPOSES AND BACKGROUND

The aim of the study was to measure performance under three environmental conditions: dry land, warm water, and cold water conditions. A range of performance variables was selected in order to determine any differential effects between type of performance and environmental conditions. The functions tested were:

Sensory Function
 tactile sensitivity of the fingers
Motor Function
 grip strength
Psychomotor Functions
 manual movement of objects
 manual dexterity
 two-hand coordinated tracking
 group assembly of a structure
Metal Functions
 mental arithmetic
 symbol processing
 simple problem-solving
 short-term tasks
Multiple Task
two-hand coordinated tracking plus
 vigilance for specified auditory signal

To provide an estimate of body core temperature change, adequate samples of pre- and post-dive urine temperatures were taken. In addition, an attempt was made to record skin temperatures and heart action. In the event, due to equipment difficulties, two recordings of skin temperatures for the cold water condition and one recording of EKG for the cold water condition were accomplished. Divers were measured to provide an estimate of body fat fraction. Each diver completed a debriefing form giving his subjective impression of each test dive.

In this manner, the tests aimed to give an account of the impact of the water on the diver and to begin to diagnose the differential effects the water environment may have on man. Each test was chosen as being representative of functions that may be thought of as fairly distinct from one another, of functions likely to be effected by the water environment, and of functions which, in one form or another, are required activities in most work diving operations.

The general purpose of the study was to add to our understanding of the effects of cold-water immersion on human function. Much of the research on cold-water immersion has not been oriented toward performance; thus, the literature on survivability is almost entirely physiologically oriented and deals with much more extreme body states than are contemplated as possible working conditions.

For the most part, the effects of cold have been studied when men have been exposed to cold air. A recent and thorough review (Fox, 1967) on human performance in the cold does not mention a single case of full-body immersion in cold water; with one known exception (Baddeley, 1966; see below), experimenters have not gone beyond immersion of the hands in cold water.

Cold air studies have shown that when hand skin temperature falls below about 55° F., even when the body is kept warm, manual performance is impaired. The body surface may be cooled down to at least 78° F., without further impairment appearing (Gaydos and Dusek, 1958). Lockhart (1966) found that cooling the body surface further, to 69° F., impaired performance even when the hands were kept warm. However, this degree of body cooling with the hands warm produced less impairment than cooling the hands alone to 55° F. When the body surface temperature and hand surface temperature were simultaneously reduced to 69° F. and 55° F., respectively, the greatest impairment occurred. Impairment, at hand surface temperatures of 55° F., tends to increase over the first forty minutes but may not change after that to 60 minutes (Clark, 1961).

These data suggest that when the whole body is cooled, two effects take place. There is a local effect at the periphery, the hand, associated with direct interference effects on the sensory-motor functions, and there is a general and central effect influencing the higher centers which serve to control, direct and coordinate action.

The direct effects on the hand are well established. Cooling the skin impairs tactile sensitivity (Mackworth, 1956; Mills, 1957). Cooling of the deeper tissues, which occurs when exposure is severe, reduces muscle strength (Horvath and Freedman, 1947), slows movements of joints (Hunter, 1957) and reduces the accuracy of placement and movement of the extremities. At low temperatures, synovial fluid that serves as a lubricant for joints becomes more viscous, blood becomes more dense and flows more slowly (even independently of vasoconstriction), and, at temperatures below about 48° F., neural conduction is impaired (Edholm and Burton, 1955).

With regard to more central effects, there is little direct evidence. Baddeley (1966) reports that divers, after diving in seawater at 39° F., suffered an impairment in their ability to judge time, judging a minute to be equal to a longer period of time than they did at normal temperatures. Thus, it is possible that an impaired sense of time might affect the timing of subactivities in a complex task. Certainly a number of the manual tasks that have been performed less well in cold air were relatively complex and involved numerous perceptual and cognitive elements; for example, the tuning and operation of radio and radar equipment (Blair and Gottschalk, 1947), multidimensional tracking (Payne, 1959) and typing (Rohles, 1953). However, no clear distinction can be made between the proportion of the impairment that may have been due to attrition of the hand as opposed to attrition of central psychological capability.

Finally, we may notice that there is evidence suggesting that the reflex physiological responses to cold vary as a function of the individual and his affective state. At initial exposure to cold, vasoconstriction at the periphery occurs, thereby achieving a degree of thermal insulation at the periphery and conserving body heat. When the hand skin temperature falls to about 50° F., or below, a reflex vasodilation may occur which increases and raises skin temperature a few degrees; vasoconstriction followed by vasodilation may continue in an alternating sequence (Rubin, 1957; Endholm and Burton, 1955). The alternating effect is greatest when the body remains warm, and may be suppressed if the body is cooled. Individuals differ in the extent to which they exhibit cold-induced vasodilation; those who delay or tend not to vasodilate in cold appear to be highly aroused individuals in other characteristics. The latency of the response can be lengthened by threats of electric shock or by involving a person in a frustrating experience by means of a "conflict-uncertainty" task (Teichner, 1965). These findings would seem to indicate that persons of a "calm" disposition will be better able to tolerate cold water, and that the anxiety-provoking nature of diving may bring about a lowered tolerance to cold.

Of these various issues, the present studies bear most upon the issue of whether and in what degree and kind there is a central effect following body cooling. Thus, the range of tests covers simple and complex psychomotor tasks and various kinds of mental activities. By comparing the data from the various tests, it was hoped that further clarification of peripheral vs. central consequences of exposure to cold would be elicited.

TEST SITES AND CONDITIONS

Two test sites were used: a water tower and a flooded quarry. The water tower measured 8′ in diameter and 25′ to the water mark. Tests were conducted at the bottom of the tower and could be observed through a window. The quarry provided a relatively large body of water into which a platform was lowered from a derrick. The platform measured 8′ × 8′ at the bottom.

Temperature control of the tower permitted a cold water temperature of 47° F. (±1° F.), and a warm water temperature of 72° F. (±2° F.) Temperature control at the quarry was obtained by changing the depth of the platform; cold water temperature was 44°F. (±1° F.) at about 36′, and warm water temperature was 62° F. (±2° F.) at about 3′, with depth being measured from surface to level of chest.

Except for the group assembly test, which was conducted on a floor area, all tests at both sites were conducted on a table. Two 750-watt underwater lights provided ample illumination. A "Yack-Yack" voice transducer provided clear speech from the topside test conductor to the divers. At the tower, the diver responded by hand signals (observed through the window); at the quarry, the diver activated an electric switch and could respond YES or NO to any question from topside and could indicate the end of a timed test.

Care was taken to ensure diver safety. Since the various precautions effectively removed most of the hazards of diving (it may be suspected that perceived hazard will interact with diver performance), the safety precautions will be described briefly.

All equipment was routinely checked before a dive. In addition to a standard full-body wet suit, each subject wore a diver's lifejacket. The SCUBA regulators were equipped with pressure gauges enabling the diver to read remaining air pressure. Subjects dove in pairs, with pairings kept as constant as possible, and agreed on and practiced buddy-breathing techniques; if a diver dove alone, a safety diver, in a ready-to-go state, was either on the surface platform or in the water at the surface. Diving depth for performing the tests, normally did not exceed 32′, and never exceeded 36′ to the chest; a single test dive never exceeded 45 minutes in length, hence no compression penalty was ever incurred. A tank, with a regulator ready to breathe from, was strapped to the underwater platform, within an arm's reach of the test divers. There were two emergency signals. An inflated, highly buoyant tube was attached by a quick-release knot to the platform. A positive pull would release it to float to the surface. Second, the response switches on the worktable could both be placed in a locked position, uncancellable from topside. Placing them in a locked position caused a buzzer and two lights to come on and stay on at the surface control station in front of the test conductor. Divers were always in the vicinity of the conductor at the surface and could be available within a minute or so to undertake emergency action in the water. Only one incident ever occurred, when the second stage of a single-hose regulator failed. The diver happened to be alone on the platform; he breathed from the safety tank and was joined in less than a minute by his safety diver. They buddy-breathed to the surface.

The diving conditions were extremely safe; much safer in fact than would ever be the normal case in any operational dive.

THE TESTS

Tactile Sensitivity: "V" Test

A version of the Mackworth "V" test (Mackworth, 1953) was used. Two upright straight edges were clamped together to form a shallow V. Two divers cooperated in measuring each other's thresholds. The end-pad of the right-hand digit finger was successively placed on the V and, by a process of bracketing, a threshold for two-point sensitivity was established.

Grip Strength

A standard hand dynamometer was used. The subject grasped the instrument and made a single maximum closure of his hand.

Manual Movement: Pegs and Ring Test

An upright board had 12 pegs let into it in a 4 × 3 pattern on 5″ centers. An upright peg at the bottom of the board had twelve 3″ diameter rings on it. The subject's task was to take each ring in turn and place it on a peg and then remove each ring in turn back to the starting peg. Performance was with one hand and the score was the time required to complete the task.

Manual Dexterity: Screw Plate Test

A version of the Baddeley screw plate test (Baddeley, 1965, 1966) was used. An upright 6″ × 6″ plate had 16 holes drilled in it in a 4 × 4 pattern on 1-3/8″ centers. Eight nuts and bolts were located in one half of the grid. The bolts were 3/4″ long and 1/8″ in diameter, with round heads 1/4″ in diameter and 1/8″ high; the nuts were hexagonal, 3/8″ in diameter and 3/32″

high; the thread was 24 turns to the inch. The subject's task was to move the eight nuts and bolts to the other eight holes in the grid as quickly as possible without dropping them. Score was in terms of time taken. Any drops or fumbles were to be noted; however, after initial practice, none occurred.

Tracking: Two-Hand Tracking Test

The subject moved a peg mechanically along a a twisting track by appropriate rotation of two knobs which moved the peg in the X and Y coordinates. The time to move the peg along the length of the track was recorded. As soon as the peg reached one end of the track, the subject reversed direction and moved the peg to the other end. A test lasted for five minutes and scoring was in terms of the times taken to complete excursions along the track.

Group Assembly

The group assembly task required a group of men (groups of three and groups of four men were used) to cooperate in assembling a structure. A diagram illustrated the complete structure, which was completely disassembled into its individual components at the start of the test. The components included various lengths of 1/2″ tubing and various kinds of connecting units; the structure was assembled by screwing the components together. Performance was scored in terms of time to assemble, and a rating was awarded according to the firmness and symmetry of the structure when it had been assembled.

Mental Arithmetic Test

This test required the addition and subtraction of three-digit numbers in the form:

$$\begin{array}{r} 789 \\ +\ 123 \\ \hline -\ 456 \\ \hline \\ \hline \end{array}$$

The subject did as many problems as possible in three minutes. Problems were printed on a plastic sheet and the subject wrote on the sheet in grease pencil.

Symbol Processing

This test required a series of operations to be performed on symbolic material. The steps in the series for any one problem were:

- Subject read an entry which listed in sequence a code number and four colors
- By entering a 10 × 10 matrix (10 colors and 10 digits) and utilizing the code number and each color in turn, he found a numerical value for each color
- Subject read a "problem" number, and found the specified "problem" from an array of problems.
- The "problem" provided four numbers in sequence; the subject paired each of these with the previously ascertained numerical values of each of the four colors; he multiplied each pair and summed the products to obtain the answer.
- Subject indicated the sum obtained by checking a number in an answer column with a grease pencil.

Scoring was in terms of time required to complete four problems and number of problems correct.

Simple Problem Solving: Set Exceptions Test

Each problem was in the following form:

70 105 10 42 21

The task was to discover the one number which does not have a common denominator with the other four and to check it with a grease pencil. The possible common denominators for four or fewer of the numbers were 2, 3, 5, 7, and 11. In the example above, the answer is 10, the other four numbers being divisible by 7; also, three of the numbers are divisible by 2, another three by 3, and a third three by 5. All problems were constructed on this arithmetical basis. The subject did as many problems as he could in three minutes; scoring was in terms of number attempted, number correct and number omitted from the sequence.

Short-Term Memory: Clock Test

A panel displayed eight clock faces in two rows of four with movable hour and minute hands. Predetermined times were put on the clocks at random, with the restriction that the minute hand be put only at 15, 30 or 45 minutes past the hour. The subject inspected the board for one minute, waited 30 seconds without seeing the board, and then recorded his recall during the next minute by marking with a grease pencil hour and minute hands on a similarly laid out board. The responses were scored in terms of the number of recalls attempted and the ratio of number correct to number attempted.

Multiple Task: Tracking and Audio Vigilance

The tracking test as described above was used. In addition, the subject listened to a series of two-digit numbers occurring in random sequence. In the ten-minute test run, certain numbers were repeated in immediate succession. In a first version of the test used at the tower, the numbers were spoken at intervals of 1.7 seconds, and 18 of the numbers were repeated. In a second version of the test, used at the quarry, the numbers were spoken at intervals of five seconds, and 10 of the numbers were repeated. Various difficulties associated with listening in the water prompted the change to a slower rate of presentation. Scoring of the tracking task was as before; the vigilance test was scored in terms of number of signals missed.

TEST PROCEDURES

On entry into the water, each subject wore a complete 3/16″ neoprene wet suit, consisting of hood, jacket, trousers, gloves, bootees, mask, life jacket and weight belt. His breathing equipment was a tank and regulator.

For the main experiments the procedure was as follows. After "splash-in" the divers positioned themselves at the underwater test station. Usually, they would be settled and prepared to start the tests within three minutes. At 2-3/4 minutes, or as soon thereafter as the divers were ready, they were instructed to remove their gloves. This "gloves-off" time was taken as the start point for purposes of recording exposure periods. The test conductor then gave appropriate instructions with respect to starting and stopping each phase of the test schedule. The basic form of the test schedule may be represented as follows:

	Tests		*Tests*
Diver 1	A B C	mid-point	B C A
Diver 2	A C B	mid-point	C B A

where, for example, a group of tests was: Test A, Grip Strength; Test B, Pegs and Rings; Test C, Set Exceptions. Total time for the sequence averaged 30.5 minutes; maximum variation was plus 7 and minus 3 minutes. A detailed time record was made for each man so that the cumulative time from "splash-in" and from "gloves-off" was documented precisely. Exposure time from the midpoint of each individual test for each person was recorded.

Prior practice on each of the tests was afforded the divers on an unlimited basis and no exact record was kept of practice times. It is noted that the various tests that might be specifically learned (i.e., the arithmetic, symbol processing, set-exceptions and audio-vigilance tests) were produced in numerous versions and none of the subjects reported that they recognized specific test items. After this practice, dry-land trials were conducted and dry-land control data were accepted when it was apparent that test-re-test scores showed no consistent signs that learning was still taking place and when the individuals felt that they had thoroughly mastered the techniques required to perform the various tests. However, it is probable that some learning and adaptation to performing the tests in the water occurred during the test trials.

In the case of the group assembly test, assembly was demonstrated to the subjects and pointers to efficient assembly were given. Dry-land practice sessions were then afforded until two assemblies in sequence were completed in essentially the same time. This was followed by dry-land assemblies when the subjects were prohibited from speaking; this dry-land test trial was intended to simulate the voiceless underwater condition.

Tests were performed by each subject under the warm water and under the cold water conditions. Sequence of testing was counterbalanced across subjects. After each water trial, each subject debriefed himself by completing a questionnaire and writing free comment. He recounted his reaction to the test situation in terms of discomfort, feelings of coldness, etc. During the quarry trials, subjects urinated into a small vacuum flask after emerging from the water and a temperature reading was taken. Control urine temperature records were obtained when the subject was in a normal state during the day.

While the daily schedule was not absolutely set, the pattern adhered to was that any given diver dove once in the morning and once in the afternoon. A minimum of two hours elapsed between dives. After a cold water dive, divers found that it took about two hours to feel normal again, even with the help of hot food and drink, a hot shower (at the diving tower) and a hot-room where they could rest and often slept.

The series of tests started with a preliminary experiment at the quarry site where test diving procedures and equipment were developed and data was collected on the Screw Plate and "V" tests over a range of water temperatures. Next, a group of test trials was conducted in the water tower and, later, a second group of test trials was conducted at the quarry. For identification these are called Preliminary Trials, Tower Trials, and Quarry Trials.

SUBJECTS

Sixteen subjects were used in all. However, a difficulty of the study was the uneven availability of the subjects for participation in the tests. The actual participation was as follows.

Preliminary Trials

Four subjects provided data (Subjects A, B, C, and D). It is noted that two other subjects were dropped during the preliminary trials due to incomplete and/or atypical results: These two subjects experienced a number of aborted runs, suffered considerable personal discomfort, and were subject to uncontrollable shivering, "the shakes," at the colder temperatures. This point requires notice because the other subjects could tolerate the conditions and hence are a selected group.

Tower Trials

Five subjects provided data (Subjects A, E, F, G, and H).

Quarry Trials

Eleven subjects provided data (Subjects A, E, F, G, H, I, J, K, L, M, and N). Of these, six subjects, E, F, G, H, I, J, were intended to be the main working group, undertaking all tests systematically. However, Subject J developed an ear infection after he had completed one-third of his trials, and Subject A substituted for him. This action preserved the requirement that divers dive in pairs; however, only limited data were collected on Subjects A and J for the quarry trials.

Divers A through J were employees of Dunlap and Associates, Inc. Divers K, L, M, and N joined the quarry trials for four days and performed the Group Assembly Test and provided limited additional data on the Grip Strength, Pegs and Rings and Set Exceptions test. Diver N dropped out after two days, due to an ear infection. It is noted here, for the record, that Subject A was the author and principal investigator of the studies. While it may be considered less than desirable for the experimenter to serve as a subject, the need in these studies to maintain a reasonable *N* in the subject groups, combined with the need to develop test devices and procedures from personal experience, prompted the decision to suspend an otherwise good experimental practice.

Each diver subject had passed an accredited SCUBA diving course. Experience in diving ranged from six weeks to ten years.

DATA TREATMENT

Two sets of data were established for each test. First, the raw scores across subjects were compiled for each test condition and for the two lengths of exposure; exposure periods are termed "short" when less than 15 minutes, and "long" when greater than 15 minutes. Second, deviational scores were established for each subject and for each test by finding the difference between the dry-land control score and the water condition scores across the same conditions as above. Appropriate analyses of variance were run for each test on these two sets of scores. In no case was it found that the two analyses yielded different statistical inferences with respect to changes occurring as a function of the test conditions or of exposure time. The inference may be drawn that subject differences in absolute level of performance did not interact with the effects due to test conditions sufficiently to alter the influence of the test conditions on performance. Hence, all the data reported are in raw score form.

Wherever possible, the data from the tower trials and the quarry trials were combined. Subjects A, E, F, G, and H performed at both locations. The tower trials covered the conditions of dry land, 72° F., in water, and 47° F., in water; the quarry trials covered the conditions of dry land, 62° F., in water and 47° F., in water. Hence, data for the dry land and 47° F., in water were combined directly. However, before combination was undertaken, the two sets of scores were tested for differences and combined scores are reported only where there were no statistical differences in the scores for these two conditions obtained from the different sites. In all other cases, the data are reported for all the subjects who participated in the test at either site.

Throughout the statistical treatment, a conservative course was taken whenever a choice was presented. For example, the number of acceptable runs made by different subjects for any one test/condition combination varied from one to eight. Many practical circumstances militated against collecting an even amount of data from each subject. Therefore, the course followed was that of taking an average single score for each subject/test/condition combination. Secondly, in interpreting the F ratios of the analyses of variance performed on each test data set, each term was tested against the lowest order interaction term which was significant and contained the term to be tested. These policies were pursued in the belief that in this form of applied psychological research, little is to be gained from chasing down minor effects which, even if veridical, are probably of little consequence and are fairly likely to be spurious consequences of the variability which inevitably exists in field conditions.

Many of the tests showed that subjects performed at different levels. Without claiming that an exhaustive inquiry was made for all the possible correlational terms that might exist between subject parameters and performance, certain likely avenues were explored. Thus, diving experience, age and body fat fraction were compared against water performance, and level of dry-land performance was compared against decrements of performance in the water condition of 47° F., long exposure. The results of the exploration were almost entirely fruitless. In only one case was a rank correlation (r_s) of 0.3 or greater found. It is noted in the data and existed between tactile sensitivity and body fat fraction. It seems probable that the negative results are more a product of the small and relatively homogeneous subject group used than a true reflection of the absence of associations between individual differences and performance capability. From familiarity with diving operations, the author believes that a fruitful line of research would be to determine the properties that are selective of proficient diving performance; evidence supporting this view may be found in Pauli & Clapper (1967).

PRELIMINARY EXPERIMENT

The preliminary experiment was conducted in the quarry on a submersible platform. The Screw Plate Test of manual dexterity and the "V" Test of tactile sensitivity were used. The divers did not wear gloves. After an average of two minutes taken to descend to the platform, in which the divers went through water decreasing in temperature, the average scheduling of testing was:

Screw Plate Test	1st run	2 minutes of exposure at mid-point of test
Screw Plate Test	2nd run	9 minutes of exposure at mid-point of test
Screw Plate Test	3rd run	16 minutes of exposure at mid-point of test
"V" Test		12 minutes of exposure at mid-point of test

Variability in this schedule amounted to about two minutes either way. Divers performed this schedule on dry land and at water temperatures of 70°, 61°, 54°, 49° and 44° F. Four divers completed at least one run at all the conditions; 55%

of the runs were replicated. The temperature conditions were experienced in different random orders by the divers.

For the Screw Plate Test, no differences in performance existed for the three runs; hence the data were compiled and averaged and are reported in Table 1. Mean time of performance increased significantly ($p < .001$) as a function of water temperature.

TABLE 1
Preliminary Experiment, Screw Plate Test: Average Times of Performance for Four Divers Across a Range of Water Temperatures

Condition	*Dry*	*70° F.*	*61° F.*	*54° F.*	*49° F.*	*44° F.*
Performance Time in Seconds	62.8	77.2	82.5	89.0	97.5	108.0

The averaged data for the "V" Test of tactile sensitivity for the same subjects is reported in Table 2. Mean threshhold values increased significantly ($p < .001$) as a function of water temperature.

TABLE 2
Preliminary Experiment, "V" Test of Tactile Sensitivity: Average Thresholds For Four Divers Across a Range of Water Temperatures

Condition	*Dry*	*70° F.*	*61° F.*	*54° F.*	*49° F.*	*44° F.*
Two-Point Threshold in Inches	0.13	0.19	0.19	0.21	0.31	0.33

The data from this preliminary experiment indicates a decrease in manual dexterity and a loss of tactile sensitivity as a function of cold. It should be noted that the warm water condition (70° F.) occasioned a loss in manual dexterity (23%). Water at 70° F., experienced in a wet suit is comfortable and no subjective feeling of chilling was reported by the divers, although some loss in tactile sensitivity was found. On a provisional basis, therefore, there was distinguished a "water" effect; that is, the differences between dry land and warm water performance; and a "cold" effect; that is, the added difference contributed by the cold-water condition.

As there appeared to be an orderly decline in performance as a function of temperature, the further experiments were planned to be undertaken at a cold temperature of from 45° to 50° F., and a warm temperature of at least 60° F., or higher. By this decision, a much wider range of psychological functions could be tested within the effort available for the study.

MAIN EXPERIMENTS

The data described below were collected at the tower and quarry sites and have been consolidated in the manner previously described.

Body Cooling

During the trials at the quarry site, body (urine) temperatures were taken. Water immersion averaged 30-1/2 minutes and urine temperatures were obtained as quickly as possible following completion of the dive. Control, dry land, and urine temperatures were taken on each subject during the working day. The technique, while simple, requires care in implementation and a willingness to discard any suspect readings. Readings were discarded if the subject was unable to urinate within five or so minutes following a dive, if the volume was less than approximately 2/3 pint, or if, inadvertently, water dripped in any volume from the wet suit into the vacuum bottle. It was found that relatively costly medical thermometers varied considerably among themselves; subsequently, only one thermometer was used and previously collected temperature data were discarded. The average readings from seven subjects were:

Dry Land	96.97° F.
After immersion in 62° F.	96.55° F.
After immersion in 47° F.	96.50° F.

The data indicate that central body temperature fell about 1/2° F., after immersion for one-half hour in either 62° or 47° F., water; the greatest average drop for an individual being 1.65° F., and the smallest being zero. The temperature drops were compared to the estimate of body fat fraction available by the skin-fold technique (Consolazio et al., 1963). The technique provided estimates of body fat fraction varying from 9.5%

to 16.9%. Rank correlation between body fat fraction and average post-dive temperature for seven subjects yielded an r_s of +0.82. The data are thus internally consistent, and we may believe that persons will experience a drop in core temperature of up to 1.5° F., averaging approximately 1/2° F., under these conditions, and that the amount of temperature drop is determined to a considerable extent by their body fat fraction.

Successful skin temperature recordings were achieved on only two subjects. However, these were taken during typical test runs at 47° F., and there is no reason to believe that the recordings are not representative. Thermistors were located over the heart, on the inside of the leg about one inch below the crotch, and on the top and center of the instep of the foot. The equipment consisted of transmitting and receiving hydrophones operating at an ultrasonic frequency of 55 k.c. The transmitter, strapped to the diver's tanks, was 3″ in diameter and 12″ in length; accuracy of the device was ±.5° F.

The subjects gave very similar recordings; the average differences between the records for the two subjects were 2.0°, 2.4°, and 4.8° F., for the heart, crotch and foot locations respectively. The averaged skin temperatures are depicted in Figure 1.

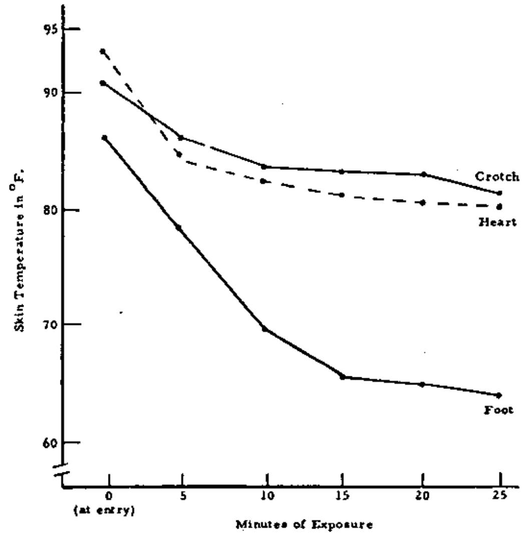

Figure 1. Average skin temperatures for two subjects in 47° F. water.

The data indicate that the skin temperature of the torso region falls some 8° to 10° F., in the first ten minutes, with a very slight further decline thereafter. The skin temperature of the foot decreases some 20° F., in the first 15 minutes, with, again, a very slight subsequent decline. It thus appears that, following the initial thermal loss from the periphery, there is a physiological adjustment which puts the outer layer of the body in a quasistable state. The periods of testing referred to as "Short Exposure" and "Long Exposure" occurred during the first and second 15-minute periods. These thus coincided with an adjustment period when the outer layers were cooling and with a quasi-stable period when the outer layers had cooled and showed only slight further change. In addition, one successful EKG recording was achieved. The diver performed a normal 30-minute trial at 47° F. The protocol of this subject indicates that his normal heart rate of 88 per minute was maintained over the diving period, except that there occurred periodic slowings of the heart down to 68 per minute; slight deviations from the normal EKG were also noted following one minute and 15 minute exposure.

These primary physiological indications describe the degree of thermal stress experienced by the subjects. Additional evidence is provided by the statements of the subjects after emerging from a dive, as entered on two scales referring to the degrees of cold and of pain experienced.

The scale for subjective cold was: 1. Normal; 2. Cool; 3. Slightly Cold; 4. Cold; and 5. Very Cold. The averages of seven subjects for subjective cold feeling expressed after immersion in 62° F., was 2.0; and after 47° F., was 4.3. The scale for pain was: 1. No Pain; 2. Slight Pain; 3. Some Pain; 4. Moderate Pain; 5. Severe Pain. The averages of seven subjects for pain feeling expressed after immersion in 62° F., was 1.9; and after 47° F., was 3.0. At 72° F., no diver reported any significant sense of cooling or of pain. There is, therefore, a clear discrimination in subjective state between the feeling of cold and pain after 30-minute immersion in 72°, 62°, and 47° F. water.

The debriefings of the divers produced the following picture of the experience of cold.

At 47° F., all divers experienced stress. At "splash-in," the water did not feel uncomfortable as it seeped into the wet suit; it was more exhilarating than uncomfortable. However, exposing the hands at "gloves-off" produced definite pain in the hands. Somewhere between 15 and 30 minutes, depending on the person, shivering started; one had much less control over the limbs than normal. As the trial progressed, discomfort, pain and numbness increased.

There was no subjective acclimatization to the cold. In fact, the general trend was to feel the water as colder in the later trials. Divers reported that, as the trial progressed, they increasingly looked toward its end as an escape from increasingly intolerable conditions. Toward the end of some trials, some divers felt symptoms of depersonalization and reported "mind-wandering" and difficulty in concentrating. On emerging from the water, all divers were shivering, some violently. Often there was difficulty in talking and breathing was quick and shallow. It took at least one hour to warm up, and frequently longer. Some divers reported that they experienced minor lapses of memory or concentration for two to three hours after a cold immersion. All divers reported very long sleep hours (10 hours or more) during the nights following the cold trials. No diver reported the difficulty in sleeping which has been noted elsewhere (Raymond,[1] 1967).

Impairment of the Hands

Tactile threshold. Tactile thresholds were measured after an average of 2 minutes, 15 seconds (Short Exposure), and 24 minutes, 48 seconds (Long Exposure) after gloves-off.

TABLE 3

Average Tactile Sensitivity Thresholds in Inches for Five Subjects on Dry Land and for Three Water Temperature Conditions

Condition	*Dry*	*72° F.*	*62° F.*	*47° F.*
Short Exposure	0.21	0.46	0.33	0.60
Long Exposure	0.22	0.41	0.34	0.96

The larger thresholds found in this experiment as compared to those in the preliminary experiment were probably due to the use of a new "V" Test device with slightly different edges to touch. By analysis of variance, it was shown that subjects were different ($p < .05$), that conditions were different ($p < .001$), and that the exposure × conditions interaction was significant at $p < .025$.

The subject difference was examined by correlating body fat rank against tactile threshold rank at 47° F., after long exposure; a correlation r, of $+0.3$ was found, indicating a probable association between body fat fraction and relative preservation of tactile sensitivity.

The data indicate a fairly steady drop of tactile sensitivity with temperature and that long exposure combined with the lowest water temperature produces a dramatic decrease of 336% from the dry land measure.

Grip strength. Grip strength was measured after an average of 2 minutes, 10 seconds (short exposure) and 24 minutes, 20 seconds (long exposure) after gloves-off.

TABLE 4

Average Grip Strength in Kilos for Ten Subjects on Dry Land and for Two Water Temperature Conditions

Condition	*Dry*	*62° F.*	*47° F.*
Short Exposure	55.4	54.1	54.1
Long Exposure	55.4	52.1	47.4

By analysis of variance, it was found that subjects were different ($p < .001$) and that the conditions × exposure interaction was significant at $p < .01$.

The same trends are found in this data as in the data for tactile threshold, although the percentage change from dry land to the long exposure in cold water condition is much less (14%). Grip strength relies upon the large muscles in the arm (for the most part), and these will not have cooled and lost their functionality to the same extent as the tactile sensors in the surface layers of the hand.

The losses in tactile sensitivity and grip strength in the hands demonstrate the assault of low water temperatures in decreasing the effectiveness of the hand as a manipulative device. These measures, closely correlated, it may be assumed, with

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[1] Raymond, L. Personal communication, April, 1967.

physiological events caused by exposure to cold water, show trends similar to those for skin temperature. Exposure to cold over time brings about the lowered functionality.

Impairment in Psychomotor Performance

Pegs and Rings Test. The Pegs and Rings Test was performed after an average of 7 minutes, 30 seconds (short exposure) and 17 minutes, 19 seconds (long exposure) after gloves-off.

TABLE 5
Pegs and Rings Test: Average Performance Time in Seconds for Five Subjects on Dry Land and for Three Water Temperature Conditions

Condition	*Dry*	*72° F.*	*62° F.*	*47° F.*
Short Exposure	26.06	31.20	34.20	34.38
Long Exposure	26.22	33.24	32.78	41.88

Analysis of variance indicates that the combined effect of the conditions and the exposure variables depressed performance (exposure × conditions interaction significant at $p < .05$). The decrement from dry land conditions is 60% for the condition of 47° F., water and long exposure.

Screw Plate Test. The Screw Plate Test was performed after an average of 6 minutes, 17 seconds (short exposure) and 16 minutes, 27 seconds (long exposure). However, there were no statistical differences between the data for short and long exposures.

TABLE 6
Screw Plate Test: Average Performance Time in Seconds for Five Subjects on Dry Land and for Three Water Temperature Conditions

Condition	*Dry*	*72° F.*	*62° F.*	*47° F.*
Performance Time in Seconds	69.44	78.12	84.09	90.36

Analysis of variance indicates that conditions are different at $p < .25$. The data indicate a progressive slowing of performance as a function of water temperature, the loss at the coldest water temperature being 30%.

Two-Hand Tracking Test. The Two-Hand Tracking Test was performed for a five-minute period and occurred after an average of 6 minutes, 34 seconds (short exposure), and 20 minutes, 57 seconds (long exposure). However, there were no statistical differences between the data for short and long exposures.

TABLE 7
Two-Hand Tracking Test: Average Performance Time in Seconds for Completing One Excursion Along Track for Six Subjects for Dry Land and Two Water Temperature Conditions

Condition	*Dry*	*62° F.*	*47° F.*
Mean Time for Track Excursion in Seconds	36.18	44.75	56.10

Analysis of variance indicates that subjects were different ($p < .01$), and that conditions were different ($p < .001$). The data indicate a progressive slowing of performance as a function of water temperature, the loss at the coldest water temperature being 55%.

Group Assembly Test. The most complex manipulative task was the Group Assembly Test. Two teams performed the test, one team of four persons, the other team of four persons except that one series of tests (i.e., for dry, 62° F. water and 47° F., water) was performed by only three persons. No statistical differences were found in the scores of this group compared to the other groups. Average exposure time for the test was 8 minutes, 10 seconds.

TABLE 8
Group Assembly Test: Average Performance Time in Minutes for Completing Assembly for Three Subject Groups for Dry Land and Two Water Temperature Conditions

Condition	*Dry*	*62° F.*	*47° F.*
Assembly Time in Minutes	6.16	7.28	8.67

Analysis of variance indicates that conditions are different ($p < .025$).

Ratings for "goodness" of assembled structure showed no significant differences across the conditions, though there was some tendency for the structures assembled in the water to be of poorer quality.

Summary of Manual Performance Decrements and Discussion

Figure 2 provides a composite picture of the decrements for the various forms of manual performance that were measured.

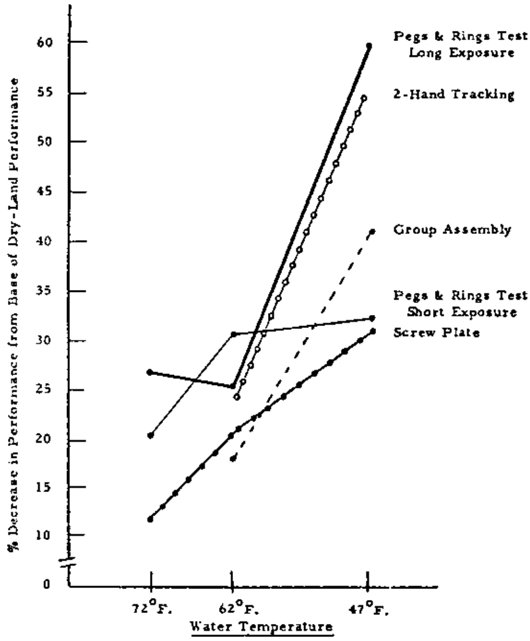

Figure 2. Average percent performance decrements from dry land conditions on four manual performance tests.

The measures of manipulative function form an approximate group indicating losses of about 20% at 72° F.; 25% at 62° F.; and 45% at 47° F. The only substantial exception to the trend is the data for the Pegs and Rings Test for short exposure, which, after an initial loss for warm-water conditions, show little further loss for cold-water conditions. Performance on this test depends primarily on arm and shoulder motions and thus is subserved by relatively massive muscles which will take time to cool. With continued exposure to cold water, performance loss becomes considerable.

An important feature of the data is the loss recorded for performance in water at 72° F. Water at this temperature provides a comfortable thermal environment for the diver; over half an hour, there is no sense of chilling although, in fact, the "V" Test record makes clear that the hands are experiencing changes, probably undergoing peripheral vasoconstriction. Physiological changes in the periphery may or may not be a sufficient explanation of the reduction in performance. Because subjects reported no sense of chill, the decrement has been termed the "water effect" in the belief that the thermal effects play a slight role in comparison to other effects. These other effects include the neutral buoyancy (approximately) of the diver, the viscous resistance of the water to manual motion, the general impairment of sensory feedback affecting in some degree all of the sense, etc. Thermal effects, acting on top of the water effects, are evidenced chiefly by the changes in performance occurring between 62° F., and 47° F. These are termed "cold effects," and may be considered to have pronounced influence on performance at approximately 55° F.

A second feature of the data which may be meaningful is the rank order of the tests in terms of the percentage loss in the cold-water condition. Most loss is suffered by the Pegs and Rings Test. This is the only test dependent on rapid, whole-arm movement and it is thought that the loss sustained is due to the combination of viscous resistance and the lowered muscle tone of the involved muscles. Credibility is lent to this hypothesis by the fact that this was the only test of the group which showed an effect of exposure. While the performance on the other tests showed a downward trend in both the first and second periods, decrement in performance on the Pegs and Rings Test occurred chiefly in the second period of testing. Therefore, it follows more closely the pattern established for the psychophysiological parameters of the hand. Performance on the other tests, by implication, may not be so dependent upon these psychophysiological parameters, and the decrements observed may be attributable to attenuation of "skill" components such as control of movement and the coordination ability required to string together action sequences.

After the Pegs and Rings Test, the rank order of percent loss at 47° F., is: Two-Hand Tracking, Group Assembly, and Screw Plate. Undoubtedly, the Screw Plate Test was the simplest of these three. The Two-Hand Tracking Test required continuous attention and psychomotor coordination; the Group Assembly Test required, in addition to manual dexterity, clear thinking about the sequencing of the task. Although the evidence is no more than suggestive, it is possible to hypothesize that the more complex psychomotor tasks suffer more, due, perhaps, to the hypothesized attenuation of central processes underlying skilled performance.

Direct tests of the hypothesis of the attenuation of central processes were undertaken by the use of a group of mental tests.

Changes in Mental Function

Arithmetic Test. The arithmetic Test was conducted in the diving tower and yielded the data shown in Table 9.

TABLE 9
Mental Arithmetic Test: Averages of Number Attempted and Ratio of Corrects/Attempted for Five Subjects for Dry Land and Two Water Temperature Conditions

Condition	*Dry*	*72° F.*	*47° F.*
Number Attempted	36.1	29.3	24.8
Corrects/Attempted Ratio	.95	.92	.94

Statistically, the decrease in number attempted is significant at $p < .001$; no effects of exposure were found. It is to be noted that there was no evidence of any drop in accuracy as a function of water temperature. The slowing down effect, as demonstrated by the decrease in number attempted as a function of temperature, can be attributed, it is believed, to the problem of writing. The subjects had to write six to eight digits in responding to each item. In the cold condition, in addition to the hand's becoming cold, less motile and a locus of pain, especially when gripping a grease pencil, the grease pencil itself became hard, brittle and difficult to use. The drop in number attempted from dry land to 72° F., conditions was due, presumably, to what we have referred to as the "water effect"; that is, a variety of hindrance factors having most effect, probably, on the motor component of the response.

Symbol Processing Test. With this evidence in hand, the Symbol Processing Test was developed. This test emphasizes mental processing of symbols and the use of immediate memory; the same basic mental skills as are used in mental arithmetic, but the task for the subject was more complex and prolonged. Secondly, the motor response to a question was reduced to the minimum possible.

Exposure times for the test averaged 6 minutes, 26 seconds (short exposure), and 20 minutes, 10 seconds (long exposure). However, no effects of exposure were found in the data.

TABLE 10
Symbol Processing Test: Averages of Performance Time and Ratio of Corrects/Attempted for Six Subjects for Dry Land and Two Water Temperature Conditions

Condition	*Dry*	*62° F.*	*47° F.*
Performance Time in Seconds	229	212	205
Corrects/Attempted Ratio	.64	.56	.57

The data indicate that the subjects were less accurate ($p < .01$) in the water than on dry land. The apparent trend for performing faster in the water is not statistically significant; nevertheless, it does indicate that the motor response did not represent any difficulty. The loss in accuracy, amounting to 12%, indicates a difficulty in this form of mental processing underwater, provided the task is sufficiently difficult.

Set Exceptions Test. The Set Exceptions Test emphasizes problem solving in a simple form. Exposure time averaged 8 minutes, 54 seconds, and 18 minutes, 42 seconds. No effects of exposure were found.

The test data were scored for number attempted, the ratio of corrects/attempted, and the number of omissions. The five subjects of the test differed among themselves in number attempted and the ratio of corrects/attempted, but there were no other statistically different variations. However, in terms of omissions, the data showed a definite and statistically significant trend.

TABLE 11
Set Exceptions Test: Average Number of Omissions per Trial for Five Subjects for Dry Land and Three Water Temperature Conditions

Condition	*Dry*	*72° F.*	*62° F.*	*47° F.*
Average Number of Omissions per Trial	.50	.55	.72	1.00

By X^2 the frequency of omissions increases from the dry land rate at $p < .001$. On the average, 19 test items were attempted during each three-minute test, so that in 47° F., water, a subject would omit about 5% of the items. An omission was counted whenever no answer was provided to an item in the sequence of items. The subjects reported that the omitted questions were attempted and that no answer could be found in a reasonable length of time. They felt "blocked," and, rather than persevere, they went on to the next item.

Clock Test. The Clock Test of short-term memory required the subject to observe and memorize material for a short period. Exposure times averaged 6 minutes, 46 seconds, and 16 minutes, 42 seconds. No effects of exposure were found.

The data from this test were statistically unstable until sufficient practice had been afforded. By the time the test venue had moved to the quarry site, it seemed that the subjects had settled on prefererred observation and memorization techniques; consequently, the data gained stability.

No changes occurred across conditions in terms of number of items for which recalls were attempted. However, the ratio of corrects to attempted did change.

TABLE 12
Clock Test: Average Ratios of Corrects/Attempted for Five Subjects for Dry Land and Two Water Temperature Conditions

Condition	*Dry*	*62° F.*	*47° F.*
Corrects/Attempted Ratio	.79	.62	.61

The loss in the water condition, amounting to 22%, is significant at $p < .025$. The water condition, either at 62° F., or 47° F., made the subjects recall less accurately while attempting to recall the same amount as on dry land.

Multiple Task Test. Before discussing these results, we note an unsuccessful attempt at experimenting with a Multiple Task Test. This test used the Two-Hand tracking Test and a sequence of audio signals. The signals were numbers, a few of which were repeated. The subject had to detect the repeats.

This test was first used in the tower with a signal rate of one signal every 1.7 seconds. While the data indicated a drop in the probability of detection (probabilities of detection for dry, 72° F., and 47° F., conditions were .95, .73 and .57 respectively), the data was suspect due to the fact that the noise of breathing tended to obscure the audio signals. An observer attempted to note whether on each occasion of a double signal the subject was exhaling; produced most of the masking noise. If exhalation coincided with the occurrence of a double signal, the occasion was discounted. However, some uncertainty was felt about how well this observation related to the level of noise in the tank. At the quarry site, the rate of the audio signals was decreased to one every five seconds in an attempt to allow the subject to regulate his breathing so as to have minimum ambient noise coinciding with the signal. This experimental design much lowered the inherent difficulty, or attention-demanding, nature of the task. The result was that there was no change from dry land to the water conditions in the level of detection, which stayed high at an average of .94. It is possible that the data are genuine in the sense that, when a vigilance type task of a multiple task is difficult enough, the conditions of diving affect the detection rate; and, when the task is made less demanding, the conditions of diving do not affect the detection rate. However, the practical difficulties of experimentation cast doubt on any such claim. It was thought that possibly the rate of performance on the Two-Hand Tracking Test might change as a function of whether the secondary vigilance task had also to be accomplished. However, the appropriate comparisons between the scores for the Two-Hand Tracking Test done alone and done with the audio vigilance test showed that performance was not affected either way.

DISCUSSION AND CONCLUSIONS

In considering the data of this study, certain provisos need to be kept in mind. The subject group was small and relatively inexperienced in diving compared to operational divers. However, the safety of the test diving conditions may have encouraged about the same level of *sang froid* that can be observed in operational divers. The great majority of the data is taken from diver-scientists, who formed a relatively homogeneous group, having high motivation for the study and, probably, greater intelligence than the average diver. Of importance, also, was the fact that the subjects did not exercise, except to a minor extent, in doing the tests. There was, therefore, little mechanical stimulation of vascular flow or mechanical energy expenditure stimuli for increased metabolic rate. Operational divers have performed tasks requiring considerable physical exercise in much colder water for much longer periods of time. These divers report such conditions to be tolerable and to have achieved their purposes. However, data concerning skin and body temperatures are not available for these situations. The generality of the findings are, therefore, uncertain, and further studies on experienced operational divers are required.

The results of the study may conveniently be grouped in terms of effects on the periphery, effects on psychomotor skills, and effects on mental processes. Peripheral effects are those associated with lower temperatures at the body surface and on less well protected musculature. With cooling, sensation and strength are considerably impaired. Psychomotor skills are impaired partly as a consequence of peripheral attenuation and partly, it is believed, through some attenuation of central processes underlying skillful activity. Mental performance is impaired provided the tasks are sufficiently demanding in terms of concentration and short-term memory requirements. The data support the hypothesis that cold-water environments, acting upon the individual, are distracting and interfere with the continuity of mental focus.

The data indicate that divers experience two causes of impairment, termed the "water" effect and the "cold" effect. The "water" effect is thought to be due to the several factors, present even in warm water, which burden the diver and claim his attention. Among these are neutral buoyancy, viscosity, reduced sensation, encumbrance by equipment, and the attention to diving procedures necessary to assure personal safety. The "cold" effect is superimposed on the "water" effect and acts both directly, in spoiling psychomotor performance, and, more indirectly, on central processes probably by causing distraction from the task at hand.

Performance which is dependent primarily on integrity at the periphery (tactile sensation, grip strength, simple manual movement) demonstrates impairment as a joint function of water temperature and exposure time. The course of decreased performance follows the measures of skin temperature decrease that were obtained. Performance on tests which involve manual and mental skill does not exhibit this dependence on exposure time. In these tests, if decrement is going to occur, it occurs soon after immersion. This implies that the process of cooling is about as adverse as being cool, at least over the range where average body (urine) temperature changes on the average about 1/2° F., in 30 minutes. This conclusion is taken to support the distraction hypothesis, in that the rather rapid changes of physiological state occurring just after immersion cause considerable discomfort and are not easily excluded from consciousness.

The results have various practical implications. Acceptance of the distraction hypothesis implies that one should select persons who are not overly aroused by the circumstances. The SeaLab II report (Pauli & Clapper, 1967) mentions this point. The distraction potential of the environment is likely to be reduced by training and familiarity with the diving situation. Hence, experienced divers would be expected to show less decrement due to distraction. The evidence of psychomotor loss has implications for human engineering of man-operated equipment; underwater equipment should not require critical dependence on the application of considerable force, on tactile sensation, on speed of operation or on considerable displacement motions. Tasks requiring mental processes should not be made dependent on prolonged undiverted attention or on the accuracy of short-term memory. Alternatively, the individual must be more fully protected and insulated from the impingement of the environment so that his normal, dryland levels of function are preserved.

While heated diving suits will clearly alleviate the behavioral impairments described in this study, it would be optimistic to believe that a diver will regain by this means all his normal dryland capability. The evidence of these studies concerning a "water" effect could be joined to much anecdotal evidence concerning the inefficiency, stupidity and self-endangering activity which divers have exhibited from time to time. To make man truly effective under the sea, we need the thematic development of man/suit, man/tool, and man/machine combinations which will allow the full range of human capability to be deployed in this challenging, though often discomforting, environment.

ACKNOWLEDGEMENTS

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We wish to record our indebtedness to the counsel and enthusiasm of Dr. James W. Miller, Head of the Engineering Psychology Branch. Mr. Alan Slater, of the Philadelphia General Hospital, supplied the equipment and expertise required to record EKG and skin temperatures; Dr. Samuel Bellett, of the same institution, supplied the interpretation of the EKG recording. Mr. George C. Wiswell, Jr., of Marine Contracting, Inc., Southport, Connecticut, advised on diving procedures and made available his company's diving tower facility in which part of the experiments were conducted.

The project would not have been possible without the subject divers, who voluntarily endured the great discomfort of the cold-water conditions in the interests of research. While interest competes with discomfort on the first occasion of becoming really cold, enduring the subsequent trials is a matter of determination; their fortitude should not go unnoticed. The subject divers were: J. Fucigna, B. Stowens, R. Pepler, G. Guinness, A. Hale, J. Roden, J. Hamilton, J. Kowal, R. Warner and S. Truesdale, employees of Dunlap and Associates, Inc., and P. Kramer, J. Starkey, J. Kern and W. Eccles, from the Submarine Explorers Association of Stamford, Connecticut.

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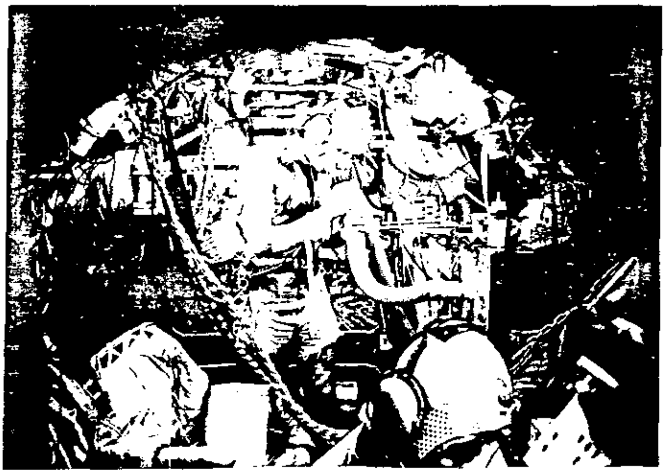
PREDICTIVE STUDIES IV

WORK CAPABILITY AND PHYSIOLOGICAL EFFECTS IN He - O_2 EXCURSIONS TO PRESSURES OF 400-800-1200 AND 1600 FEET OF SEA WATER

A COLLABORATIVE INVESTIGATION

EDITED BY
C.J. LAMBERTSEN, R. GELFAND AND J.M. CLARK



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E-10. Perceptual, Memory, Cognitive and Psychomotor Functions

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It is generally agreed that rapid compression to high pressure with helium-oxygen can produce decrements in human performance, with indications that effects on psychomotor performance are most marked and that recovery may be prompt after compression is completed (4,6,7,16,29). Concurrent observations have included lowered alertness with electroencephalographic changes consistent with that state, fatigue, muscle tremor, fasciculations, and impaired coordination.

The performance experiments conducted in Predictive Studies IV were designed to survey systematically and quantitatively a broad range of perceptual, memory, cognitive and psychomotor effects of rapid compression to pressure equivalents of 400, 800, 1200 and 1600 fsw. Compression rates were selected to elicit, rather than prevent, definite symptoms and effects. Because these performance measurements were made at the same time as other studies of peripheral and central nervous system function and other physiological studies (22) (Sections D and E), the overall design of this study provided the means of comprehensively describing the functional state of individual subjects under different conditions of compression and hydrostatic pressure.

Measurements were made in some subjects both prior to and during periods of light exercise to assess effects of motor stimuli concurrent with compression-pressure effects on performance. Performance and physiological measurements were repeated in measurement modules (Section D) before, during and following changes in exposure conditions to permit

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tracking of the development of and recovery from effects of compression and hydrostatic pressure. Predictive Studies IV also provided an opportunity to assess the usefulness of a computer-controlled system for investigation of human performance under stress (19). It is anticipated that this performance measurement system may provide a means of overcoming limitations in laboratory-to-laboratory comparability of performance test results which currently exist because of the wide variety of tests now in use (3).

METHODS

TESTS, ABILITIES TESTED AND TEST SEQUENCES

Individual performance tests were selected to provide efficient and non-redundant assessment of a range of performance abilities. These tests and abilities are described in discussions concerning factor analytic performance experiments (14,17,19,20,21). From the wide range of human abilities which have been identified in such discussions, abilities were selected which were judged either to be related to effects of the "high pressure nervous syndrome" or to be prominently involved in performance tests included in previous studies of exposure to increased ambient pressure (1,2,4,12,16,29).

The 12 performance tests administered are listed in Table I. Each test was modified from its more conventional form (3,17,20,26,28) to adapt procedures and scoring to the performance test system (19), to reduce administration time and to permit many repetitions of a test to a subject.

Three test sequences, each of three minutes' duration, were composed from subgroups of the 12 performance tests (Table I). The psychomotor test sequence (one reaction time, two dexterity and two tracking tests) and the memory and cognitive test sequence (one cognitive and two memory tests) were administered to the rest subjects. The perceptual and psychomotor test sequence (two speed and two orientation tests) was administered to the exercise subjects.

The brief administration time of individual tests in close succession was required practically by the time limitations imposed by the overall measurement module system of

TABLE I. Design of Performance Experiments

Test Sequence	Test Name	Ability Assumed Tested	Test Time (sec)	Subject Assignment	
				Phase I	Phase II
Psychomotor	One-hand compensatory control test	Manual tracking	45		
	Key insertion test	Finger dexterity	20		
	Visual reaction time test	Reaction time	30	FS	FS
	Wrench and cylinder test	Manual dexterity	40		
	Two-hand compensatory coordination test	Multiple limb coordination	45		
Memory and cognitive	Word-number test	Associative memory	60		
	Arithmetic test	Number facility	60	LJ	MP
	Visual digit span test	Memory span	60		
Perceptual and psychomotor	Choice reaction time test	*Response orientation*	60		
	Number comparison test	Perceptual speed	45	WS CC	GM CC
	Grip speed test	Wrist-finger speed	15		
	Card rotations test	Spatial orientation	60		

tracking time-related changes (Section D). For purposes of performance testing, this three-minute group of tests is considered as a synthetic task (2). This mode of test administration was expected to maintain the motivation of the operationally experienced subjects involved in these studies. In addition, performance on the synthetic task (as opposed to scores for the individual tests) provides a measure of the skills and strategies required to perform complex operational procedures (14,16,18,19).

SUBJECT TRAINING AND ASSIGNMENT

The subjects were trained in each of the three performance test sequences. Initially, each test was performed separately without the time limitations of the actual exposures. Subsequently, groups of tests were practiced as three-minute sequences. Finally, the three-minute performance test sequences were combined with physiological tests in the major measurement modules (Section D). The measurement modules were administered in the dry chamber, both at sea level and during shallow dives, until test scores appeared to reach stable levels.

Each of six subjects was assigned to a two-man team, composed of one rest subject and one exercise subject. Table I describes the pattern according to which each subject performed one of the test sequences throughout one or both phases. In each team, the rest subject performed either the psychomotor test sequence or the memory and cognitive test sequence. The exercise subject performed the perceptual and psychomotor test sequence both prior to and during a six-minute period of light exercise on a bicycle ergometer. The temporal relationships within a measurement module between a performance test sequence and other measurements are shown in Section D.

APPARATUS

The performance testing apparatus was derived from the human test systems of PEMCON (26) and SINDBAD (28). The apparatus was redesigned at this Institute to permit on-line control of test administration and data acquisition and off-line data analysis by a general purpose digital minicomputer. A report on the design criteria of this system has been presented elsewhere (19).

Two performance test stations were used, one for the rest subjects and another for the exercise subjects. At the rest subject station (Figs. 1 and 3), the subject sat in a chair facing a 5-1/2 inch diameter viewport, with a test console mounted on a slide-out table. Test display apparatus inside the pressure chamber included: a 23-cell display-response panel adapted by electronics and computer programming for direct computer control ; a computer-controlled 3-digit numeric display; and a rear projection screen which could be slid in front of the port. This test station could be set up in seconds for either the psychomotor test sequence or the memory and cognitive test sequence. Outside the chamber at the viewport, a computer-controlled, random-access projector and a nine-inch closed circuit television receiver were mounted on separate swing-away supports which allowed each to be presented for visual transmission through the port. The television receiver was used to present tracking tasks generated on the computer's video terminal; the 3-digit display was used to present the visual digit span test; the projector and display-response panel presented all other test stimuli.

STUDIES AT REST

The rest subject's responses, for transmission to the computer, were implemented by two force-operated hand control sticks for tracking tests, and by three response devices fabricated with magnetic cores for use with the display-response panel for all other tests (Fig. 1). Each cell of the display-response panel contained a lamp for display (illumination of selected cells), and a magnetically activated reed switch for response (closure of the reed switch when its cell was entered by a response device). The stylus was used for the memory and cognitive test sequences and for the visual reaction time test of the psychomotor test sequence. The wrench and cylinder device and the key insertion device were used for the other tests of the psychomotor test sequence in conjunction with a template which converted the round apertures of the 10 numeric cells on the display-response panel into alternating square and round apertures. These apertures were sized so that round and square ends of the dexterity devices would fit snugly.

The "on" or "off" state of each lamp and the "open" or "closed" state of each reed switch of the display-response panel were, respectively, controlled by the computer and "read" by the computer. Illumination of a green cell indicated a test sequence was in progress; a red cell was illuminated at other times. A cell marked "RT" and a white cell were used for the visual reaction time test. Ten cells marked 0 to 9 were used by a subject to guide his order of responding or to indicate numeric answers to test items. A cell marked with an asterisk indicated that an answer to a test item had been completed.

STUDIES DURING EXERCISE

At the exercise subject station, the subject sat on a bicycle ergometer also facing a 5-1/2 inch diameter viewport (Fig. 5). The performance test apparatus at this station was limited by the requirement that this subject hold the bicycle ergometer handlebars while pedaling. Accordingly, exercise subjects' responses to test displays presented by a second projector and screen were by means of two grip-operated switches attached to the bicycle ergometer's handlebar grips. One of the four possible response combinations provided by the open and closed positions of the two switches (i.e., both switches closed) indicated the subject was ready for the next test within the test sequence or the next item within a test.

TEST PROCEDURES AND RESULTS

Each performance test sequence included different tests and was administered to different subjects (Table I). Therefore, each sequence is treated as a separate experiment in the following discussion, with a brief description of test procedures followed by the presentation of results. Additional details of procedures (19) and a brief summary of results (18) have been reported elsewhere. An appendix to this section provides in tabular form all of the test scores obtained (Appendix Tables 1-8); scores are also shown in graphic form in Figs. 2,4,6 and 7.

Scores for each test were based both upon counts of responses during the allotted test time and time characteristics of responses with respect to preceding stimuli or responses. The number of responses completed estimates production level; the number of responses correct or the number correct minus number incorrect estimates quality of performance; the number of errors estimates carefulness. The mean of inter-response times or mean reaction time estimates rate or speed of responding; the standard deviation of inter-response times or reaction times estimates stability in rate or speed of responding.

PSYCHOMOTOR TEST SEQUENCE: PROCEDURES

The reaction time test, the two dexterity tests and the two tracking tests which comprise this sequence are described in the order in which they were administered to subject FS in Phases I and II (Table I) at the test station as shown in Fig. 1.

One-Hand Compensatory Control Test

This test was designed to assess the ability of Manual Tracking, which is defined as precise, continuous adjustment of one or more axes of control to follow or to compensate for changes in a target's position, speed and/or acceleration. The subject attempted to keep a moving dot as close as possible to a stationary, centered reference mark. Uncompensated motion of the dot as generated by the computer and viewed on the closed circuit television screen was along a 4-1/2 inch straight line inclined at 45^o of arc from the vertical. For a right-handed subject, the dot moved between the upper right and the lower left quadrants of the display, following a sinusoidal temporal pattern with a frequency of 25.5 cycles/minute. The subject's response was by means of the control stick on the side of his preferred hand.

The error score was computed and expressed separately for the horizontal and vertical axes. During 40 seconds of tracking, approximately 1300 samples of both x-axis and y-axis error voltages were stored in computer memory. Each x-y pair of voltages defined the extent to which the dot

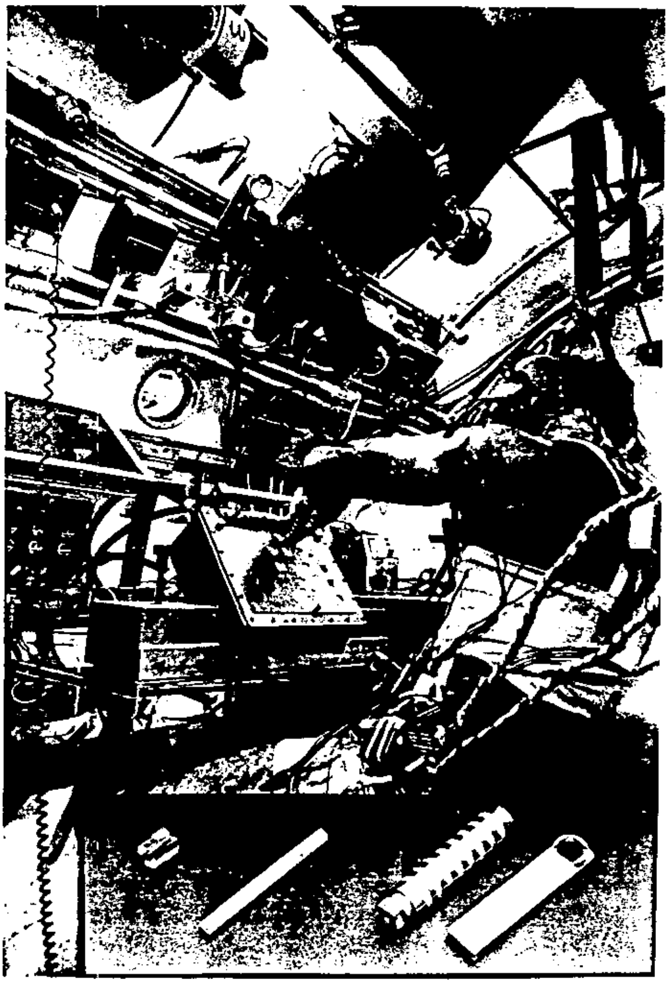

FIG. 1. The rest subject performance test station during administration of the psychomotor test sequence. The response devices used with the display-response panel are shown in the inset.

PSYCHOMOTOR TEST SEQUENCE: RESULTS

Test scores obtained during Phases I and II for subject FS (Table I) are presented graphically in Fig. 2. These must be related to the symptomatic and objective indices of compression effect described in Section E-1, with particular attention to the prominent general malaise experienced on first arrival at the 1200-fsw pressure in Phase II.

Reaction Time Test

Mean reaction time increased during the 80-minute compression from sea level to 800 fsw in Phase I and thereafter did not return to the control level. The test result at 1200 fsw on day 1 of this phase was not graphed because the subject produced only one response even after he was reminded that the test had begun.

Mean reaction time increased during the 50-minute compression to 800 fsw on the first day of Phase II. Performance in this test also decreased after reaching 800 and 1200 fsw, but it returned to the control level by the end of that day. It was at the control level at the start and end of days 2 and 3, although it increased transiently at the start of excursion-decompressions on those days.

Recovery from decrements was rapid and complete in Phase II, but in Phase I both the mean reaction time score and number of responses completed showed sustained decrements during exposure days 1 and 2. Considerable but very brief increases in mean and standard deviation of reaction time prior to the start of compression to 1200 fsw on the first day of each phase suggest that these scores are sensitive to anticipatory effects.

Dexterity Tests

Results for the key insertion test of Finger Dexterity show that performance decrements in number of responses completed did not persist throughout an exposure day except for the first day of Phase I and the first excursion from 1200 to 1600 fsw in Phase II. Decrements occurred in Phase I after compressions to 800 fsw and 1200 fsw, and in Phase II during and after compressions to 800, 1200 and 1600 fsw. The alternative scores appear to be closely associated with the number of responses completed, with the exception of the error score in Phase II. The number of errors

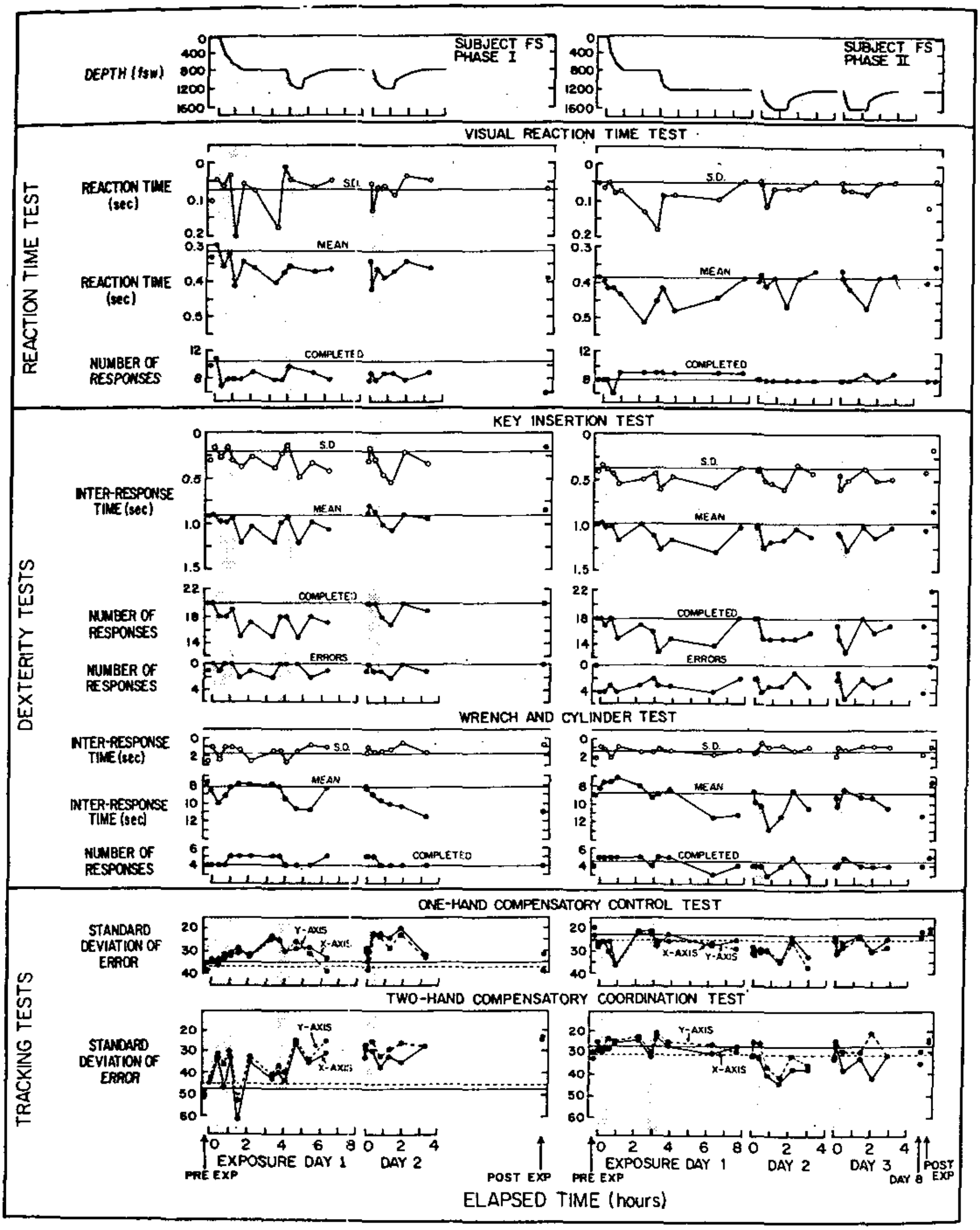

FIG. 2. Psychomotor test sequence results for subject FS in Phases I and II.

throughout that exposure phase are greater than those recorded in Phase I or in pre-exposure and post-exposure measurements.

For the wrench and cylinder test of Manual Dexterity, the number of responses completed in the 40-second test covered so narrow a range as to be insensitive to exposure conditions. In terms of the more sensitive score of mean inter-response time, results were not entirely consistent in that a decrement in performance occurred on the Phase I compression from 1 ata to 800 fsw but not during the faster compression to 800 fsw in Phase II. Mean inter-response time increased markedly during and after compression to 1200 fsw only in Phase I, and during only the first compression to 1600 fsw in Phase II. For the first exposure to a condition, the amount of decrement was apparently related to depth. Recovery appeared to be more rapid with successive exposures. Although recovery was often not complete at the end of a test day, the next exposure day started with performance at the control level.

Tracking Tests

Despite the training which preceded the exposures of Phase I, the scores in both tracking tests continued to improve throughout this phase, stabilizing at the improved level in Phase II. This overall learning trend in the one-hand compensatory control test of Manual Control was overcome in Phase I by an overall performance decrement at the end of each exposure day, perhaps related to fatigue. For the two-hand compensatory coordination test of Multiple Limb Coordination but not for the one-hand test of Manual Control, the learning trend in Phase I appeared to be interrupted by performance decrement following compression from sea level to 800 fsw and, perhaps, from 800 to 1200 fsw. In Phase II, there were decrements in the compensatory tracking scores for the One-Hand Compensatory Control test during compression from sea level to 800 fsw and for the Two-Hand Compensatory Coordination test during excursions from 1200 to 1600 fsw.

Throughout both phases and for both tracking tests, the x-axis and the y-axis error scores were usually closely associated. Exceptions occurred during excursions for the test of Multiple Limb Coordination. During the second excursion in Phase I from 800 fsw to 1200 fsw and during both excursions in Phase II from 1200 fsw to 1600 fsw, the y-axis error score (vertical control with the right-hand joystick) was less affected than was the x-axis score (horizontal control with the left-hand joystick), but they returned to similar values following decompression to saturation pressures.

MEMORY AND COGNITIVE TEST SEQUENCE: PROCEDURES

The two memory tests and the one cognitive test which made up this performance test sequence (Table I and Fig. 3) are described below in the order administered.

Word-Number Test

This paired associates test was included to estimate the ability of Associative Memory, i.e., commission to memory by rote and recall of bits of material, regardless of complexity or meaningfulness. In each test administration the subject was given 30 seconds to memorize the six word-number pairs shown. In each word-number pair a different familiar one-syllable noun was paired with a two-digit number selected randomly from the numbers 10 through 99. When a second response slide carrying only the six words in a different order was shown, the subject used the stylus to indicate (by means of the display-response panel) the two-digit number which had been paired with each word. In Phase I the study slide was shown at the start of the three-minute test sequence and the response slide was shown two minutes later in the last 30 seconds of the sequence. Thus, the subject had to retain the word-number associations while solving arithmetic problems and recalling number series. This interference produced scores so low that the test was rendered insensitive. It was modified in Phase II by presenting the response slide immediately following the study slide.

The conventional score of the number of correct responses was supplemented with scores describing the rate of

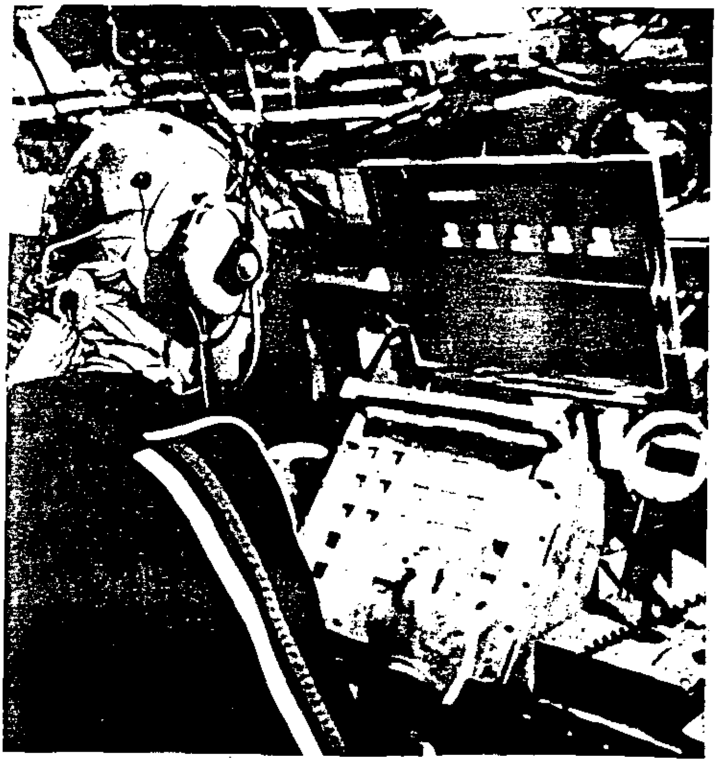

FIG. 3. The rest subject performance test station during administration of the memory and cognitive test sequence.

producing the 12 required responses and the steadiness of responding, as the mean and the standard deviation of inter-response times, respectively.

Arithmetic Test

The Number Facility ability, requiring the rapid mental manipulation of familiar symbols according to simple and overlearned operations, was tested by having the subject solve as many simple addition, subtraction, multiplication and division problems as possible in 60 seconds. Problems were presented by slide projection, with five problems requiring one kind of operation on each slide. The subject indicated the numerical solution to each problem by means of the stylus and the display-response panel. Inter-response time was calculated as the time between two successive solutions.

The scores for this test included the conventional score of the number of correct responses made in the allotted time. In addition, the number of responses completed in the test time, the mean of inter-response times and the standard deviation of inter-response times were also computed.

Visual Digit Span Test

Relatively short-term memory was tested by means of the visual digit span test. The ability of Memory Span may be defined as accurate reproduction of recently presented material. Within each administration of this test, a trial began as a series of one-digit numerals ordered randomly were shown on the three-digit display at the rate of one numeral per second. In Phase I the series length increased from three to nine digits in two-digit steps. In Phase II the series length increased from four to seven digits in one-digit steps. This modification had little effect upon test difficulty and was introduced to avoid ending a 60-second test administration with the presentation of a long digit series to which the subject did not have an opportunity to respond. Each digit series was complete when the digital display showed all zeroes. The subject then attempted to reproduce the numerals in the same order in which they had been presented, using the stylus and the display-response panel.

In conventional administration of a memory span test, the score is the longest series correctly reproduced, with the subject permitted two attempts at a given series length. This scoring method was not compatible with the time limitation of the present testing situation. For this application, each reproduced digit was treated as a separate response and was scored as correct if it were in a sequence of at least three digits reproduced correctly with regard to the numeral indicated and the position. This score of number of correct responses was supplemented with the score of number of responses completed. Within a reproduced digit series, inter-response time was calculated between successive digits, regardless of correctness. The mean and the standard deviation of these inter-response times were calculated for each administration of the test.

MEMORY AND COGNITIVE TEST SEQUENCE: RESULTS

The scores obtained for the two memory tests and the cognitive test in this test sequence are presented in Fig. 4 for subject LJ in Phase I and for subject MP in Phase II.

Memory Tests

Scores were consistently low in the word-number test of Associative Memory in Phase I, probably due to the two-minute delay between the presentation of the study and the response slides. Over this narrow range of scores, performance was usually at a lower level during exposures to pressure than at 1 ata. A broader range of scores was produced in Phase II for a different subject and with the test modified so that the response slide was presented immediately after the study slide. In Phase II the score of number of correct responses decreased very early in compression to 800 fsw, in compression to 1200 fsw on day 1 and during excursions to 1600 fsw on days 2 and 3. Scores at the beginning and end of each exposure day were near the control level. The scores of mean and standard deviation

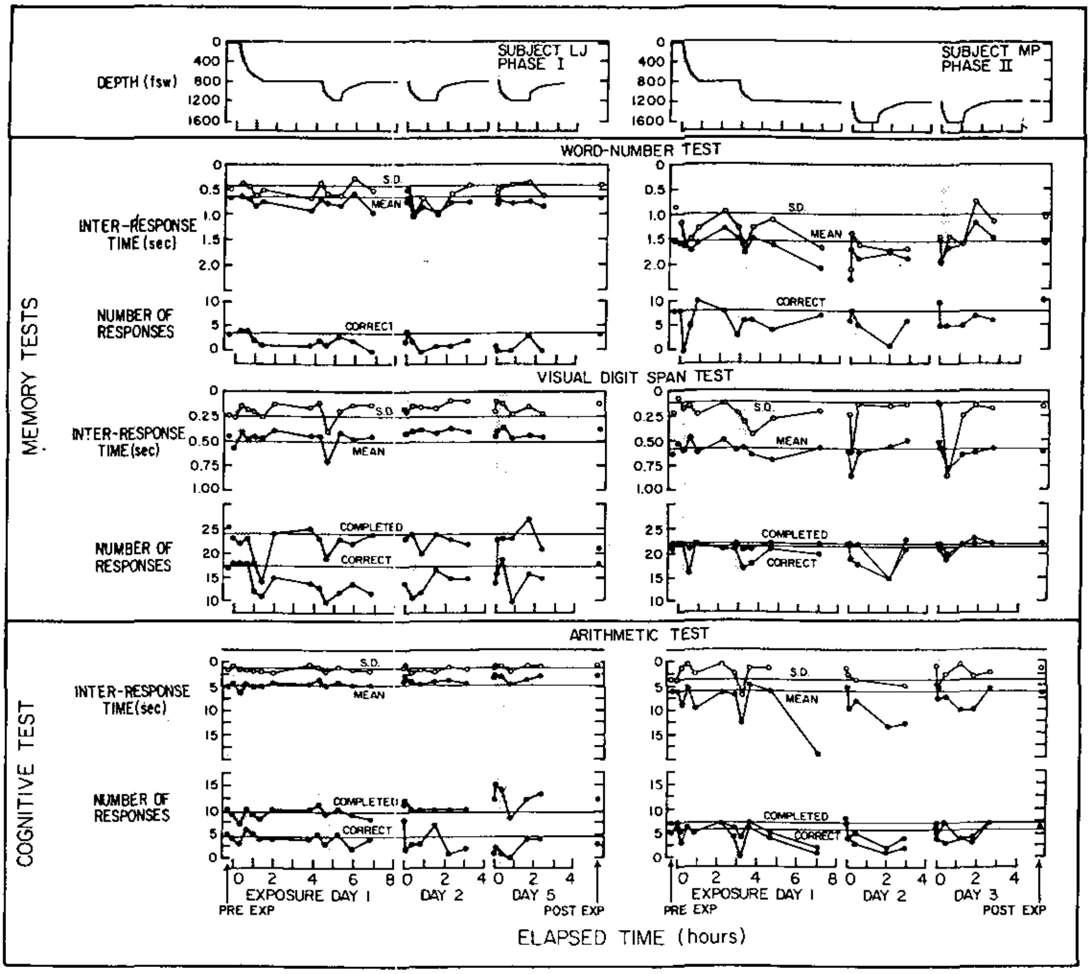

FIG. 4. Memory and cognitive test sequence results for subject LJ in Phase I and for subject MP in Phase II.

of inter-response time indicate similar relationships to exposure in Phase I, but in Phase II both mean and standard deviation of inter-response time increased during day 1, remained high on day 2, and returned to control levels by the end of day 3.

For the visual digit span test of Memory Span both subject LJ in Phase I and subject MP in Phase II usually showed performance decrements during or immediately after compression. For subject MP in Phase II the time required to recover from performance decrement increased with the first excursion to 1600 fsw as compared with compression to 1200 fsw, but recovery was more rapid for the second 1200-to-1600-fsw excursion than for the first. Similar relationships were not apparent in Phase I for LJ, who began and ended exposure days with the score of number of correct responses below the initial control level.

The two subjects also differed in the relationships between their scores based on counts of responses and scores based on inter-response times. For subject LJ the scores concerning number of responses vary with exposure condition throughout Phase I while his scores based on time characteristics of responding remain relatively constant throughout the excursions on exposure days 2 and 5. For subject MP, time-related scores follow a pattern similar to number-related scores throughout Phase II, with the exception that the standard deviation of inter-response times is more affected by compression than are other scores. For this subject the adaptation to successive excursions to 1600 fsw is evident in the scores of number of responses completed and number of responses correct but is not evident in the mean and the standard deviation of inter-response times.

Cognitive Test

All scores of the arithmetic test of Number Facility showed little change with exposure condition in Phase I. Although the score of number of correct responses did vary from the control level on days 2 and 5, the effects of compression rate, pressure and excursions were unclear because scores were not near the control level at the beginning of these exposure days. However, the pattern of the relationship between the number of correct responses and the number of responses completed on day 5 is the same for this test as for the visual digit span test. Both tests suggest that the subject began this day at a lowered performance level and increased his response production in an apparent attempt to compensate for this lower level.

As for the other tests in this test sequence, the arithmetic test scores for subject MP in Phase II are clearer than are the scores for subject LJ in Phase I, because MP typically began test days with scores near their respective control levels. This subject demonstrated cognitive performance decrement during compressions from 800 fsw to 1200 fsw, and from 1200 fsw to 1600 fsw. Performance recovery appeared to be slower as pressure increased but to be more rapid after the second compression to 1600 fsw on day 3 than on the first such compression on day 2. Decrement late in day 1 while at 1200 fsw may have been due to fatigue.

PERCEPTUAL AND PSYCHOMOTOR TEST SEQUENCE: PROCEDURES

This performance test sequence was administered to exercise subjects at the test station illustrated in Fig. 5. The sequence (Table I) consisted of two speed tests (number comparison test and grip speed test) and two orientation tests (card rotations test and choice reaction time test). In each pair of tests, the first emphasizes perceptual function while the second emphasizes psychomotor function. In each measurement module, this sequence was first administered prior to exercise and again six minutes later during the second half of a six-minute period of light bicycle ergometer exercise. Each of the four tests which comprise this three-minute test sequence are described below in the order in which the tests were administered.

Choice Reaction Time Test

This test was developed to measure the ability of Response Orientation--rapid choice from two or more response alternatives of the response appropriate to each of two or more alternative stimulus situations. For each trial, one of three simple figures selected at random was presented to the subject after a delay which varied randomly from 1.00 to 3.00 seconds. Using the grip-operated switches, the

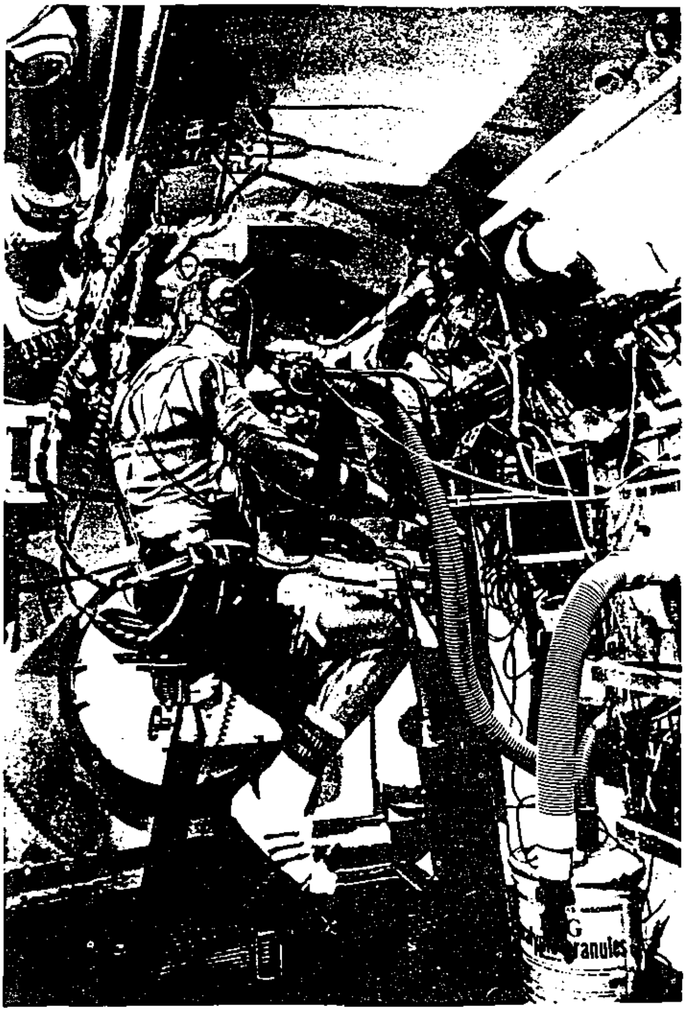

FIG. 5. The exercise subject performance test station during administration of the perceptual and psychomotor test sequence.

subject was instructed to respond as rapidly as possible with one of three possible responses associated with the presented figure. When the correct response was made, the stimulus figure was removed. When the subject indicated that he was ready for the next trial by closing both grip-operated switches, another trial began. Trials continued in this manner for 60 seconds.

For each trial, a reaction time score was calculated from the onset of the stimulus to the beginning of the subject's correct response. The mean of these reaction times for all trials completed in the test time was taken as the conventional score. The standard deviation of reaction times was calculated as an estimate of blocking. The number of responses completed and the number of incorrect responses made during the test time were also recorded.

Number Comparison Test

The number comparison test was administered to the exercise subjects as an estimate of the ability of Perceptual Speed--rapid identification, comparison or classification of familiar symbols according to simple criteria. Each slide presented to a subject carried six pairs of numbers. For each number pair, the subject was instructed to open the right-hand grip-operated switch if the two numbers were the same and to open the left-hand switch if the two numbers were different. The numbers varied only in one digit if they were intended to be different. Number length varied from 3 to 13 digits. The subject was also instructed to complete as many responses as possible in the 45 seconds allotted.

The more conventional score of the number of correct responses minus the number of incorrect responses was supplemented with scores of the number of responses completed, the number correct, mean inter-response time and standard deviation of inter-response time.

Grip Speed Test

To assess the ability of Wrist-Finger Speed (rapid repetition of simple wrist, hand and/or finger movements), the subject alternately grasped and released the switch on the side of his preferred hand, working as rapidly as possible for 15 seconds. A slide carrying the test name was shown to the subject for this time period to cue the subject when to start and stop this test.

Response speed was scored by mean inter-response time; the standard deviation of inter-response time was also computed.

Card Rotations Test

The fourth test in the perceptual and psychomotor test sequence evaluated the ability of Spatial Orientation, i.e., rapid perception of the position or configuration of figures in space with respect to the subject. Each slide presented to the subject included a reference figure and five test figures. The subject was instructed to indicate for each test figure whether the figure was the same as or different from the reference. A test figure was considered the same as the reference if it were rotated but not inverted (mirror image). If two figures were the same, the right-hand switch was opened; if different, the left-hand switch was opened.

Scores concerning counts of responses were number of responses completed in the 60-second test duration, number correct, and number correct minus number incorrect. The latter score was considered the conventional score for this test. Scores concerning time characteristics of response were the mean and the standard deviation of inter-response times.

PERCEPTUAL AND PSYCHOMOTOR TEST SEQUENCE: RESULTS PRIOR TO EXERCISE

Results obtained during the perceptual and psychomotor test sequence prior to exercise are presented in Fig. 6 for subject WS in Phase I and for subject GM in Phase II, and in Fig. 7 for subject CC in both phases. Results obtained during exercise are compared with these pre-exercise results in the following section.

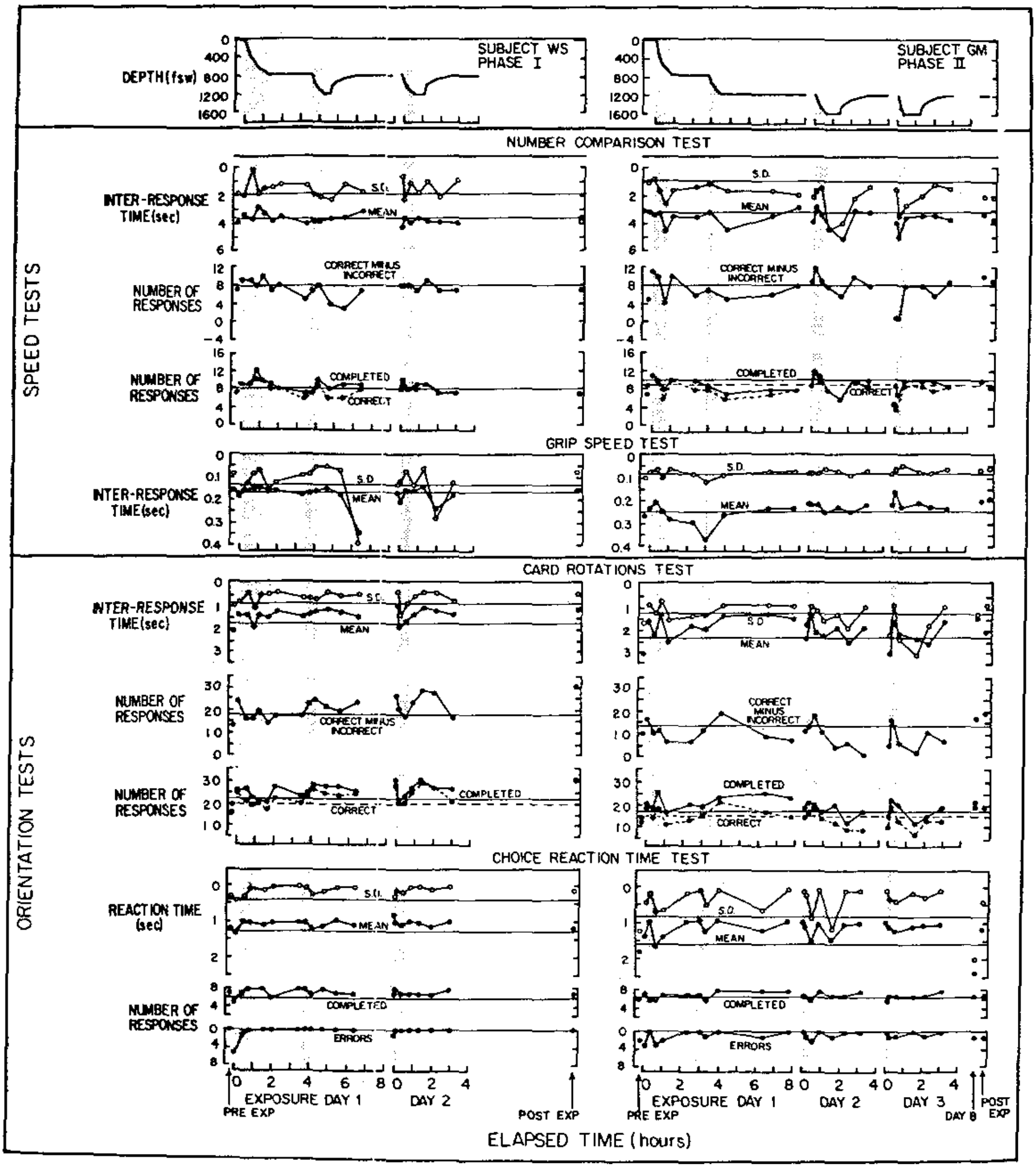

FIG. 6. Perceptual and psychomotor test sequence results for subject WS in Phase I and for subject GM in Phase II.

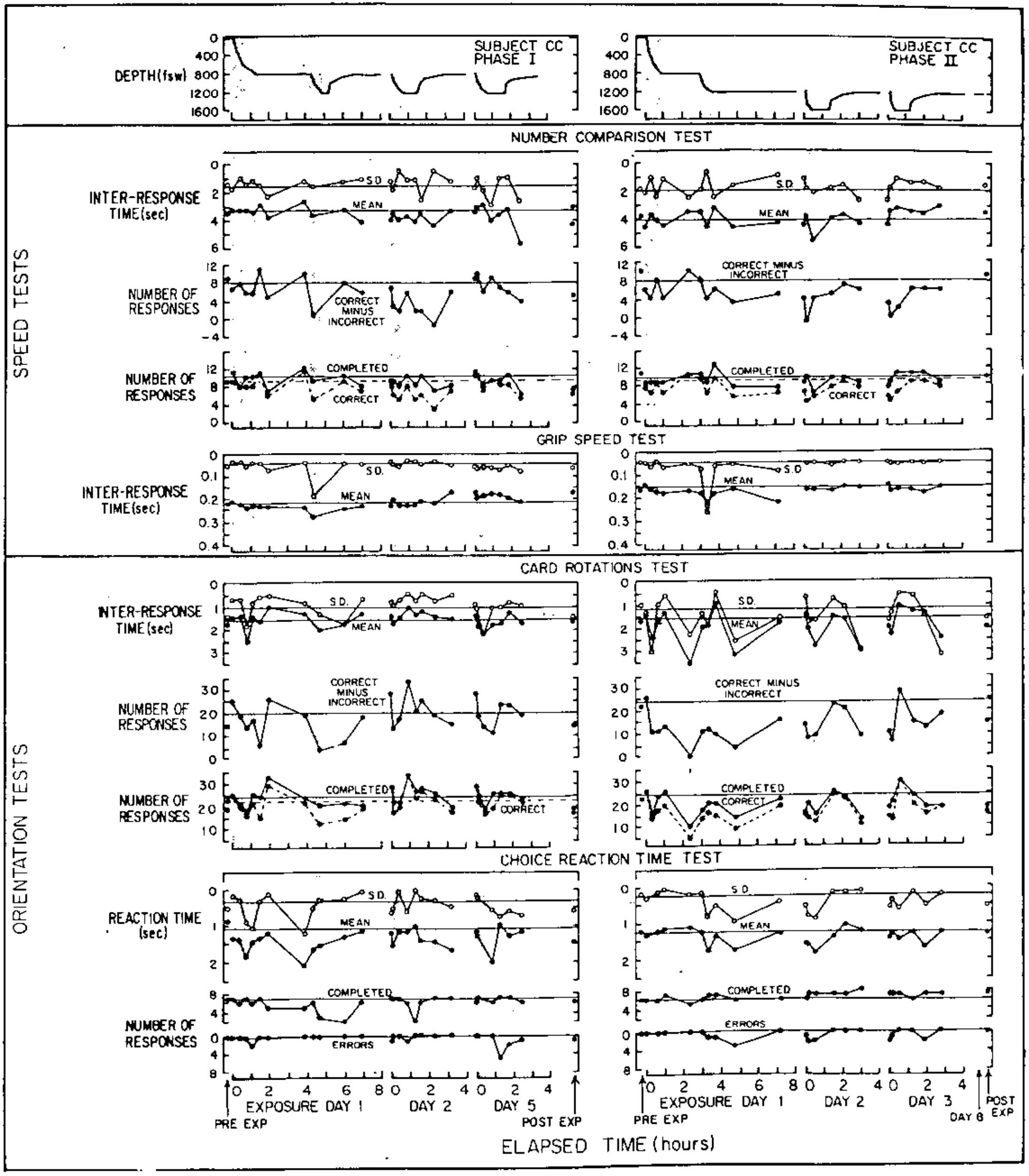

FIG. 7. Perceptual and psychomotor test sequence results for subject CC in Phases I and II.

Speed Tests

For the number comparison test of Perceptual Speed, compressions from 1 ata to 800 fsw were associated with performance decrement only to a minor extent (Figs. 6 and 7). Decrements were slightly greater during the 50-minute compressions in Phase II than in the 80-minute compressions of Phase I. Performance decrements of varying extent occurred in or after compressions to 1200 fsw usually with prompt recovery. Decrements also usually occurred in Phase II during or after compressions to 1600 fsw; recovery was usually less complete than in Phase I. Successive excursions over the same depth range appear to have progressively smaller effects upon these test scores. The scores of number of responses correct and of number correct minus incorrect (estimates of quality of performance) depart from their respective control values for subject GM at the beginning of day 3 in Phase II and for subject CC from the end of day 1 through day 3 of Phase II; other scores return to their respective control values at the beginning and the end of these exposure days. For all subjects and for all scores, sea level score values fluctuated over a wider range than was the case for other tests in this test sequence or in the other test sequences. Thus this test is probably lower in reliability than the other tests, or it may be more sensitive to variations in details of the experimental situation than the other tests.

Few performance decrements were shown in the grip speed test scores. Subject WS in Phase I performed at a relatively constant level except for a drop in performance at the end of day 1 after decompression from 1200 to 800 fsw and on day 2 during decompression. Subjects GM in Phase II and CC in Phases I and II performed this test at a relatively constant level except for transitory increases in the mean and the standard deviation of inter-response times during the compression from 800 to 1200 fsw on day 1.

Orientation Tests

The control levels for the card rotations test of Spatial Orientation may be biased by the pre-exposure scores which were low for all subjects when compared with scores obtained at 1 ata on day 1 of each phase. Subject CC's post-dive test scores were also below the control level. Test scores for GM and CC in Phase II were low at the end of most exposure days, while subject CC's scores were low at the beginning of excursion days in Phase II as well. These variations make it difficult to interpret the effects of compression and pressure upon the card rotations test scores. Although these variations may be partially due to relatively low test reliability, some may be related to exposure. Generally, scores for this test were lower in Phase II than in Phase I. Within day 1, compression from sea level to 800 fsw was associated with performance decrements in all subjects. Decrements were considerably greater in Phase II than in Phase I. Subject CC had larger decrements and slower recovery in Phase II than did GM. On this day only subject CC had performance decrements during and after compression to 1200 fsw.

Response Orientation, as estimated by the mean reaction time score obtained in the choice reaction time test, appeared to be little affected by compression or pressure for subject WS in Phase I or for subject GM in Phase II. Subject CC demonstrated increased mean reaction times and increased scatter of reaction times--more so in Phase I than in Phase II. However, there were no consistent relationships between these performance decrements and compression or pressure. The score of number of errors remained constant at the zero level for subject WS but showed some relationship to compression and decompression for subjects GM and CC. This score reflects long-term memory of the very simple association between three alternative responses and three stimulus figures. The three subjects rank in the same order with respect to increased errors and increases in reaction time.

PERCEPTUAL AND PSYCHOMOTOR TEST SEQUENCE: RESULTS--EFFECTS OF EXERCISE

In addition to the results discussed previously for the perceptual and psychomotor test sequence with the subjects at rest before exercise, measurements were made in each measurement module a second time during light exercise (Section E-14). Exercise was not performed during decompressions. The scores obtained while the subject was exercising are compared with the pre-exercise results in

Appendix Tables 5C (subject WS, Phase I), 6C (subject GM, Phase II), 7C (subject CC, Phase I) and 8C (subject CC, Phase II). Each value in the table is a difference between exercise and pre-exercise test scores, with the sign of the difference adjusted so that a plus sign indicates improved performance during exercise.

For measurements made at sea level (pre-exposure, first observation on day 1, and post-exposure) over all subjects and tests, scores obtained during light exercise are not systematically better or worse than scores obtained prior to exercise. However, when the mean and standard deviation of reaction time for the choice reaction time test are considered alone, performance is better with light exercise than before exercise. This pattern of comparisons also describes scores obtained at the beginning of each test day during each exposure. Because the choice reaction time test is most likely to be sensitive to the alertness of a subject in responding rapidly and correctly to environmental stimuli, these comparisons suggest that the activities preceding the test administration with light exercise and, possibly, the exercise itself may have served to alert the subject and, therefore, improve his test performance.

During compressions and exposures to high hydrostatic pressures only the score of mean inter-response time for the grip speed test was consistently affected by a repetition of the test sequence with exercise (subjects WS, GM, CC). This effect was more pronounced for subjects GM and CC than for WS. It should be noted that this effect of exercise upon the grip speed test may simply reflect an entrainment of grip speed performance by the rhythmic activity of operating the bicycle ergometer.

For all tests and all subjects during exposures, test scores concerning the temporal characteristics of performance were affected more than the other test scores by a second test administration with exercise, but the direction of the effect was not consistent from test to test or from subject to subject.

DISCUSSION

In selecting the perceptual, memory, cognitive and psychomotor performance tests administered in Predictive Studies IV, emphasis was placed on comprehensively describing the individual subject's change in performance abilities due to rapid compression and high pressure. Breadth of study was necessary since individuals can be expected to vary widely in their susceptibility to HPNS effects and to the manner in which effects are expressed (7,16,23,29). The compression circumstances selected for the overall purposes of the study were intended to induce demonstrable but not persistently incapacitating effects on most of the subjects (Section D).

SECONDARY STRESSES

Stresses secondary to compression and pressure may be expected to have nonspecific effects upon performance and to exaggerate primary effects. The symptoms of compression to high pressure (Section E-1) may distract a subject and therefore modify all abilities tested. The general fatigue of the prolonged experiment itself may have the same effect. Such fatigue which was sometimes reported by the subjects (Sections E-1 and E-5), as well as other residual effects of compression, may continue to affect performance at stable pressure after compression has been completed and adaptation to compression has occurred. In no studies has it been practical to accomplish full separation of such factors.

Other sources of potential discomfort and distraction have included increased noise during compression (Section E-9), ambient temperature which in the present studies was abruptly increased during compression from 1 ata to maintain thermal comfort (Section E-15), and some unwanted, residual temperature and humidity changes which occurred during excursion-compressions and decompressions (Section E-15).

PHYSIOLOGICAL STATE

The performance abilities of a subject are necessarily related to certain aspects of physiological status. Sporadic electroencephalographic changes consistent with lowered states of alertness were observed during compression in the subjects (Section E-2). Other physiological changes reflecting central nervous system function in these performance studies included alterations in: visual evoked cortical responses (Section E-3), vestibular function and balance (Section E-6), and tremor and somatosensory evoked cortical responses (Section E-4). Relevant studies of auditory, visual and cardiac functions are discussed in Sections E-7, E-8, and E-13, respectively.

COMPRESSION VS. ABSOLUTE PRESSURE

The module system of repetitively testing the same subjects as time progressed made it possible to examine effects of stress on performance of individual subjects during actual compression and at stable pressure after compression was completed. Residual effects from compressions were probably present even after actual compressions ended and a stable, higher pressure was attained. Thus, while a complete separation of compression (change in pressure) and pressure effects may not be possible, transient changes during compression may be distinguished from sustained effects at a fixed pressure. The extent of recovery over the course of an exposure day and the performance at the start of a new day are relevant to the interpretation of the results.

Decrements in the scores of various performance tests were observed in the present study. Recovery occurred in some cases over a very brief time interval, such as during the compression which elicited the change. At other times, recovery took place over longer time periods, such as during the course of a day or overnight.

GENERAL ABILITIES

While the decrements signify reduction in specific performance abilities, the subjects were, with only a few temporary exceptions (Section E-1), able to carry out and complete a rigorous schedule of preparation for and conduct of experiment modules. During the days when performance measures were taken and decrements in specific test scores occurred, the subjects instrumented themselves for the complex series of experiments, served as assistant investigators as well as subjects during the experiments, stowed the instrumentation gear and performed all housekeeping tasks within the pressure chambers.

From saturation at 1200 fsw they were compressed to 1600 fsw in 20 minutes and performed timed physical work requiring strength and dexterity on an oil wellhead underwater as effectively as during control experiments at 10 fsw (Section F). Thus, except for several periods during compressions from 1 ata when symptoms were most severe (Section E-1), the subjects were in general functionally capable even when test scores indicated marked decrements in specific aspects of performance.

COMPARISON OF PHASE I WITH PHASE II

Subjects FS and CC participated in Phases I and II. The exposures of Phase II were more severe than those of Phase I in terms of compression rate and pressures attained and therefore may be expected to produce greater effects on measures of performance in these subjects. However, since the less severe exposures were always scheduled first, adaptation to these initial exposures may have reduced the response to the subsequent, more severe exposures.

For the five tests administered to subject FS (Fig. 2), changes in performance on the first exposure days during compressions to 800 fsw and at 800 fsw were not clearly different between Phases I and II, despite the more rapid compression of Phase II. A comparison of excursions to 1200 fsw in Phase I and to 1600 fsw in Phase II shows that the key insertion test and the wrench and cylinder test gave similar results in both phases. Results of the visual reaction time test for excursions in both phases were also similar, with brief anticipatory decrements early in compression or decompression. The two tracking tasks are difficult to compare in the two phases because of prominent effects of learning and fatigue in Phase I; otherwise, the tracking scores were similar in the two phases.

Of the four tests administered to Subject CC (Fig. 7), only the choice reaction time test results differed in the two phases, with greater decrements during and after compression from 1 ata to 800 fsw and at 800 fsw in Phase I when compared with Phase II. When the results during excursions were compared, scores were similar in the two phases for both the grip speed test and the choice reaction time test. The number comparison and the card rotations tests demonstrated considerable scatter in scores obtained at 1 ata. This relatively low reliability, seen also in an earlier study (5), makes it difficult to compare perceptual test scores between the two separate studies, Phases I and II.

In summary, exposures in Phase I may have resulted in undefined adaptation, decreasing the effects of the more severe Phase II exposures. Any such adaptation is purely conjectural, with no supporting indications from the study.

EFFECTS OF SUCCESSIVE EXCURSIONS

In Phase I successive excursions from 800 to 1200 fsw on days 1, 2 and 5 can be compared for subjects LJ and CC, and successive excursions on days 1 and 2, for subjects FS and WS. For LJ and WS there were no consistent trends in performance level with repetition of excursion-compressions (Figs. 4 and 6). All of CC's scores showed improvement with successive excursions (Fig. 7). Subject FS showed adaptation in only the key insertion test (Fig. 2); of the five psychomotor tests administered to subject FS, this one is the most likely to be affected by tremor.

In Phase II successive excursions from 1200 to 1600 fsw on days 2 and 3 can be compared in subjects FS, MP, GM and CC. There was little apparent effect on the scores of the perceptual and psychomotor test sequence of repetition of excursion-compressions on those two days for subjects GM and CC (Figs. 6 and 7). All of subject MP's scores improved during the second excursion (Fig. 4), as did all of FS's scores, except the visual reaction time score (Fig. 2).

In general, the extent of adaptation in the performance capabilities tested due to successive exposures to excursions appears to vary with the subject and the ability tested.

EFFECTS OF COMPRESSION RATE IN EXCURSIONS

All excursion-compressions from 800 to 1200 fsw in Phase I were at the same rate and lasted 40 minutes (Section D). In Phase II the first compression from 1200 to 1600 fsw for GM and FS lasted 40 minutes; their second excursion-compression and all compressions over the same range for CC and MP were completed in 20 minutes. The increased excursion-compression rate on the second excursion did not result in greater deterioration in performance for subject GM and was associated with less decrement on four of the five tests administered to FS.

Adaptation to the increased pressure conditions may have masked any effect of the faster compression rate.

EFFECTS OF PRESSURE

Sustained effects of pressure on levels of performance would be demonstrated by a decrement which persisted from day to day. However, similar effects could result from other environmental stresses associated with the conditions of confinement.

Characteristically, most performance test scores in these studies were at or near control levels at the start of each exposure day, with a few exceptions as follows. For subject FS (Fig. 2), both tests involving coordination (the wrench and cylinder test and the two-hand compensatory coordination test) showed decrements at the end of days 2 and 3 and on day 8. For subject LJ (Fig. 4), all test scores were depressed at the end of day 2 and at the beginning of day 5. For subject CC in Phase II (Fig. 7), perceptual test results (the number comparison test and the card rotations test) were low at the end and beginning of test days.

Thus, there were few apparent sustained effects of pressure on the test scores. In some cases, scores during test days (and during pressure) improve; this may have been due to increased alertness due to testing, per se.

SCORES DURING EXCURSION-DECOMPRESSIONS

Marked decrements in test scores were sometimes observed during excursion-decompressions, particularly at the start of decompression. The novel, rapid decompressions (Section G-1) introduced in this Predictive Study or the activities associated with preparation for decompression may have been distracting to the subjects. Such transitory distractions may be indicated by the short-term decrements in mean reaction time at the beginning of decompression from 1600 fsw to 1200 fsw (Fig. 2).

EFFECTS OF EXERCISE

A major purpose in scheduling performance tests both before and during exercise related to the possibility that exercise might exacerbate effects of compression and pressure (Sections D, E-14), resulting in a performance decrement greater than at rest. Only the grip speed test showed such evidence of an interaction between exercise and performance, and even this result may represent an artifact of "lock-in" between gripping speed and pedaling rate. However, the possibility of such interactions deserves further study.

EFFECTS OF ABILITY TESTED AND COMPARISON WITH OTHER EXPERIMENTS

In comparing the results of Predictive Studies IV with those of other studies, it is necessary to consider differences in environmental conditions, in subjects and in test procedures (3,19). The results of these studies are compared with other recent data, (1,4,6,7,16,29) reviewed in the following section.

Perceptual Abilities

Perceptual function, as distinguished from cognitive function, has been studied infrequently during compression and pressure exposures. Different tests have led to different conclusions (29, p.404) concerning the speed of perception. The number comparison test of Perceptual Speed showed a small but significant decrement in score at 500 fsw, reached at 15 feet/minute (25). The card rotations test of Spatial Orientation showed significant decrement in that study and also during a prolonged exposure to 1600 fsw, reached at 20 feet/hour (30).

In the present studies Perceptual Speed scores (the number comparison test) revealed decrements at 1200 fsw and 1600 fsw in subjects WS, GM and CC (Figs. 6 and 7). Decrements in Spatial Orientation (card rotations test) were shown at 800, 1200 and 1600 fsw (subjects GM and CC) (Figs. 6 and 7).

These two perceptual tests, of the twelve administered, appeared to be the lowest in test reliability. Low reliability was determined in an earlier evaluation of similar tests as well (5).

Memory Abilities

Memory abilities have not been found to be reduced by stresses of lesser rates of compression and lesser pressures in helium-oxygen, except for retention over relatively long time periods (29, p. 404) perhaps because of complicating factors such as anxiety and fatigue (10,11,25,30).

In the present studies subject LJ showed sustained decrements in Associative Memory test scores at pressure, without recovery from day to day; subject MP demonstrated decrements which were of short duration, with recovery from one day to another (Fig. 4). Brief decrements in MP's scores early in compressions and decompressions may have been due to anticipation, while fatigue was apparently a factor in LJ's scores on his exposure day 1.

Memory is also tested by the error score of the choice reaction time test. In this case more errors occurred in Phase II than in Phase I (Figs. 6 and 7).

In the visual digit span test of Memory Span (Fig. 4), both subjects demonstrated greater memory decrement with increased pressure, but there were different extents of decrement for the two subjects. Both recovered relatively rapidly.

Cognitive Abilities

Cognitive aspects of performance have been assessed in previous exposures to high helium-oxygen pressures, with mixed results (29 , p.404 ff). Tests of cognitive function, including the arithmetic test, were not significantly affected during saturation exposure at 1600 fsw after compressions very much slower than those in the present study (9,30). However, a number ordination test has shown a sustained decrement of up to 50% at 2001 fsw after multi-day, slow compression (15). At intermediate depths (to 1200 fsw) other studies have shown lesser decrement, with rapid recovery at stable pressure following the completion of compression but with considerable variation among subjects (6).

The results for the arithmetic test of Number Facility (Fig. 4) show considerable decrement in cognitive ability for subject LJ on exposure days 2 and 5 in Phase I and for MP on all three exposure days in Phase II.

Psychomotor Abilities

Psychomotor aspects of performance have been emphasized in earlier studies as well as in Predictive Studies IV because motor disturbances are known to be prominent signs of the "high pressure nervous syndrome" (6). Seven of the twelve performance tests administered in the present studies concern psychomotor function, including five tests in the psychomotor test sequence (Figs. 6 and 7).

In earlier studies, tapping and dotting tests of speed of response showed decrements of nearly 20 percent at depths of 1600 fsw (15). In the present study, using the grip speed test of Wrist-Finger Speed (Figs. 6,7), subject WS showed decrements only at the end of the first long exposure day and at the beginning of decompression on day 2. Subject CC showed evidence of blocking during compressions to 1200 fsw on the first day of both Phases I and II (Fig. 7). Both GM (Fig. 6) and CC (Fig. 7) produced almost constant scores except for moderate decrements during or immediately after their first compressions from 800 fsw to 1200 fsw.

While the grip speed test involves continuous rapid response, the reaction time test involves discrete response to a single stimulus. No performance decrement in the visual reaction time test score was observed at 800 fsw following compression at a rate of 91 feet/minute (8).

In the present studies short-term decrements immediiately prior to or early in compressions and decompressions (Fig. 2) suggest anticipatory influences. Such decrements were greater in Phase II than in Phase I.

Choice reaction time tests of Response Orientation require not only rapid response to a stimulus but also choice of the appropriate response. Test results for this ability are more widely available in the literature than for the psychomotor abilities discussed in the preceding paragraphs. Little or no decrement in choice reaction time was found in exposures up to 1092 fsw following relatively high compression rates (25,27). Increased choice reaction times, typically of 10%-30% but of as much as about 25%, were observed during exposures up to 2001 fsw following slow compression over many days (15,24).

In Predictive Studies IV choice reaction time remained at or better than the control level for two subjects (WS and GM) (Fig. 6). For the third subject (CC) (Fig. 7) choice reaction time increased in Phases I and II, with greater effects in the former.

The abilities of Aiming, Finger Dexterity and Manual Dexterity have received considerable attention in earlier studies. These require rapid but precise positioning movements, rapid finger movements and rapid coordination of hand movements, respectively. In one experiment with a test involving mainly the Aiming ability, a maximum decrement of 16% was observed at 1000 fsw following compression at 16.7 feet/minute (13). Finger Dexterity has been measured with a variety of tests. In various experiments there has been no consistent relationship between the amount of decrement (ranging from 0% to approximately 35%) and hydrostatic pressure (up to 2001 fsw) or compression rate (ranging from 0.1 to 40 feet/minute) (6).

In the present studies, key insertion test scores assessing the Finger Dexterity ability deteriorated considerably in both phases (Fig. 2) as pressure was increased.

The ball-bearing test which has been administered in many previous studies, involves not only Finger Dexterity ability, but also Manual Dexterity ability. Test results have shown decrements in performance as great as 70% in compressions to pressures as great as 1500 fsw. However, performance decrements for this test were typically lower, in the range of 20%-50% in exposures to 1000 fsw. These decrements were related to compression rate and were maximal immediately after compression ended. The rate of recovery appeared to be slower than for other psychomotor abilities and to become slower as pressure increased (6).

The Manual Dexterity ability per se has been evaluated with a variety of tests at pressures to 2001 fsw. Decrements of 0%-60% have been observed, with no clear relationship between performance scores and pressure or compression rate. For example, scores with the wrench and cylinder test did not decrease in multi-day compressions up to 1600 fsw (30).

In the present studies performance on the wrench and cylinder test deteriorated during the rapid compression and exposure to pressure (Fig. 2). Fatigue may have been a more prominent factor in this test than in the other psychomotor tests since it is the more physically demanding.

Abilities assessed by means of precise tracking tests have not been widely used in compression-pressure exposures. In one experiment where a tracking test was administered, no decrement was observed during sustained exposure to 1600 fsw (30).

In Predictive Studies IV transitory loss of control and coordination was associated with rapid compression to 800 fsw. Additional decrements in control and coordination occurred during excursions from 1200 to 1600 fsw (Fig. 2). The learning effects, observed in these tracking tests throughout Phase I, are important in demonstrating that considerable learning can occur during exposure to rapid compression and high pressure.

SUMMARY

Measures of perceptual, memory, cognitive and psychomotor performance were obtained during compression, at stable high pressures following compression, during decompression from excursions, and at stable high pressures following excursion-decompressions. Results varied widely among subjects both with test administered and with exposure conditions; there were few consistent performance decrements. Recovery time from decrements varied from minutes to overnight.

The subjects were functionally competent even when test scores indicated marked performance decrements, except for several periods when signs and symptoms of compression and pressure were most severe.

No marked differences in performance test results were observed in the more severe exposures of Phase II as compared with Phase I in the two subjects who participated in both exposure phases. This lack of correlation between performance decrement and exposure severity may be due to adaptation during exposure to the less severe circumstances of Phase I which preceded Phase II.

Successive exposures to excursions from 800 fsw to 1200 fsw (Phase I) resulted in adaptation (progressive improvement in test scores) in one subject (CC) but no change in three subjects (LJ, WS, FS). Successive excursions from 1200 fsw to 1600 fsw (Phase II) resulted in adaptation in two subjects (MP, FS) and no change in two subjects (CC, GM).

There were essentially no evident sustained effects of high pressure on performance levels. Most test scores were at or near control levels at the start of each exposure day.

General physiological activation of exercise did not interact with compression-pressure effects. Performance scores during exercise were essentially the same as before exercise.

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APPENDIX TABLE 1. Psychomotor Test Sequence Scores for Subject FS in Phase I

Exposure Day	Depth (fsw)	Elapsed Time[a] (hr:min)	REACTION TIME TEST			DEXTERITY TESTS							TRACKING TESTS			
			VISUAL REACTION TIME TEST			KEY INSERTION TEST				WRENCH AND CYLINDER TEST			ONE-HAND COMPENSATORY CONTROL TEST		TWO-HAND COMPENSATORY COORDINATION TEST	
			Reaction Time (sec)		Number of Responses	Number of Responses		Inter-response Time (sec)		Number of Responses	Inter-response Time (sec)		Standard Deviation of Errors			
			Mean	SD	Completed	Completed	Errors	Mean	SD	Completed	Mean	SD	x axis	y axis	x axis	y axis
Pre-exp.	0	-	0.33	0.10	10	20[b]	1[b]	0.91	0.30	5.33[b]	7.68	2.29	35.43	38.92	50.39	48.23
1	0	0	0.30	0.04	11	20	0	0.89	0.15	4	8.60	0.88	34.05	34.82	44.89	42.53
	410	0:23	0.35	0.06	7	18	1	0.97	0.27	4	9.93	2.18	34.06	36.28	34.02	32.06
	600	0:43	0.32	0.03	8	18	0	0.98	0.16	4	9.27	0.76	31.65	33.54	46.97	36.84
	703	1:03	0.41	0.20	8	19	0	0.93	0.29	5	8.22	0.77	31.16	32.28	33.63	31.07
	800	1:30	0.34	0.05	8	15	2	1.21	0.38	5	7.89	1.14	29.25	31.21	61.36	53.17
	800	2:06	0.36	0.07	9	17	1	1.03	0.26	5	8.00	2.31	32.90	31.76	35.34	32.89
	800	3:20	0.40	0.17	8	15	2	1.19	0.38	5	7.94	1.20	23.57	25.02	43.12	40.78
	820	3:42	0.37	0.01	8	18	0	0.99	0.23	5	8.24	1.12	25.25	25.17	40.13	36.93
	1105	4:02	0.36	0.04	10	18	0	0.93	0.13	4	9.50	2.47	30.32	30.44	43.89	40.10
	1025	4:42	-	-	-	15	0	1.21	0.49	4	10.63	1.32	29.06	25.95	27.65	26.19
	880	5:22	0.37	0.06	9	18	2	0.97	0.32	4	10.75	0.57	28.48	31.05	35.37	34.80
	800	6:18	0.36	0.04	8	17	1	1.06	0.42	5	8.37	0.89	33.50	39.33	31.47	26.27
2	800	0	0.34	0.05	8	20	1	0.87	0.30	5	8.11	1.45	28.84	30.64	32.95	27.49
	820	0:01	0.42	0.12	9	20	0	0.80	0.16	5	8.45	0.82	34.79	38.49	29.00	29.05
	1105	0:21	0.36	0.06	8	20	1	0.87	0.29	5	9.06	1.37	22.50	22.10	30.34	25.99
	1200	0:46	0.39	0.06	9	18	1	1.00	0.45	4	9.78	1.19	22.39	23.78	37.23	32.60
	1025	1:16	0.37	0.08	9	17	2	1.07	0.55	4	10.08	1.07	24.72	28.87	32.62	29.26
	880	1:56	0.34	0.03	8	20	0	0.89	0.20	4	10.33	0.32	20.33	22.46	35.39	26.75
	800	2:52	0.36	0.04	9	19	1	0.94	0.34	4	11.52	1.37	32.10	33.35	27.96	28.22
Post-exp.	0	-	0.39	0.07	6	20	0	0.84	0.15	4	10.85	0.53	32.24	39.30	24.73	23.87

[a] Elapsed times are calculated from start of compression on each day as zero time to one minute into the three-minute measurement periods. Depths correspond to these times.

[b] In pre-exposure measurements for Subject FS test times were 30 sec for both the key insertion and wrench and cylinder tests. All other test times were 20 sec for the key insertion test and 40 sec for the wrench and cylinder test. These scores have been adjusted for this difference.

APPENDIX TABLE 2. Psychomotor Test Sequence Scores for Subject FS in Phase II

Exposure Day	Depth (fsw)	Elapsed Time[a] (hr:min)	REACTION TIME TEST			DEXTERITY TESTS							TRACKING TESTS			
			VISUAL REACTION TIME TEST			KEY INSERTION TEST				WRENCH AND CYLINDER TEST			ONE-HAND COMPENSATORY CONTROL TEST		TWO-HAND COMPENSATORY COORDINATION TEST	
			Reaction Time (sec)		Number of Responses	Number of Responses		Inter-response Time (sec)		Number of Responses	Inter-response Time (sec)		Standard Deviation of Errors			
			Mean	SD	Com-pleted	Com-pleted	Errors	Mean	SD	Com-pleted	Mean	SD	x axis	y axis	x axis	y axis
Pre-exp.	0	-	0.38	0.04	8	18	0	0.99	0.40	4	9.16	1.82	19.54	23.29	29.78	32.25
1	0	0	0.39	0.06	8	18	4	0.97	0.33	5	8.37	0.62	27.34	27.79	25.22	28.88
	417	0:14	0.41	0.04	8	17	4	1.01	0.39	5	7.62	1.00	24.79	26.23	28.89	29.49
	659	0:33	0.41	0.07	6	18	3	1.00	0.44	5	7.58	1.84	26.47	30.11	28.00	23.84
	800	0:56	0.43	0.07	9	15	4	1.17	0.55	5	7.15	0.64	36.53	37.06	25.58	25.02
	800	2:13	0.51	0.13	9	17	3	0.99	0.49	5	8.00	1.28	21.54	22.34	24.48	22.55
	880	2:54	0.45	0.18	9	16	2	1.13	0.43	4	9.29	1.33	21.72	23.29	31.54	29.66
	1115	3:13	0.41	0.08	9	13	3	1.28	0.60	5	8.92	0.93	28.34	26.19	23.37	20.86
	1200	3:51	0.48	0.08	9	15	3	1.15	0.45	5	8.43	1.20	23.09	25.82	27.01	24.84
	1200	6:15	0.44	0.09	9	14	4	1.30	0.58	3	11.61	1.63	28.24	27.13	29.91	26.23
	1200	7:38	0.39	0.04	9	18	2	1.02	0.37	4	11.28	1.10	25.81	29.34	27.15	29.44
2	1200	0	0.39	0.04	8	18	2	1.01	0.39	4	8.63	1.35	31.35	28.50	31.56	31.09
	1280	0:04	0.37	0.04	8	18	2	1.00	0.37	4	9.85	1.30	30.31	31.58	30.84	24.84
	1515	0:23	0.40	0.11	8	15	4	1.24	0.51	4	10.23	0.24	29.58	31.11	31.27	25.36
	1600	0:46	0.38	0.06	8	15	3	1.18	0.52	3	12.96	0.76	29.98	29.65	39.42	35.61
	1420	1:29	0.46	0.06	8	15	3	1.16	0.59	4	11.51	0.59	35.80	34.81	43.17	41.06
	1280	2:09	0.38	0.06	8	15	1	1.03	0.33	5	8.52	1.12	24.31	26.40	36.43	30.58
	1200	3:00	0.36	0.04	8	16	3	1.12	0.42	3	10.52	0.65	32.48	37.72	36.66	34.78
3	1200	0	0.36	0.04	8	17	2	1.07	0.43	4	9.41	1.67	24.12	25.54	32.02	31.48
	1320	0:03	0.38	0.06	8	15	1	1.09	0.59	4	10.22	0.75	31.29	31.42	25.87	24.40
	1600	0:26	0.41	0.06	8	13	5	1.26	0.49	5	8.39	1.07	27.03	29.03	37.45	29.02
	1420	1:22	0.47	0.07	9	18	2	1.00	0.36	4	9.28	0.66	23.71	24.51	31.98	29.25
	1285	2:01	0.38	0.04	8	16	3	1.12	0.49	4	9.26	0.59	29.98	30.83	40.62	20.56
	1200	2:52	0.38	0.04	9	17	2	1.02	0.48	4	10.49	0.63	25.01	28.44	30.88	31.20
8	1200	-	0.39	0.11	8	17	4	1.04	0.40	4	11.43	1.45	21.73	24.60	34.20	29.05
Post-exp.	0	-	0.35	0.04	8	22	0	0.82	0.15	5	7.76	0.76	20.91	22.36	24.74	24.00

[a] Elapsed times are calculated from start of compression on each day as zero time to one minute into the three-minute measurement periods. Depths correspond to these times.

APPENDIX TABLE 3. Memory and Cognitive Test Sequence Scores for Subject LJ in Phase I

			MEMORY TESTS							COGNITIVE TEST			
			WORD-NUMBER TEST			VISUAL DIGIT SPAN TEST				ARITHMETIC TEST			
Exposure Day	Depth (fsw)	Elapsed Time[a] (hr:min)	Number of Responses	Inter-response Time (sec)		Number of Responses		Inter-response Time (sec)		Number of Responses		Inter-response Time (sec)	
			Correct	Mean	SD	Correct	Completed	Mean	SD	Correct	Completed	Mean	SD
Pre-exp.	0	-	3	0.65	0.47	17	25	0.44	0.25	5	10	5.02	1.55
1	0	0	-	-	-	18	23	0.57	0.27	4	9	4.44	0.98
	411	0:21	4	0.62	0.36	18	22	0.41	0.15	3	7	6.34	1.48
	610	0:41	4	0.66	0.40	18	23	0.48	0.19	6	10	4.45	1.76
	708	1:01	2	0.80	0.62	12	18	0.46	0.21	5	9	5.03	1.95
	800	1:24	1	0.73	0.49	11	14	0.48	0.26	4	8	5.13	1.84
	800	2:00	-	-	-	15	24	0.40	0.13	4	10	4.27	2.24
	800	3:47	1	0.91	0.66	14	25	0.45	0.16	4	10	4.44	0.58
	840	4:15	2	0.66	0.34	13	23	0.45	0.12	5	11	3.73	1.08
	1118	4:35	1	0.75	0.58	10	19	0.73	0.42	3	9	4.93	2.13
	1025	5:14	3	0.79	0.61	12	23	0.42	0.19	5	10	4.14	1.12
	885	5:54	2	0.55	0.25	14	22	0.47	0.13	2	9	4.86	1.70
	800	6:50	0	0.94	0.51	12	24	0.45	0.13	4	8	4.81	1.95
2	800	0	2	0.72	0.50	14	23	0.42	0.17	8	11	3.95	1.17
	820	0:01	4	0.64	0.49	14	23	0.41	0.20	2	12	2.78	0.70
	1105	0:21	2	1.03	1.00	11	24	0.40	0.14	3	10	4.14	2.37
	1200	0:47	0	0.83	0.65	12	20	0.39	0.16	3	10	4.64	1.59
	1025	1:31	1	0.95	0.97	17	24	0.42	0.16	7	10	4.03	2.13
	875	2:14	1	0.73	0.56	15	23	0.37	0.08	1	10	3.74	1.02
	800	3:07	2	0.73	0.40	15	22	0.40	0.09	2	10	4.32	1.63
5	800	0	1	0.77	0.55	14	16	0.44	0.19	1	12	3.32	0.92
	820	0:01	0	0.70	0.47	16	23	0.40	0.08	2	15	2.77	0.76
	1105	0:21	-	-	-	19	23	0.36	0.12	1	14	2.99	0.78
	1200	0:47	0	0.75	0.38	10	23	0.45	0.22	0	8	4.59	1.97
	1020	1:41	3	0.71	0.35	16	27	0.44	0.15	4	12	3.48	0.72
	910	2:21	0	0.82	0.61	15	21	0.46	0.22	4	13	2.92	1.05
Post-exp.	0	-	3	0.65	0.39	18	21	0.38	0.12	3	12	2.69	0.63

[a] Elapsed times are calculated from start of compression on each day as zero time to one minute into the three-minute measurement periods. Depths correspond to these times.

APPENDIX TABLE 4. Memory and Cognitive Test Sequence Scores for Subject MP in Phase II

			MEMORY TESTS							COGNITIVE TEST			
			WORD-NUMBER TEST			VISUAL DIGIT SPAN TEST				ARITHMETIC TEST			
Exposure Day	Depth (fsw)	Elapsed Time[a] (hr:min)	Number of Responses	Inter-response Time (sec)		Number of Responses		Inter-response Time (sec)		Number of Responses		Inter-response Time (sec)	
			Correct	Mean	SD	Correct	Completed	Mean	SD	Correct	Completed	Mean	SD
Pre-exp.	0	-	8	1.52	0.83	21	22	0.63	0.21	5	7	5.98	3.73
1	0	0	8	1.55	1.13	22	22	0.53	0.06	6	7	6.18	3.87
	450	0:14	0	1.57	1.58	22	22	0.60	0.17	3	5	8.92	1.62
	680	0:33	5	1.70	1.47	16	21	0.48	0.15	6	6	5.51	0.75
	800	0:54	10	1.55	1.25	22	22	0.61	0.23	5	5	9.76	2.63
	800	2:15	8	1.27	0.92	21	21	0.50	0.11	7	7	6.32	0.57
	880	2:54	3	1.48	1.25	21	22	0.59	0.22	4	6	7.13	2.65
	1115	3:13	6	1.75	1.64	17	21	0.58	0.32	0	4	12.56	7.19
	1200	3:37	6	1.48	1.24	18	21	0.64	0.45	6	7	4.94	1.55
	1200	4:38	4	1.60	1.10	21	22	0.70	0.28	4	5	6.12	1.49
	1200	7:03	7	2.05	1.64	20	22	0.57	0.20	1	2	19.00	-
2	1200	0	6	2.28	2.06	22	22	0.61	0.22	7	8	5.31	1.58
	1320	0:03	8	1.68	1.34	19	22	0.85	0.61	4	4	9.60	2.77
	1600	0:26	5	1.88	1.60	18	22	0.61	0.13	3	5	8.03	3.91
	1410	1:24	-	-	-	-	-	-	-	-	-	-	-
	1280	2:02	1	1.75	1.71	15	15	0.55	0.14	1	2	13.30	-
	1200	2:53	6	1.87	1.67	21	23	0.49	0.13	2	4	12.80	4.99
3	1200	0	10	1.51	1.43	22	22	0.50	0.11	6	7	4.73	0.97
	1320	0:03	5	1.91	1.94	21	22	0.56	0.13	4	5	7.73	5.66
	1600	0:26	5	1.64	1.43	19	20	0.77	0.84	3	7	7.29	2.77
	1420	1:11	5	1.56	1.58	22	22	0.64	0.25	4	4	9.88	0.64
	1285	1:50	7	1.14	0.72	22	23	0.61	0.14	3	4	9.83	3.08
	1200	2:41	6	1.46	1.14	22	22	0.58	0.18	7	7	5.62	2.36
Post-exp.	0	-	10	1.56	1.05	22	22	0.60	0.15	6	6	6.52	1.53

[a] Elapsed times are calculated from start of compression on each day as zero time to one minute into the three-minute measurement periods. Depths correspond to these times.

APPENDIX TABLE 5A. Perceptual and Psychomotor Test Sequence Scores for Subject WS in Phase I. Measurements Made with Subject at Rest.

Exposure Day	Depth (fsw)	Elapsed Time[a] (hr:min)	SPEED TESTS							ORIENTATION TESTS								
			NUMBER COMPARISON TEST					GRIP SPEED TEST		CARD ROTATIONS TEST					CHOICE REACTION TIME TEST			
			Number of Responses			Inter-response Time (sec)		Inter-response Time (sec)		Number of Responses			Inter-response Time (sec)		Reaction Time (sec)		Number of Responses	
			Correct minus Incorrect	Correct	Com-pleted	Mean	SD	Mean	SD	Correct minus Incorrect	Correct	Com-pleted	Mean	SD	Mean	SD	Com-pleted	Errors
Pre-exp.	0	-	7	7	7	3.92	1.86	0.15	0.09	13	16	19	2.11	0.97	1.21	0.34	7	0
1	0	0	9	9	9	3.35	1.98	0.17	0.18	23	24	25	1.37	0.81	1.33	0.44	5	5
	448	0:27	9	9	9	3.72	0.16	0.16	0.12	16	21	26	1.38	0.43	1.01	0.32	7	1
	625	0:47	8	10	12	2.87	1.84	0.15	0.08	16	19	22	1.90	1.09	1.04	0.13	8	0
	723	1:07	10	10	10	3.21	1.44	0.14	0.07	19	20	21	1.39	0.52	-	-	-	-
	800	1:34	7	8	9	3.79	1.39	0.16	0.15	14	17	20	1.52	0.49	1.11	0.17	8	0
	800	1:59	8	8	8	3.53	1.19	0.16	0.12	17	22	27	1.25	0.40	1.05	0.07	6	0
	800	3:24	5	6	7	4.05	1.22	0.18	0.09	17	20	23	1.47	0.66	1.04	0.05	8	0
	900	3:46	7	7	7	3.91	1.94	0.17	0.08	22	23	24	1.39	0.66	1.06	0.10	8	0
	1125	4:06	8	9	10	3.91	2.08	0.16	0.05	24	26	28	1.22	0.68	1.20	0.28	7	0
	1000	4:46	4	6	8	3.71	2.32	0.15	0.05	21	24	27	1.15	0.40	1.16	0.21	8	0
	870	5:26	3	6	9	3.60	1.14	0.17	0.06	19	23	27	1.28	0.57	0.99	0.08	7	0
	800	6:23	7	8	9	3.08	1.68	0.35	0.39	23	24	25	1.45	0.49	1.11	0.08	7	0
2	800	0	8	8	8	4.26	0.61	0.17	0.13	26	28	30	1.01	0.38	0.87	0.33	7	1
	900	0:05	8	9	10	3.61	2.30	0.21	0.12	20	20	20	1.89	1.43	1.03	0.17	8	0
	1125	0:25	8	8	8	4.04	1.11	0.16	0.07	17	20	23	1.67	0.87	1.10	0.21	7	0
	1200	0:50	7	8	9	3.64	1.82	0.16	0.13	23	25	27	1.37	0.56	1.01	0.08	7	0
	1005	1:20	9	9	9	3.86	0.97	0.14	0.06	28	29	30	1.06	0.39	1.04	0.07	7	0
	870	2:00	7	7	7	3.92	2.12	0.24	0.28	27	27	27	1.17	0.40	1.14	0.13	7	0
	800	2:57	7	7	7	3.98	0.89	0.18	0.12	16	21	26	1.36	0.77	1.02	0.06	8	0
Post-exp.	0	-	7	7	7	3.59	3.85	0.15	0.08	30	30	30	1.09	0.43	1.17	0.19	7	0

[a] Elapsed times are calculated from start of compression on each day as zero time to one minute into the three-minute measurement periods. Depths correspond to these times.

APPENDIX TABLE 5B. Perceptual and Psychomotor Test Sequence Scores for Subject WS in Phase I. Measurements Made While Subject Performing Light Exercise.

Exposure Day	Depth (fsw)	Elapsed Time^a (hr:min	SPEED TESTS							ORIENTATION TESTS								
			NUMBER COMPARISON TEST					GRIP SPEED TEST		CARD ROTATIONS TEST					CHOICE REACTION TIME TEST			
			Number of Responses			Inter-response Time (sec)		Inter-response Time (sec)		Number of Responses			Inter-response Time (sec)		Reaction Time (sec)		Number of Responses	
			Correct minus Incorrect	Correct	Com-pleted	Mean	SD	Mean	SD	Correct minus Incorrect	Correct	Com-pleted	Mean	SD	Mean	SD	Com-pleced	Errors
Pre-exp.	0	-	8	8	8	4.46	1.58	0.13	0.05	18	19	20	2.22	1.05	1.05	0.12	8	0
1	0	0	8	8	8	4.50	1.48	0.15	0.08	19	23	27	1.32	0.54	0.67	0.28	6	7
	504	0:33	8	8	8	4.06	1.01	0.17	0.12	14	19	24	1.53	0.43	1.05	0.07	7	0
	659	0:53	7	8	9	3.77	1.03	0.18	0.11	9	17	25	1.51	0.50	1.02	0.12	8	0
	752	1:13	8	8	8	4.20	1.79	0.17	0.07	11	16	21	1.86	0.83	1.05	0.08	8	0
	800	1:40	8	8	8	4.68	1.32	0.16	0.08	16	20	24	1.64	1.06	1.04	0.09	8	0
	800	2:15	8	8	8	4.07	1.12	0.17	0.07	17	21	25	1.57	0.58	1.05	0.12	8	0
	800	3:30	6	7	8	3.33	1.18	0.16	0.06	23	24	25	1.39	0.58	1.07	0.09	8	0
	1010	3:52	8	8	8	4.54	0.65	0.16	0.08	21	23	25	1.36	0.65	1.00	0.05	8	0
	1155	4:12	7	8	9	3.93	1.16	0.18	0.07	17	21	25	1.39	0.59	1.01	0.14	8	0
2	800	0	4	6	8	3.72	1.15	0.17	0.07	15	20	25	1.41	0.64	1.05	0.16	8	0
	1010	0:11	6	7	8	3.53	2.23	0.19	0.09	23	24	25	1.35	0.37	0.99	0.06	7	0
	1155	0:31	6	7	8	4.47	3.07	0.22	0.14	25	28	31	1.13	0.40	1.05	0.05	8	0
	1200	0:56	9	9	9	4.00	1.31	0.20	0.12	26	26	26	1.41	0.51	1.03	0.10	8	0
Post-exp.	0	-	9	9	9	3.71	1.11	0.17	0.06	23	24	25	1.56	0.48	1.01	0.09	8	0

[a] Elapsed times are calculated from start of compression on each day as zero time to one minute into the three-minute measurement periods. Depths correspond to these times.

APPENDIX TABLE 5C. Effect of Exercise on Perceptual and Psychomotor Test Sequence Scores for Subject WS in Phase I[a]

Exposure Day	Depth Range (fsw)	Elapsed Time[b] (hr:min)	SPEED TESTS							ORIENTATION TESTS								
			NUMBER COMPARISON TEST					GRIP SPEED TEST		CARD ROTATIONS TEST					CHOICE REACTION TIME TEST			
			Number of Responses			Inter-response Time (sec)		Inter-response Time (sec)		Number of Responses			Inter-response Time (sec)		Reaction Time (sec)		Number of Responses	
			Correct minus Incorrect	Correct	Completed	Mean	SD	Mean	SD	Correct minus Incorrect	Correct	Completed	Mean	SD	Mean	SD	Completed	Errors
Pre-exp.	0	-	+1	+1	+1	-0.54	+0.28	+0.02	+0.04	+ 5	+3	+1	-0.11	-0.08	+0.16	+0.22	+1	0
1	0	0	-1	-1	-1	-1.15	+0.50	+0.02	+0.10	- 4	-1	+2	+0.05	+0.27	+0.66	+0.16	+1	-2
	448-504	0:27	-1	-1	-1	-0.34	-0.85	-0.01	0.00	- 2	-2	-2	-0.15	0.00	-0.04	+0.25	0	+1
	625-659	0:47	-1	-2	-3	-0.90	+0.81	-0.03	-0.03	- 7	-2	+3	+0.39	+0.59	+0.02	+0.01	0	0
	723-752	1:07	-2	-2	-2	-0.99	-0.35	-0.03	0.00	- 8	-4	0	-0.47	-0.31	-	-	-	-
	800	1:34	+1	0	-1	-0.89	+0.07	0.00	+0.07	+ 2	+3	+4	-0.12	-0.57	+0.07	+0.08	0	0
	800	1:59	0	0	0	-0.54	+0.07	-0.01	+0.05	0	-1	-2	-0.32	-0.18	0.00	-0.05	+2	0
	800	3:24	+1	+1	+1	+0.72	+0.04	+0.02	+0.03	+ 6	+4	+2	+0.08	+0.08	-0.03	-0.04	0	0
	900-1010	3:46	+1	+1	+1	-0.63	+1.29	+0.01	0.00	- 1	0	+1	+0.03	+0.01	+0.06	+0.05	0	0
	1125-1155	4:06	-1	-1	-1	-0.02	+0.92	-0.02	-0.02	- 7	-5	-3	-0.17	+0.09	+0.19	+0.14	+1	0
2	800	0	-4	-2	0	+0.54	-0.54	0.00	+0.06	-11	-8	-5	-0.40	-0.26	-0.18	+0.17	+1	+1
	900-1010	0:05	-2	-2	-2	+0.08	+0.07	+0.02	+0.03	+ 3	+4	+5	+0.54	+1.06	+0.04	+0.11	-1	0
	1125-1155	0:25	-2	-1	0	-0.43	-1.96	-0.06	-0.07	+ 8	+8	+8	+0.54	+0.47	+0.05	+0.16	+1	0
	1200	0:50	+2	+1	0	-0.36	+0.51	-0.04	+0.01	+ 3	+1	-1	-0.04	+0.05	-0.02	-0.02	+1	0
Post-exp.	0	-	+2	+2	+2	-0.12	+2.74	-0.02	+0.02	- 7	-6	-5	-0.47	-0.05	+0.16	+0.10	+1	0

[a] Each entry is the absolute value of the difference between the value measured with the subject at rest and the value measured while the subject performed light exercise. The symbol (+) indicates that performance improved with exercise; the symbol (-) indicates that the subject's performance was poorer during exercise than while at rest.

[b] Elapsed times are those for the rest measurement periods given in part A of this table; the exercise periods occur six minutes later. Depth ranges are based on the depth given for rest (part A) and exercise (part B).

APPENDIX TABLE 6A. Perceptual and Psychomotor Test Sequence Scores for Subject GM in Phase II. Measurements Made with Subject at Rest.

			SPEED TESTS							ORIENTATION TESTS								
			NUMBER COMPARISON TEST					GRIP SPEED TEST		CARD ROTATIONS TEST					CHOICE REACTION TIME TEST			
Exposure Day	Depth (fsw)	Elapsed Time[a] (hr:min)	Number of Responses			Inter-response Time (sec)		Inter-response Time (sec)		Number of Responses			Inter-response Time (sec)		Reaction Time (sec)		Number of Responses	
			Correct minus Incorrect	Correct	Completed	Mean	SD	Mean	SD	Correct minus Incorrect	Correct	Completed	Mean	SD	Mean	SD	Completed	Errors
Pre-exp.	0	-	5	7	9	3.16	0.99	0.27	0.10	10	12	14	3.09	1.75	1.77	1.20	6	2
1	0	0	11	11	11	3.35	0.77	0.23	0.07	16	18	20	1.68	0.96	1.35	0.41	7	3
	484	0:18	10	10	10	3.25	1.63	0.21	0.06	10	14	18	2.25	1.34	0.95	0.16	6	0
	689	0:37	4	6	8	4.54	2.59	0.25	0.10	11	18	25	1.43	0.78	1.60	0.67	6	3
	800	1:00	10	10	10	3.49	1.60	0.28	0.06	6	11	16	2.57	1.62	1.36	0.64	7	2
	800	2:17	6	8	10	3.52	1.34	0.30	0.09	6	13	20	1.85	1.44	0.94	0.17	7	0
	960	2:58	7	8	9	3.19	1.09	0.37	0.12	11	15	19	1.99	1.41	0.90	0.08	7	0
	1135	3:17	-	-	-	-	-	-	-	-	-	-	-	-	1.18	0.49	6	1
	1200	3:55	5	6	7	4.46	1.67	0.26	0.09	19	21	23	1.43	0.96	0.91	0.08	8	0
	1200	6:19	6	7	8	3.44	1.62	0.23	0.07	9	17	25	1.35	0.94	1.17	0.63	8	1
	1200	7:42	8	8	8	2.20	1.88	0.23	0.07	7	15	23	1.52	0.97	0.91	0.06	8	0
2	1200	0	9	9	9	3.85	2.02	0.21	0.07	11	15	19	2.38	1.77	0.94	0.12	7	0
	1360	0:08	12	12	12	2.77	1.61	0.22	0.07	13	17	21	1.36	0.94	1.05	0.18	7	1
	1535	0:27	9	10	11	3.28	1.38	0.21	0.08	18	19	20	2.12	1.13	1.47	0.84	6	2
	1600	0:50	8	8	8	4.37	4.39	0.25	0.06	11	14	17	2.30	1.63	0.99	0.08	8	0
	1400	1:33	6	6	6	5.09	3.93	0.23	0.07	4	12	20	1.91	1.35	1.41	1.13	7	1
	1270	2:13	10	10	10	3.03	2.09	0.24	0.09	6	9	12	2.53	1.92	1.00	0.09	7	0
	1200	3:04	8	9	10	3.15	1.30	0.22	0.07	1	9	17	1.90	1.00	0.94	0.10	8	0
3	1200	0	1	5	9	3.93	1.47	0.22	0.08	5	10	15	3.03	2.24	0.94	0.08	6	0
	1440	0:07	1	4	7	4.99	3.42	0.16	0.06	16	19	22	1.61	0.88	1.06	0.32	7	1
	1600	0:30	8	9	10	3.54	2.63	0.22	0.04	6	13	20	2.13	2.37	1.18	0.37	7	1
	1400	1:26	8	9	10	3.39	1.91	0.21	0.07	2	7	12	2.36	3.06	1.07	0.14	7	0
	1275	2:05	6	8	10	3.38	1.08	0.22	0.08	11	13	15	2.59	1.79	1.03	0.24	7	1
	1200	2:56	9	9	9	3.66	1.38	0.23	0.06	7	13	19	1.64	0.93	1.01	0.09	8	0
8	1200	-	10	10	10	3.29	2.07	0.20	0.07	17	19	21	1.46	1.28	1.92	2.31	7	1
Post-exp.	0	-	9	9	9	3.71	2.10	0.19	0.06	19	19	19	2.06	0.91	1.12	0.38	7	1

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[a] Elapsed times are calculated from start of compression on each day as zero time to one minute into the three-minute measurement periods. Depths correspond to these times.

APPENDIX TABLE 6B. Perceptual and Psychomotor Test Sequence Scores for Subject GM in Phase II. *Measurements Made While Subject Performing Light Exercise.*

Exposure Day	Depth (fsw)	Elapsed Time[a] (hr:min)	SPEED TESTS							ORIENTATION TESTS									
			NUMBER COMPARISON TEST					GRIP SPEED TEST		CARD ROTATIONS TEST					CHOICE REACTION TIME TEST			
			Number of Responses			Inter-response Time (sec)		Inter-response Time (sec)		Number of Responses			Inter-response Time (sec)		Reaction Time (sec)		Number of Responses	
			Correct minus Incorrect	Correct	Completed	Mean	SD	Mean	SD	Correct minus Incorrect	Correct	Completed	Mean	SD	Mean	SD	Completed	Errors
Pre-exp.	0	-	7	8	9	3.57	1.53	0.29	0.12	3	8	13	3.04	0.62	1.19	0.59	8	1
1	0	0	10	10	10	3.43	1.70	0.22	0.08	20	20	20	2.11	1.03	1.05	0.33	7	1
	584	0:24	4	6	8	3.48	1.60	0.24	0.06	4	10	16	2.60	1.42	1.17	0.72	8	1
	733	0:43	6	7	8	4.92	1.75	0.29	0.08	10	14	18	2.09	1.30	1.38	0.62	7	3
	800	1:06	8	8	8	4.51	1.08	0.29	0.08	7	11	15	2.89	1.26	0.94	0.13	8	0
	800	2:23	9	9	9	2.49	1.70	0.23	0.08	13	17	21	1.71	0.77	1.11	0.18	8	2
	1040	3:04	5	6	7	3.81	2.76	0.28	0.10	7	16	25	1.48	0.92	1.36	0.60	7	1
	1165	3:23	2	4	6	2.95	1.77	0.22	0.08	-1	4	9	4.23	4.05	0.92	0.07	6	0
	1200	4:01	9	9	9	4.22	5.03	0.23	0.08	12	16	20	2.08	1.80	0.93	0.12	8	0
	1200	6:25	10	10	10	3.20	1.80	0.32	0.10	14	18	22	1.65	1.22	2.54	2.53	6	5
	1200	7:48	8	9	10	3.31	1.77	0.28	0.10	-6	7	20	2.41	2.02	1.83	1.86	7	4
2	1200	0	11	11	11	2.74	2.08	0.23	0.09	-1	8	17	2.07	1.70	0.93	0.07	7	0
	1440	0:14	9	10	11	2.80	1.52	0.25	0.07	5	10	15	2.86	3.46	0.98	0.11	8	0
	1565	0:33	5	7	9	2.38	1.92	0.30	0.12	5	12	19	2.23	1.31	1.45	0.62	7	3
	1600	0:56	10	10	10	3.05	1.52	0.27	0.08	2	9	16	2.53	1.75	1.00	0.04	7	0
3	1200	0	7	8	9	3.05	1.73	0.23	0.08	12	16	20	2.08	1.47	1.09	0.25	7	0
	1530	0:13	8	8	8	3.70	2.68	0.21	0.08	7	11	15	2.96	3.74	1.08	0.37	7	1
	1600	0:36	7	9	11	3.13	0.89	0.27	0.09	12	16	20	1.96	2.54	1.08	0.32	7	1
8	1200	-	8	9	10	3.19	1.04	0.26	0.07	18	19	20	1.96	1.06	0.90	0.11	7	0
Post-exp.	0	-	7	8	9	2.69	1.09	0.18	0.08	16	16	16	2.46	1.57	1.03	0.37	7	1

[a] Elapsed times are calculated from start of compression on each day as zero time to one minute into the three-minute measurement periods. Depths correspond to these times.

APPENDIX TABLE 6C. Effect of Exercise on Perceptual and Psychomotor Test Sequence Scores for Subject GM in Phase II[a]

Exposure Day	Depth Range (fsw)	Elapsed Time[b] (hr:min)	SPEED TESTS							ORIENTATION TESTS								
			NUMBER COMPARISON TEST					GRIP SPEED TEST		CARD ROTATIONS TEST					CHOICE REACTION TIME TEST			
			Number of Responses			Inter-response Time (sec)		Inter-response Time (sec)		Number of Responses			Inter-response Time (sec)		Reaction Time (sec)		Number of Responses	
			Correct minus Incorrect	Correct	Completed	Mean	SD	Mean	SD	Correct minus Incorrect	Correct	Completed	Mean	SD	Mean	SD	Completed	Errors
Pre-exp.	0	-	+2	+1	0	-0.41	-0.54	-0.02	-0.02	- 7	-4	-1	+0.05	+1.13	+0.58	+0.61	+2	+1
1	0	0	-1	-1	-1	-0.08	-0.93	+0.01	-0.01	+ 4	+2	0	-0.43	-0.07	+0.30	+0.08	0	+2
	484-584	0:18	-6	-4	-2	-0.23	+0.03	-0.03	0.00	- 6	-4	-2	-0.35	-0.08	-0.22	-0.56	+2	-1
	689-733	0:37	+2	+1	0	-0.38	+0.84	-0.04	+0.02	- 1	-4	-7	-0.66	-0.52	+0.22	+0.05	+1	0
	800	1:00	-2	-2	-2	-1.02	+0.52	-0.01	-0.02	+ 1	0	-1	-0.32	+0.36	+0.42	+0.51	+1	+2
	800	2:17	+3	+1	-1	+1.03	-0.36	+0.07	+0.01	+ 7	+4	+1	+0.14	+0.67	-0.17	-0.01	+1	-2
	960-1040	2:58	-2	-2	-2	-0.62	-1.67	+0.09	+0.02	- 4	+1	+6	+0.51	+0.49	-0.46	-0.52	0	-1
	1135-1165	3:17	-	-	-	-	-	-	-	-	-	-	-	-	+0.26	+0.42	0	+1
	1200	3:55	+4	+3	+2	+0.24	-3.36	+0.03	+0.01	- 7	-5	-3	-0.65	-0.84	-0.02	-0.04	0	0
	1200	6:19	+4	+3	+2	+0.24	-0.18	-0.09	-0.03	+ 5	+1	-3	-0.30	-0.28	-1.37	-1.90	-2	-4
	1200	7:42	0	+1	+2	-1.11	+0.11	-0.05	-0.03	-13	-8	-3	-0.89	-1.05	-0.92	-1.80	-1	-4
2	1200	0	+2	+2	+2	+1.11	-0.06	-0.02	-0.02	-12	-7	-2	+0.31	+0.07	+0.01	+0.05	0	0
	1360-1440	0:08	-3	-2	-1	-0.03	+0.09	-0.03	0.00	- 8	-7	-6	-1.50	-2.52	+0.07	+0.07	+1	+1
	1535-1565	0:27	-4	-3	-2	+0.90	-0.54	-0.09	-0.04	-13	-7	-1	-0.11	-0.18	+0.02	+0.22	+1	-1
	1600	0:50	+2	+2	+2	+1.32	+2.87	-0.02	-0.02	- 9	-5	-1	-0.23	-0.12	-0.01	+0.04	-1	0
3	1200	0	+6	+3	0	+0.88	-0.26	-0.01	0.00	+ 7	+6	+5	+0.95	+0.77	-0.15	-0.17	+1	0
	1440-1530	0:07	+7	+4	+1	+1.29	+0.74	-0.05	-0.02	- 9	-8	-7	-1.35	-2.86	-0.02	-0.05	0	0
	1600	0:30	-1	0	+1	+0.41	+1.74	-0.05	-0.05	+ 6	+3	0	+0.17	-0.17	+0.10	+0.05	0	0
8	1200	-	-2	-1	0	+0.10	+1.03	-0.06	0.00	+ 1	0	-1	-0.50	+0.22	+1.02	+2.20	0	+1
Post-exp.	0	-	-2	-1	0	+1.02	+1.01	+0.01	-0.02	- 3	-3	-3	-0.40	-0.66	+0.09	+0.01	0	0

[a] Each entry is the absolute value of the difference between the value measured with the subject at rest and the value measured while the subject performed light exercise. The symbol (+) indicates that performance improved with exercise; the symbol (-) indicates that the subject's performance was poorer during exercise than while at rest.

[b] Elapsed times are those for the rest measurement periods given in part A of this table; the exercise periods occur six minutes later. Depth ranges are based on the depth given for rest (part A) and exercise (part B).

APPENDIX TABLE 7A. Perceptual and Psychomotor Test Sequence Scores for Subject CC in Phase I. Measurements Made with Subject at Rest.

Exposure Day	Depth (fsw)	Elapsed Time[a] (hr:min)	SPEED TESTS							ORIENTATION TESTS								
			NUMBER COMPARISON TEST					GRIP SPEED TEST		CARD ROTATIONS TEST					CHOICE REACTION TIME TEST			
			Number of Responses			Inter-response Time (sec)		Inter-response Time (sec)		Number of Responses			Inter-response Time (sec)		Reaction Time (sec)		Number of Responses	
			Correct minus Incorrect	Correct	Completed	Mean	SD	Mean	SD	Correct minus Incorrect	Correct	Completed	Mean	SD	Mean	SD	Completed	Errors
Pre-exp.	0	-	9	9	9	3.37	1.31	0.21	0.05	15	19	23	1.66	1.35	0.84	0.49	7	0
1	0	0	7	9	11	3.16	1.68	0.20	0.04	25	25	25	1.40	0.66	1.32	0.17	7	0
	454	0:25	8	8	8	3.12	0.92	0.22	0.03	19	20	21	1.36	0.63	1.35	0.27	6	0
	629	0:45	6	8	10	3:18	1.31	0.23	0.05	14	16	18	2.43	1.80	1.78	0.86	7	0
	727	1:05	6	8	10	3.34	1.09	0.23	0.04	17	21	25	1.40	0.77	1.42	1.05	6	2
	800	1:28	11	11	11	2.79	1.40	0.23	0.04	6	15	24	1.55	0.56	1.33	0.31	7	0
	800	1:54	5	6	7	3.70	2.18	0.23	0.07	26	29	32	0.99	0.48	1.19	0.12	5	0
	800	3:52	10	11	12	2.58	1.13	0.24	0.04	19	21	23	1.27	0.81	2.08	1.21	5	0
	920	4:19	1	5	9	3.54	1.52	0.27	0.18	-	-	-	-	-	1.65	0.52	6	0
	1136	4:39	-	-	-	-	-	-	-	4	12	20	1.95	1.32	1.54	0.32	3	0
	875	5:58	8	9	10	3.16	1.18	0.24	0.04	7	14	21	1.72	1.71	1.30	0.28	2	0
	800	6:55	6	7	8	4.08	1.00	0.23	0.05	18	19	20	1.27	0.65	1.15	0.09	6	0
2	800	0	7	8	9	3.68	1.17	0.22	0.04	28	28	28	1.38	0.78	1.19	0.65	7	1
	900	0:05	3	6	9	3.51	1.82	0.20	0.05	13	17	21	1.68	0.90	1.56	0.54	7	0
	1125	0:25	2	5	8	3.88	0.33	0.22	0.06	17	19	21	1.44	0.70	1.16	0.08	7	0
	1200	0:51	6	8	10	3.68	1.06	0.22	0.03	33	33	33	1.03	0.42	1.17	0.61	6	1
	1200	1:17	2	5	8	4.05	1.03	0.22	0.03	20	23	26	1.30	0.69	1.02	0.04	2	0
	1005	1:35	2	6	10	3.45	2.51	0.21	0.05	25	26	27	1.19	0.42	1.42	0.26	6	0
	865	2:18	-1	3	7	4.29	0.45	0.21	0.04	19	22	25	1.42	0.72	1.44	0.31	7	0
	800	3:12	6	7	8	3.28	1.17	0.17	0.05	15	17	19	1.50	0.48	1.67	0.48	7	0
5	800	0	9	10	11	3.32	1.68	0.17	0.06	28	28	28	1.35	0.88	1.17	0.19	6	0
	900	0:05	10	10	10	2.99	0.95	0.19	0.07	18	21	24	1.82	1.05	1.29	0.26	7	0
	1125	0:25	6	7	8	2.79	1.82	0.18	0.06	14	16	18	2.16	2.18			-	-
	1200	0:51	9	9	9	3.99	2.83	0.17	0.06	11	18	25	1.75	1.03	2.00	0.57	6	0
	1200	1:17	7	8	9	3.58	0.96	0.18	0.07	23	24	25	1.69	0.98	1.00	0.77	7	5
	1001	1:45	6	8	10	3.16	0.87	0.19	0.05	23	24	25	1.25	0.81	1.28	0.59	7	2
	904	2:25	4	5	6	5.67	2.79	0.21	0.08	19	21	23	1.65	0.93	1.17	0.73	6	1
Post-exp.	0	-	5	6	7	4.28	3.02	0.17	0.06	14	16	18	1.61	1.47	1.47	0.59	6	1

[a] Elapsed times are calculated from start of compression on each day as zero time to one minute into the three-minute measurement periods. Depths *correspond to these times.*

APPENDIX TABLE 7B. Perceptual and Psychomotor Test Sequence Scores for Subject CC in Phase I. Measurements Made While Subject Performing Light Exercise.

Exposure Day	Depth (fsw)	Elapsed Time[a] (hr:min)	SPEED TESTS							ORIENTATION TESTS								
			NUMBER COMPARISON TEST					GRIP SPEED TEST		CARD ROTATIONS TEST					CHOICE REACTION TIME TEST			
			Number of Responses			Inter-response Time (sec)		Inter-response Time (sec)		Number of Responses			Inter-response Time (sec)		Reaction Time (sec)		Number of Responses	
			Correct minus Incorrect	Correct	Com-pleted	Mean	SD	Mean	SD	Correct minus Incorrect	Correct	Com-pleted	Mean	SD	Mean	SD	Com-pleted	Errors
Pre-exp.	0	-	5	6	7	4.07	1.33	0.21	0.06	7	13	19	2.26	2.00	1.14	0.55	6	0
1	0	0	5	6	7	4.13	2.70	0.21	0.05	19	20	21	1.68	0.90	1.71	0.55	7	1
	517	0:31	4	6	8	4.74	1.21	0.24	0.05	23	24	25	1.34	0.52	1.41	0.45	7	0
	659	0:51	3	6	9	3.89	2.05	0.22	0.06	19	22	25	1.41	0.91	1.54	1.30	7	2
	757	1:11	9	9	9	3.81	0.82	0.22	0.05	14	19	24	1.47	0.79	1.36	0.59	7	1
	800	1:34	3	7	11	3.29	1.90	0.28	0.08	19	22	25	1.40	0.64	1.57	0.41	7	0
	800	2:10	8	9	10	3.05	1.88	0.23	0.06	7	14	21	2.10	1.73	1.50	0.52	7	0
	800	3:58	7	8	9	3.80	1.18	0.26	0.05	23	26	29	1.25	0.78	1.26	0.17	8	0
	1020	4:25	10	10	10	2.93	1.23	0.30	0.09	16	21	26	1.44	0.77	1.61	0.59	7	0
	1164	4:45	-	-	-	-	-	-	-	-	-	-	-	-	2.44	1.65	5	0
2	800	0	8	8	8	3.88	0.99	0.21	0.05	15	20	25	1.28	0.57	1.22	0.60	7	1
	1010	0:11	2	5	8	3.84	3.84	0.24	0.05	17	21	25	1.51	0.77	1.03	0.38	7	1
	1155	0:31	8	9	10	2.73	1.77	0.25	0.05	17	23	29	1.18	0.56	1.40	0.44	7	0
	1200	0·57	6	8	10	3.56	1.15	0.23	0.06	20	23	26	1.29	0.44	1.54	0.66	7	0
5	800	0	10	11	12	2.81	1.67	0.20	0.06	25	26	27	1.29	0.82	1.50	0.62	7	0
	1010	0:11	7	8	9	3.63	0.93	0.20	0.08	23	23	23	1.56	0.68	1.24	0.63	7	1
	1155	0:31	-	-	-	-	-	0.19	0.06	18	22	26	1.47	0.93	1.22	0.23	8	0
	1200	0:57	9	9	9	3.45	1.88	0.24	0.07	25	26	27	1.18	0.49	1.11	0.14	7	1
Post-exp.	0	-	10	10	10	3.45	1.66	0.16	0.06	23	24	25	1.72	0.98	1.17	0.26	7	0

[a] Elapsed times are calculated from start of compression on each day as zero time to one minute into the three-minute measurement periods. Depths correspond to these times.

APPENDIX TABLE 7C. Effect of Exercise on Perceptual and Psychomotor Test Sequence Scores for Subject CC in Phase I[a]

Exposure Day	Depth Range (fsw)	Elapsed Time[b] (hr:min)	SPEED TESTS							ORIENTATION TESTS								
			NUMBER COMPARISON TEST					GRIP SPEED TEST		CARD ROTATIONS TEST					CHOICE REACTION TIME TEST			
			Number of Responses			Inter-response Time (sec)		Inter-response Time (sec)		Number of Responses			Inter-response Time (sec)		Reaction Time (sec)		Number of Responses	
			Correct minus Incorrect	Correct	Completed	Mean	SD	Mean	SD	Correct minus Incorrect	Correct	Completed	Mean	SD	Mean	SD	Completed	Errors
Pre-exp.	0	-	-4	-3	0	-0.70	-0.02	0.00	-0.01	- 8	- 5	- 4	-0.60	-0.65	-0.30	-0.06	-1	0
1	0	0	-2	-3	-4	-0.97	-1.02	0.00	-0.01	- 6	- 5	- 4	-0.28	-0.24	-0.39	-0.38	0	-1
	454-517	0:25	-4	-2	0	-1.62	-0.29	-0.02	-0.02	+ 4	+ 4	+ 4	+0.02	+0.11	-0.06	-0.18	+1	0
	629-659	0:45	-3	-2	-1	-0.71	-0.74	+0.01	-0.01	+ 5	+ 6	+ 7	+1.02	0.89	+0.24	-0.44	0	-2
	727-757	1:05	+3	+1	-1	-0.47	+0.27	+0.01	-0.01	- 3	- 2	- 1	-0.07	-0.02	+0.06	+0.46	+1	+1
	800	1:28	-8	-4	0	-0.50	-0.50	-0.05	-0.04	+13	+ 7	+ 1	+0.15	-0.08	-0.24	-0.10	0	0
	800	1:54	+3	+3	+3	+0.65	+0.30	0.00	0.01	-19	-15	-11	-1.11	-1.25	-0.31	-0.40	+2	0
	800	3:52	-3	-3	-3	-1.22	-0.05	-0.02	-0.01	+ 4	+ 5	+ 6	+0.02	+0.03	+0.82	+1.04	+3	0
	920-1020	4:19	+9	+5	+1	+0.61	+0.29	-0.03	+0.09	-	-	-	-	-	+0.04	-0.07	+1	0
	1136-1164	4:39	-	-	-	-	-	-	-	-	-	-	-	-	-0.90	-1.33	+2	0
2	800	0	+1	0	-1	-0.00	+0.18	+0.01	-0.01	-13	- 8	- 3	+0.10	+0.21	-0.03	+0.05	0	0
	900-1010	0:05	-1	-1	-1	-0.33	-2.02	-0.04	0.00	+ 4	+ 4	+ 4	+0.17	+0.13	+0.53	+0.16	0	-1
	1125-1155	0:25	+6	+4	+2	+1.15	-1.44	-0.03	+0.01	0	+ 4	+ 8	+0.26	+0.14	-0.24	-0.36	0	0
	1200	0:51	0	0	0	+0.12	-0.09	-0.01	-0.03	-13	-10	- 7	-0.26	-0.02	-0.37	-0.05	+1	+1
5	800	0	+1	+1	+1	+0.51	+0.01	-0.03	0.00	- 3	- 2	- 1	+0.06	+0.06	-0.33	-0.43	+1	0
	900-1010	0:05	-3	-2	-1	-0.64	+0.02	-0.01	-0.01	+ 5	+ 2	- 1	+0.26	+0.37	+0.05	-0.37	0	-1
	1125-1155	0:25	-	-	-	-	-	-0.01	0.00	+ 4	+ 6	+ 8	+0.69	+1.25	-	-	-	-
	1200	0:51	0	0	0	+0.54	+0.95	-0.07	-0.01	+14	+ 8	+ 2	+0.57	+0.54	+0.89	+0.43	+1	-1
Post-exp.	0	-	+5	+4	+3	+0.83	+1.36	+0.01	0.00	+ 9	+ 8	+ 7	-0.11	+0.49	+0.30	+0.33	+1	+1

[a] Each entry is the absolute value of the difference between the value measured with the subject at rest and the value measured while the subject performed light exercise. The symbol (+) indicates that performance improved with exercise; the symbol (-) indicates that the subject's performance was poorer during exercise than while at rest.

[b] Elapsed times are those for the rest measurement periods given in part A of this table; the exercise periods occur six minutes later. Depth ranges are based on the depth given for rest (part A) and exercise (part B).

APPENDIX TABLE 8A. Perceptual and Psychomotor Test Sequence Scores for Subject CC in Phase II. Measurements Made with Subject at Rest.

Exposure Day	Depth (fsw)	Elapsed Time[a] (hr:min)	SPEED TESTS							ORIENTATION TESTS								
			NUMBER COMPARISON TEST					GRIP SPEED TEST		CARD ROTATIONS TEST					CHOICE REACTION TIME REST			
			Number of Responses			Inter-response Time (sec)		Inter-response Time (sec)		Number of Responses			Inter-response Time (sec)		Reaction Time (sec)		Number of Responses	
			Correct minus Incorrect	Correct	Com-pleted	Mean	SD	Mean	SD	Correct minus Incorrect	Correct	Com-pleted	Mean	SD	Mean	SD	Com-pleted	Errors
Pre-exp.	0	-	10	10	10	3.43	1.57	0.16	0.05	22	22	22	1.71	1.03	1.21	0.21	6	0
1	0	0	6	7	8	4.20	1.81	0.15	0.05	25	25	25	1.49	1.36	1.31	0.30	6	0
	484	0:18	4	6	8	3.34	0.70	0.16	0.07	11	13	15	2.43	3.07	-	-	-	-
	696	0:37	8	8	8	3.72	2.08	0.17	0.04	11	17	23	1.63	1.02	1.21	0.17	6	0
	800	0:58	4	6	8	4.15	0.83	0.18	0.06	13	19	25	1.36	0.65	1.14	0.07	7	0
	800	2:19	10	10	10	3.16	2.21	0.17	0.05	0	5	10	3.52	2.31	1.07	0.20	5	0
	960	2:58	8	9	10	3.18	1.59	0.18	0.08	11	14	17	1.91	1.38	1.24	0.18	6	0
	1135	3:17	4	6	8	4.22	0.32	0.22	0.26	12	16	20	1.88	1.90	1.75	0.81	7	1
	1200	3:41	6	9	12	2.88	2.16	0.18	0.06	10	15	20	0.97	0.48	1.33	0.51	7	1
	1200	4:42	3	5	7	4.25	1.27	0.16	0.06	4	9	14	3.18	2.59	1.73	0.94	6	3
	1200	7:07	5	6	7	3.97	0.60	0.22	0.09	16	19	22	1.74	1.56	1.28	0.43	6	0
2	1200	0	4	6	8	4.09	0.84	-	-	14	15	16	1.42	0.70	1.57	0.57	6	1
	1440	0:07	-1	4	9	3.58	1.55	0.17	0.06	8	14	20	2.00	1.75	1.58	0.80	7	2
	1600	0:30	4	5	6	5.29	1.86	0.17	0.05	9	12	15	2.81	1.70	1.83	0.88	7	2
	1390	1:28	5	7	9	3.67	1.52	0.17	0.06	23	24	25	1.48	0.76	1.40	0.18	7	0
	1270	2:06	7	8	9	3:43	1.29	0.15	0.05	21	22	23	1.63	1.08	1.06	0.18	7	0
	1200	2:57	6	7	8	4.10	2.36	0.16	0.05	9	11	13	2.94	2.99	1.23	0.16	8	0
3	1200	0	3	5	7	4.17	2.38	0.14	0.05	10	14	18	1.93	1.67	1.40	0.55	7	2
	1440	0:07	0	4	8	3.20	1.52	0.17	0.06	6	13	20	2.25	1.41	1.31	0.40	7	1
	1600	0:30	2	6	10	3.00	0.81	0.16	0.06	28	29	30	1.05	0.53	1.47	0.61	7	0
	1400	1:15	6	8	10	3.21	1.13	0.17	0.05	15	19	23	1.29	0.62	1.29	0.19	6	0
	1275	1:54	6	8	10	3.40	1.09	0.18	0.06	12	15	18	1.40	1.37	1.64	0.52	7	2
	1200	2:45	6	7	8	3.81	1.57	0.16	0.05	18	18	18	2.48	3.18	1.24	0.23	7	0
Post-exp.	0	-	9	9	9	3.31	1.32	-	-	14	16	18	1.97	1.63	1.30	0.53	7	0

[a] Elapsed times are calculated from start of compression on each day as zero time to one minute into the three-minute measurement periods. Depths correspond to these times.

APPENDIX TABLE 8B. Perceptual and Psychomotor Test Sequence Scores for Subject CC in Phase II.
Measurements Made While Subject Performing Light Exercise.

			SPEED TESTS							ORIENTATION TESTS								
			NUMBER COMPARISON TEST					GRIP SPEED TEST		CARD ROTATIONS TEST					CHOICE REACTION TIME TEST			
Exposure Day	Depth (fsw)	Elapsed Time[a] (hr:min)	Number of Responses			Inter-response Time (sec)		Inter-response Time (sec)		Number of Responses			Inter-response Time (sec)		Reaction Time (sec)		Number of Responses	
			Correct minus Incorrect	Correct	Completed	Mean	SD	Mean	SD	Correct minus Incorrect	Correct	Completed	Mean	SD	Mean	SD	Completed	Errors
Pre-exp.	0	-	10	10	10	2.87	1.78	0.17	0.06	24	24	24	1.52	0.97	1.15	0.16	7	0
1	0	0	7	9	11	2.86	0.80	0.18	0.08	6	10	14	3.41	3.73	1.09	0.15	7	0
	584	0:24	9	10	11	3.03	2.08	0.16	0.05	14	16	18	1.50	1.48	2.03	1.02	7	0
	744	0:43	9	10	11	2.69	1.30	0.18	0.06	14	17	20	2.07	1.64	1.63	1.25	7	0
	800	1:04	6	8	10	3.33	2.27	0.18	0.05	21	23	25	1.28	0.60	1.22	0.17	8	0
	800	2:25	9	9	9	3.25	1.13	0.18	0.04	10	16	22	1.84	1.67	1.27	0.38	7	1
	1040	3:04	5	7	9	3.62	1.32	0.23	0.11	21	23	25	1.47	0.91	1.57	0.61	7	1
	1165	3:23	6	8	10	3.35	0.84	0.19	0.09	10	16	22	1.67	1.17	1.37	0.54	7	1
	1200	3:47	5	8	11	2.89	0.82	0.25	0.26	12	17	22	2.01	1.78	1.52	0.42	7	3
	1200	4:48	7	9	11	3.21	1.33	0.19	0.08	12	17	22	1.75	1.03	1.50	0.64	7	0
	1200	7:13	7	8	9	2.77	1.38	0.20	0.06	11	18	25	1.61	1.29	1.25	0.22	8	0
2	1200	0	8	8	8	2.84	2.21	0.19	0.06	20	21	22	1.50	1.01	1.44	0.46	7	0
	1530	0:13	9	10	11	2.89	1.89	0.18	0.05	11	16	21	1.41	1.09	1.62	0.53	7	1
	1600	0:36	3	5	7	4.39	4.73	0.21	0.06	14	19	24	1.52	0.71	2.02	1.12	6	3
3	1200	0	8	8	8	2.95	1.51	0.19	0.06	29	29	29	1.04	0.46	1.16	0.13	7	0
	1530	0:13	9	10	11	2.98	1.79	0.18	0.08	26	28	30	1.19	0.55	1.53	0.75	8	1
	1600	0:36	2	6	10	3.40	1.73	0.23	0.08	27	31	35	0.91	0.43	2.01	0.70	7	4
Post-exp.	0	-	6	9	12	2.79	1.15	-	-	16	18	20	2.22	1.20	1.19	0.41	8	1

[a] Elapsed times are calculated from start of compression on each day as zero time to one minute into the three-minute measurement periods. Depths correspond to these times.

APPENDIX TABLE 8C. Effect of Exercise on Perceptual and Psychomotor Test Sequence Scores for Subject CC in Phase II[a]

Exposure Day	Depth Range (fsw)	Elapsed Time[b] (hr:min)	SPEED TESTS							ORIENTATION TESTS								
			NUMBER COMPARISON TEST					GRIP SPEED TEST		CARD ROTATIONS TEST					CHOICE REACTION TIME TEST			
			Number of Responses			Inter-response Time (sec)		Inter-response Time (sec)		Number of Responses			Inter-response Time (sec)		Reaction Time (sec)		Number of Responses	
			Correct minus Incorrect	Correct	Com-pleted	Mean	SD	Mean	SD	Correct minus Incorrect	Correct	Com-pleted	Mean	SD	Mean	SD	Com-pleted	Errors
Pre-exp.	0	-	0	0	0	+0.56	-0.21	-0.01	-0.01	+ 2	+ 2	+ 2	+0.19	+0.06	+0.06	+0.05	+1	0
1	0	0	+ 1	+2	+3	+1.34	+1.01	-0.03	-0.03	-19	-15	-11	-1.92	-2.37	+0.22	+0.15	+1	0
	484-584	0:18	+ 5	+4	+3	+0.31	-1.38	0.00	+0.02	+ 3	+ 3	+ 3	+0.93	+1.59	-	-	-	-
	696-744	0:37	+ 1	+2	+3	+1.03	+0.78	-0.01	-0.02	+ 3	0	- 3	-0.44	-0.62	-0.42	-1.08	+1	0
	800	0:58	+ 2	+2	+2	+0.82	-1.44	0.00	+0.01	+ 8	+ 4	0	+0.08	+0.05	-0.08	-0.10	+1	0
	800	2:19	- 1	-1	-1	-0.09	+1.08	-0.01	+0.01	+10	+11	+12	+1.68	+0.64	-0.20	-0.18	+2	-1
	960-1040	2:58	- 3	-2	-1	-0.44	+0.27	-0.05	-0.03	+10	+ 9	+ 8	+0.44	+0.47	-0.33	-0.43	+1	-1
	1135-1165	3:17	+ 2	+2	+2	+0.87	-0.52	+0.03	+0.17	- 2	0	+ 2	+0.21	+0.73	+0.38	+0.27	0	0
	1200	3:41	- 1	-1	-1	-0.01	+1.34	-0.07	-0.20	+ 2	+ 2	+ 2	-1.04	-1.30	-0.19	+0.09	0	-2
	1200	4:42	+ 4	+4	+4	+1.04	-0.06	-0.03	-0.02	+ 8	+ 8	+ 8	+1.43	+1.56	+0.23	+0.30	+1	+3
	1200	7:07	+ 2	+2	+2	+1.20	-0.78	+0.02	+0.03	- 5	- 1	+ 3	+0.13	+0.27	+0.03	+0.21	+2	0
2	1200	0	+ 4	+2	0	+1.25	-1.37	-	-	+ 6	+ 6	+ 6	-0.08	-0.31	+0.13	+0.11	+1	+1
	1440-1530	0:07	+10	+6	+2	+0.69	-0.34	-0.01	+0.01	+ 3	+ 2	+ 1	+0.59	+0.66	-0.04	+0.27	0	+1
	1600	0:30	- 1	0	+1	+0.90	-2.87	-0.04	-0.01	+ 5	+ 7	+ 9	+1.29	+0.99	-0.19	-0.23	-1	-1
3	1200	0	+ 5	+3	+1	+1.22	+0.87	-0.05	-0.01	+19	+15	+11	+0.89	+1.21	+0.24	+0.42	0	+2
	1440-1530	0:07	+ 9	+6	+3	+0.22	-0.27	-0.01	-0.02	+20	+15	+10	+1.06	+0.86	-0.22	-0.35	+1	0
	1600	0:30	0	0	0	-0.40	-0.92	-0.07	-0.02	- 1	+ 2	+ 5	+0.14	+0.10	-0.54	-0.09	0	-4
Post-exp.	0	-	- 3	0	+3	+0.52	+0.17	-	-	+ 2	+ 2	+ 2	-0.25	+0.43	+0.11	+0.12	+1	-1

[a] Each entry is the absolute value of the difference between the value measured with the subject at rest and the value measured while the subject performed light exercise. The symbol (+) indicates that performance improved with exercise; the symbol (-) indicates that the subject's performance was poorer during exercise than while at rest.

[b] Elapsed times are those for the rest measurement periods given in part A of this table; the exercise periods occur six minutes later. Depth ranges are based on the depth given for rest (part A) and exercise (part B).

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The Influence of Increased Barometric Pressure on Man.—No. I.

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Introduction.

The classical researches of Paul Bert, (1) confirmed in recent years by v. Schrötter (2) and his co-workers, and also by Leonard Hill and J. J. R. Macleod (3 and 4), have demonstrated beyond question that the ill results observed in caisson workers and divers are to be attributed entirely to injudicious rapidity of decompression.

Experiments on animals have shown that every 100 c.c. of blood or tissue fluid dissolve, at body temperature, about 1 c.c. of nitrogen under one atmosphere of air; 2 c.c. under two atmospheres; 3 c.c. under three atmospheres, and so on (Hill and Macleod, Hill and Ham). (5)*

This nitrogen is set free as bubbles in the capillaries and tissue spaces when the decompression period is made too short, and by the embolism of some vessel, may produce symptoms varying in kind and severity.

One of us (L. H.) having determined, by numerous experiments on animals, that no ill effects follow exposure to pressures up to + seven atmospheres, if 20 minutes be allowed to each atmosphere for decompression, we determined to investigate the effects of high pressures of air upon ourselves.

The records of caisson works and the operations of deep sea divers show that owing to the rapid rates of decompression at present employed by engineers and divers, very great risk is incurred by workers in caissons at pressures of + 3 atmospheres, and by divers at depths of from 100 to 150 feet. As, however, divers usually stop a very brief time, while caisson workers outstay a shift of from 2 to 4 hours, the body fluids of the latter become saturated with nitrogen, hence their greater danger at lower pressures.

The limit for practical diving work is fixed by the great increase of mortality and illness which occurs at depths much exceeding 100 feet, while at less depths than this, accidents are by no means infrequent; being occasionally very severe or fatal in character.

The Admiralty set 120 feet as the limit of work for their divers, while the most daring pearl and sponge fishers sometimes reach depths of 145 feet; in

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* Bohr ('Nagel's Handb. d. Physiologie,' 1905, vol. 1, p. 117) gives the coefficient of absorption of arterial blood exposed to an atmosphere of N_2, at body temperature as 1·26.

this latter group accidents are numerous. Lambert, the famous diver employed by Messrs. Siebe and Gorman, salved £100,000 at a depth of about 160 feet. On each descent he passed about 20 minutes below, and about the same time in ascending. On the last journey he stayed longer and became affected on his return to the surface, permanently losing the power to retain his urine. Lambert was the man who stopped the flooding of the Severn Tunnel, going through the tunnel (dark and full of water) in a Fleuss dress to a distance of a quarter of a mile from the shaft, and closing the flood gates, which had been left open; his courage deserves to be recalled. Another diver, Erostabe, salved treasure from a depth of 171 feet, and yet another, Ridyard, from 160 feet. These three divers of Messrs. Siebe and Gorman hold the record for successful work carried out at great depths. Two other divers of the same firm, in order to test a patent kind of diving apparatus, descended to 189 and 192 feet respectively. One of these divers (Walker) tells us he was about 50 minutes over the job, taking 30 minutes to ascend. He ascribes his immunity from accident throughout his career as a deep diver to his habit of slow ascent. The deepest dive on record is one of 204 feet (+88½ lbs. pressure); the diver who made this record died from the effects of too rapidly mounting to the surface.

In 1894, at Bordeaux, H. Hersent, (7) an engineer in charge of caisson works, having first experimented on animals, found three workmen willing to submit themselves to high pressures of air. These men were enclosed in a steel chamber, and the experiments were conducted under the observation of a commission composed of five members of the Bordeaux Faculty of Medicine. Two of the workmen had had previous experience of compressed air.

In one experiment the subject was compressed to +4·800 kilos. per square centimetre (+68·27 lbs. per square inch) in 35 minutes, remained under this pressure 1 hour, and was decompressed in 2 hours 3 minutes. On quitting the chamber the man experienced a few "picotements," which lasted for half-an-hour, but no other unfavourable symptoms. In a second experiment, a pressure of +5·000 kilos. (+71·16 lbs. per square inch) was attained, without any subsequent ill effects beyond a few "picotements."

Finally, the same subject was compressed to +5·400 kilos. (+76·81 lbs. per square inch) in 45 minutes, remained under the pressure 1 hour, and was decompressed in 2 hours 25 minutes. The effects are recorded in these words: "A ressenti peu de picotements, cela tient aux bains sulfureux pris les jours précédents." (8).

Hersent's experiments justify his conclusion that "avec quelques précautions en sus de celles qu'on prend ordinairement, les hommes peuvent être comprimés et décomprimés sans danger pour leur vie, et que même leur

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santé n'est pas menacée quand on atteint des pressions allant jusqu'à 5 kg. 400."(9)

Hersent and his medical colleagues do not appear to have entered the pressure chamber themselves, so that we are not in possession of an accurate record of the subjective effects as noted by trained scientific observers. One of our objects therefore has been to study in detail the subjective and physiological changes induced by greatly increased barometric pressures; another object has been the investigation of the respiratory exchange under the same conditions. In the present memoir we shall communicate the results already obtained.

PART I.

Our experiments have been carried out in a steel cylinder kindly placed at our disposal by Messrs. Siebe and Gorman, the eminent firm of naval engineers, to whom we are further indebted for much valuable assistance.

This cylinder (*vide* photograph, p. 446) had a capacity of 42·2 cubic feet, and was provided with a mattress, blanket, and pillows, enabling the subject to adopt a comfortable attitude. Compression was effected by means of a two-cylinder motor-driven pump, which could raise the pressure to +6 atmospheres in about 40 minutes. Two decompression taps were provided, with fine bores, permitting very careful adjustment of the rate of escape. The chamber was also fitted with electric light, bell, telephone, and a thick glass observation window; the latter, however, was subsequently covered with a steel shutter for greater security. The pressure was measured by a Bourdon spring gauge, which had been tested for correctness. We shall now give an account of a typical experiment. The description is reproduced from notes taken at the time:—

Experiment II. 29.11.05.

The subject* (M. G.) entered the chamber at 10.40 A.M. In order to avoid any accumulation of CO_2, a constant ventilation at the rate of 25 litres per minute was maintained.

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* The measurements, etc., etc., of the two subjects were: L. H., age 39, weight (in clothes) 87½ kilogrammes, height 1·81 metres, vital capacity 3500 c.c., tidal air 510 c.c.; M. G., age 25, weight 53 kilogrammes, height 1·65 metres, vital capacity 4000 c.c., tidal air 300 c.c. Both were in good physical condition.

Time.	Temperature of chamber.	Pressure.	Notes.
10.40 A.M.	57° F.	+0	
10.50	62	—	
10.55	—	+16 lbs.	Voice becoming nasal and metallic.
11.5	67	—	
11.20	69	+62 lbs.	Sensation of slight vertigo.
11.34	68*	+92 „ †	
Between 11.25 and 11.40 articulation was difficult, and the subject experienced some trouble in making himself heard through the telephone.			
11.55	—	+77 lbs.	
12 noon	65	—	
Subject quite comfortable, voice still nasal but easier to produce and much more audible.			
12.4 P.M.	—	+72 lbs.	
12.10	—	—	Pulse, 40. Respirations, 9 per min.
12.37	64	+52 lbs.	
1.0	63	+31 „	Voice much better.
1.20	63½	—	Pulse, 42.
1.51	—	+0	

Period of compression, 54 minutes.

Period of decompression, 2 hours 17 minutes.

On quitting the chamber some itching was perceived in both forearms, especially the right. In about 20 minutes neuralgic pains were felt, localised in the radial side of the left forearm. These pains gradually increased in intensity, spreading up the arm; then, after remaining moderately intense for five minutes, they gradually subsided. Several minutes later (about one hour after leaving the chamber) similar pain was experienced in the right forearm. This however did not spread upwards, was less severe and quickly subsided. An hour and a half after leaving the cylinder the subject felt quite well and no subsequent ill effects resulted. As will appear later, there is good reason to suppose that the slight discomfort present at the conclusion of this experiment is attributable to the fact that the subject remained almost completely at rest during decompression. We may therefore conclude that an adult may be safely submitted to a total barometric pressure of at least 7 atmospheres, which is, we believe, a limit higher than any previously reached.

In the course of our investigation the following pressures have been attained:—

Subject, L. H.	Subject, M. G.
75 lbs., once.	90 lbs., once.
60 „ twice.	75 „ three times.
45 „ „	60 „ four „
30 „ four times.	45 „ five „
	30 „ seven „

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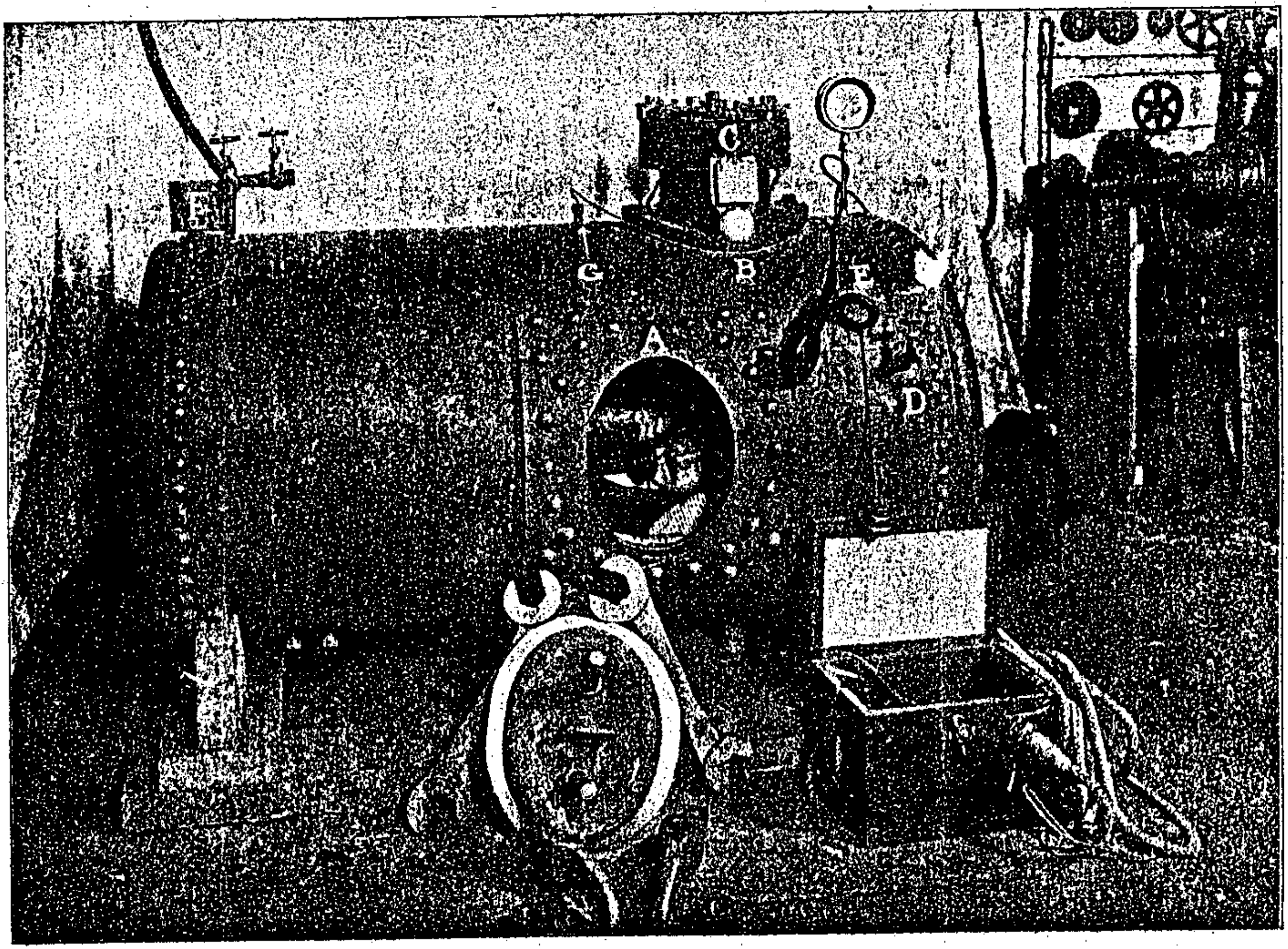
* Wet cloths were placed on the cylinder at this time.

† This reading was verified by Mr. J. A. Craw, who was present during the whole course of the experiment.



VIEW OF CYLINDER (OPEN), WITH WORKMAN INSIDE.

A. Manhole. B. Electric bell. C. Observation window (closed). D. Decompression tap.
E. Telephone. F. Compression pipe. G. Electric light wire.

In no case have any severe after effects resulted. The maximum pressure in our series corresponds to a water depth of 210 feet, which is 90 feet beyond the limit fixed by the Admiralty for their divers.

Supposing the special diving bell designed by one of us (L. H.) for the slow decompression of divers were employed, it seems quite possible that work might be carried out safely at a depth of 210 feet. Even a greater depth than this might be attained by an intrepid man, for the limit appears to be fixed by the pressure at which the toxic effects of high tension oxygen become an immediate danger.

These effects have been studied by Paul Bert, Lorrain Smith (10) and Hill and Macleod (3). When the partial pressure of oxygen reaches 2 atmospheres (corresponding to 10 atmospheres of air, or a depth of about 350 feet of water) convulsions may occur in animals within 20 minutes. The limit of *possible* safe working is therefore about 250 feet. Conceivably this limit might be extended by diluting the air with nitrogen so as to lower the partial pressure of the oxygen, but we do not claim more than that our experiments show the safe diving depth may be increased up to 210 feet.

The responsibility of those who allow short decompression periods in caisson works is clear; every death or case of paralysis from air embolism must be set down to the negligence of the contractor.

Next, as to the sensations we felt under pressure: the feeling of discomfort in the ears and deafness, due to a difference in air pressure within and without the tympanum, is too well known to need description. Owing probably to a catarrhal condition, we were unable to open our Eustachian tubes by merely swallowing, and were compelled to resort to a forced expiratory effort with mouth and nose shut, the latter being held tight by the finger and thumb.

To one of us (L. H.) who had not practised beforehand the opening of his Eustachian tubes, the first *séance* was most disturbing. The sensation of increasing deafness and discomfort, more than discomfort, in the ears, with no obvious cause, and the inability to gain relief by the recognised method of swallowing, produced a feeling of mental distress which led to his signalling to terminate the experiment. Once having learned the method of opening his tubes, no such trouble resulted on subsequent occasions.

As to whether one possesses any real sense of the amount of pressure, the answer must be in the negative. V. Schrötter and his co-workers (11), who made observations in caissons sunk in the Danube at from +0·5 to +2·65 atmospheres, say that: " Bleibt nun der Druck stationär, verweilt die Person auf längere Zeit unter einem bestimmten Drucke, so hört mehr oder minder rasch, oft mit einem Schlage, jegliche unangenehme Sensation im

Ohre auf, nur das Gefühl von Dumpfheit, das Gefühl eines vermehrten Widerstandes im Ohre, wird in der Mehrzahl der Fälle, besonders von Ungewohnten, wahrgenommen."

We found that all distinct sensations of pressure in the ears were relieved immediately the pump ceased its strokes, and the pressure in the chamber became constant. Our hearing was as acute and, in the opinion of L. H., more acute than normally. The signal of a tap with an iron spanner on the outside of the chamber was, to L. H., painful in its intensity.

Apart from the feelings of nervousness at being exposed to so high a pressure (which at times were somewhat acute, especially when we were not engaged in analytical work), we could not detect any real sense of pressure, and certainly noticed no abnormality in our bodily functions, with the trifling exception of the voice. Thus during Experiment XV the subject (L. H.) when at +60 lbs., wrote: "Very nervous all through experiment; whenever time for thought, the feelings of pressure, if any, due to non-equilibration of ears when pressure is rising." During the same experiment, when the subject learnt he was at +55 lbs., he wrote: "Thought one was lower until told. No real sense of pressure except lip and voice change." In another experiment, M. G. was nearly two atmospheres too low in his estimate of the pressure, while in a third experiment made at a period when custom had lessened the nervous effect, he replied to a question at +60 lbs., "no sense of pressure."

The voice changes, observed in all caisson workers, were well marked in ourselves. The alteration is distinct at +1 atmosphere, and very marked at +3 atmospheres. The voice has a peculiar nasal and metallic quality, losing the individual characteristics of the speaker. Thus to L. H., when speaking in the chamber, under pressure, his voice appeared like that of M. G. under pressure. So close was the resemblance that L. G. could fancy himself outside and listening to M. G. through the telephone.

At +3 atmospheres the power to whisper or whistle is almost entirely lost. L. H., who retained the power somewhat longer than M. G., could just make an audible whistling note at this pressure.

This loss of the fine vibratile movements of the tongue and lips, a loss probably resulting from the damping effects of the dense air, leads to a false sense of anæsthesia in the former parts. This conception of anæsthesia is interesting, as being solely excited by a lack of normal movement.

V. Schrötter and others have laid stress on the diminished frequency of the pulse and lowered blood pressure of caisson workers. Our observations are not sufficiently extensive to permit of any final pronouncement; but, so far as they go, we are unable to detect any *definite* change in the pulse frequency. For instance, in Experiment II, M. G.'s pulse was at the rate of 40 per minute at +70 lbs., and 42 at +63 lbs. In Experiment XIV, it was 41 per minute, at +50 lbs., 30 at +30 lbs., 42 at +10 lbs., and 41 at +2·3 lbs. This subject's pulse is normally slow, being rarely above 60 per minute in the sitting posture; hence although there appears to have been a diminution in frequency, the change is not nearly so striking as in the cases tabulated by V. Schrötter (12).* L. H. found no alteration in his pulse-rate at +5 atmospheres.

Our observations on the blood pressure have not been at all complete. The Hill and Barnard pocket sphygmometer, depending as it does upon a column of air acting as an elastic spring, is not a satisfactory instrument for high pressure work, the viscosity of the dense air lessening the excursion of the pulse very greatly.

We came to the conclusion that it was an important matter during the decompression to move in turn every muscle and joint of the body, and to change one's position frequently, so as to keep the capillary circulation active in every part. In the brain, spinal cord, and abdominal organs this circulation is kept active by the work of the respiratory pump. In the limbs, muscles, fat of the back and chest, on the other hand, the movement of the blood and lymph back to the heart depends mostly on changes of posture and the expressive action of contracting muscles. The following observations support these views.

In Experiment XIII M. G. was decompressed from +75 lbs. in 95 minutes. During decompression he flexed and extended all the limb joints at frequent intervals, with the exception of the knees. Subsequently pain and stiffness were detected in the knees and nowhere else.

In Experiment XIV the same subject was decompressed from +5 atmospheres in 120 minutes. During the compression all the limb joints, including the knees, were repeatedly moved. No after effects of any kind were experienced. A further difference between the two experiments was that in the second a pause of about five minutes was made at each atmosphere for analytical purposes. As in each of the experiments followed by pain (in the case of M. G.) no such pauses occurred, it is possible, but we think not probable, that these may also play a part in hindering the development of after effects.

The most interesting experiment in this connection is No. XV. L. H. was decompressed from +5 atmospheres in 105 minutes, a pause of five minutes being made at each atmosphere. During the decompression movements of

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* In Schrötter's cases there was no direct relation between barometric pressure and pulse frequency.

the joints and muscle of the limbs and back were carried out regularly. On emerging from the cylinder, beyond a few "picotements," no unpleasant symptoms were noticed.

On the next day the subject wrote as follows: "The only place I did not move and massage was the front of the chest, where I have plenty of subcutaneous fat. In the evening painful places were felt in the subcutaneous tissues of the anterior thoracic region; one spot under each nipple, one across the right side of the chest about the level of the ensiform cartilage, another above the left axilla in front, and one over the right upper arm in front. A red or purplish rash appeared over these tender places. They felt like a spot in which a subcutaneous injection of water has been made. Next morning the tenderness was better but still evident, and the rash was subsiding."

Forty-eight hours after the experiment this purpuric rash was still discernible, and was shown to Dr. W. Bulloch and other pathologists. An eruption occurred in a very severe case of caisson illness seen by Heller Mager and v. Schrötter (13). They give a plate of the eruption, which is described in these terms: "Haut der linken Schulter und des linken Armes an der Aussenseite, besonders in der Gegend des Olekranon und des äusseren Condylus sowie in der Gegend des Biceps mit lividen, bläulichrothen netzförmig verzweigten, inselförmigen Flecken bedeckt, ebensolche auch am Handrücken." The arm of this sufferer was much swollen and intensely painful. These observations then show the extreme importance of active movement and massage during decompression; instructions should be given to all caisson workers to perform such movements while in the air lock.

We believe the tenderness and the rash were caused by small bubbles embolising the vessels of the subcutaneous fat in the case of L. H. The pair felt by M. G. was probably due to small bubbles in the nerve sheaths in the first case, in the knee joint in the second.

PART II.

The next stage of our investigation was devoted to an inquiry as to the changes in the percentage of alveolar CO_2 under the altered conditions.

We have employed the method described by Haldane and Priestley (14) The subject breathes through a wide-bored rubber tube; after a normal expiration he expires deeply and then closes the end of the tube with his tongue. A sample was taken from the wide tube into Haldane's portable CO_2 analyser, and examined. A bench fitted up in our cylinder enabled the subject to collect and examine samples with ease. It may be remarked that it is necessary to replace the corks at the bottom of the water bath in Haldane's apparatus by well-fitting rubber ones, as the air is compressed in the corks, which leak at high pressures. Owing to the loss of the water jacket some of our earlier experiments were unsuccessful. Great care is also necessary in readjusting the potash levelling tube, as when the chamber is closed a slight fall of pressure is almost inevitable owing to escape round the washer of the door.

Haldane and Priestley have shown that the respiration is so regulated as to maintain a constant tension of CO_2 in the alveolar air, which is generally about 5 per cent. of an atmosphere. Now supposing the metabolism to be unaffected by changes of pressure, and the regulation of respiration to continue the same, the amount of CO_2 in the alveolar air must vary inversely as the pressure attained.

Thus if p be the percentage of CO_2 at normal pressure, then we should have, at two atmospheres, $p/3$ per cent. of CO_2 in the alveolar air. It will be seen that these conditions were almost exactly realised by us. The following table gives the result of two typical experiments. The figures in brackets give the percentages reduced to + 0 lb. in accordance with the above principle. Strictly speaking, the exact height of the barometer should have been recorded, and another correction ought to have been made for charges of temperature in the cylinder. As there is however a necessarily large experimental error, we think it needless to allow for these minor differences, and have accordingly assumed the normal atmospheric pressure to be 15 lbs. to the square inch, and neglected the temperature :—

Experiment XIV. 10.1.06. *Subject, M. G.*

Percentage of CO in alveolar air.		Pressure.
5·3 (5·3)		+ 0 lbs.
0·9 (5·4)	(Mean of two)	+75 „
1·0 (5·0)		+60 „
? 1·3 (5·0)		+45 „
1·8 (5·4)		+30 „
2·7 (5·4)		+15 „
5·4 (5·4)		+ 0 „

Experiment XV. 10.1.06. *Subject, L. H.*

Percentage of CO_2 in alveolar air.	Pressure.
4·7 (4·7)	+ 0 lbs.
0·9 (4·5)	+60 „
0·7 and 0·8 (4·5)	+75 „
0·95 (4·75)	+60 „
1·2 (4·8)	+45 „
1·8 (5·4)	+30 „
2·5 (5·0)	+15 „
5·0 (5·0)	+ 0 „

The next tables comprise all our results. The figures vertically beneath one another refer to the same experiment:—

Subject, M. G.

Pressure.	Alveolar percentages of CO_2.					
lbs.						
0	5·3, 5·4	5·3	5·5	5·7	5·5, 5·7	5·3, 5·4
8	3·3 (5·06) mean	—	—	—	—	—
15	2·3 (4·6) mean	—	—	—	—	2·7 (5·4)
16	—	—	—	2·7 (5·58)	2·7 (5·58)	—
22	—	—	2·1 (5·18)	—	—	—
30	—	—	1·8 (5·4)	—	—	1·8 (5·4)
31	—	—	—	1·8 (5·52)	1·8 (5·52)	—
45	—	—	—	—	—	?1·3 (5·2)
46	—	—	—	—	?1·3 (5·3)	—
60	—	—	—	—	—	1·0 (5·0)
61	—	—	—	—	0·9 (4·6)	—
75	—	—	—	—	—	0·9 (5·4)

Subject, L. H.

Positive pressure.	Alveolar percentages of CO.				
lbs.					
0	5·2, 5·3, 4·9	4·9, 5·0	5·15	4·9, 5·0	4·7, 5·0
4	3·5, 4·0 (4·8)	—	—	—	—
9	—	3·35 (5·35)	—	—	—
18	—	2·5 (5·48)	—	—	—
23	—	2·1 (5·3)	—	—	—
17	—	—	2·5 (5·3)	—	—
31	—	1·85 (5·7)	1·7 (5·2)	—	—
14½	—	—	—	2·5 (4·9)	—
30	—	—	—	1·65, 1·7 (5·0)	1·8 (5·4)
44½	—	—	—	1·25, 1·3 (5·1)	—
45	—	—	—	1·3 (5·2)	1·2 (4·8)
52	—	—	—	1·1 (4·9)	—
60	—	—	—	0·95, 1·0 (4·88)	0·9, 0·9 (4·5)
75	—	—	—	—	0·7, 0·8 (4·5)
15	—	—	—	—	2·5 (5·0)

We think these results show so close an agreement with the theoretical values as to support the conclusion that changes in the percentage of carbon dioxide in the alveolar air depend solely upon the physical conditions. No increase or decrease in the pulmonary output of CO_2 occurs. Metabolism, then, in so far as it can be determined by an investigation of the alveolar air, is not affected by increasing the barometric pressure. It is scarcely necessary to add that this criterion is by no means adequate to sustain the *final* conclusion that metabolism is, in fact, unaltered by the atmospheric conditions; so far as it goes, however, it is in favour of such an inference. Summing up the results of the present investigation :—

It is proved that—

(1) A man can be submitted to a total pressure of seven atmospheres without untoward effects, provided decompression be affected gradually, and the capillary circulation be aided by repeated contractions of muscles, joint movements, and charges of posture.

(2) We have no sense of increased barometric pressure so long as the former is constant.

It is probable—

(1) That the subjective effects of increased pressure, apart from voice changes and lip anæsthesia, depend upon psychical conditions such as anxiety and excitement.

(2) The changes in the percentage of carbon dioxide in the alveolar air are conditioned solely by physical variations, and not by any increase or diminution in the respiratory metabolism.

In conclusion we would remark that we are unable to find any evidence in support of Snell's (15) opinion, that the presence of CO_2 in the respired air exercises a peculiarly unfavourable influence under increased pressure. Thus in one experiment the percentage of CO_2 in the chamber air, at + 31 lbs. was 0·62 (equivalent to over 1·8 per cent. at + 0), and no untoward results occurred on decompression.

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Performance Comparisons of Scuba Divers vs Submersible Manipulator Controllers in Undersea Work

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This paper was prepared for presentation at the Third Annual Offshore Technology Conference to be held in Houston, Tex., April 19-21, 1971. Permission to copy is restricted to an abstract of not more than 300 words. Illustrations may not be copied. Such use of an abstract should contain conspicuous acknowledgment of where and by whom the paper is presented.

ABSTRACT

The basic problem to which this research program is devoted is the current inability of ocean engineering personnel to design undersea hardware systems which complement the capabilities of the human operator. This problem stems largely from a lack of quantitative research data on the relative shortcomings and strong points of divers and a similar lack of data describing the capabilities of various undersea manipulator work systems. The research has been oriented toward quantitative data collection which describes how rapidly, how proficiently, and under what circumstances an operator can or cannot perform tasks of what difficulty, both as a diver and as a manipulator operator aboard a submersible. The results are presented in the form of a ratio of performance time for the diver versus a manipulator. The conclusions of this research are based on data collected in a wet simulation facility. The tasks range from simple tasks such as sample gathering, valve turning and hooking to tasks of increasing difficulty such as cable rigging, unbolting, Hansen connect/disconnect functions, hole drilling, hole tapping, and pipe threading. The overall ratio for all tasks studied was 1/4; e.g., a diver was four times faster than a rate-controlled manipulator. More importantly, depending on the task, this ratio changed drastically. For example, the tapping of holes in 1/2-inch aluminum plate was performed equally fast by the diver and the manipulator (1/1); however, the diver frequently broke taps. Another task required the connecting and disconnecting of a 1/2-inch Hansen quick-disconnect fitting which the diver performed 31 times faster than the manipulator. The diver also always ensured that the connection was securely made. Conclusions are presented in this article in terms of which tasks and task aspects contributed most to the observed positive or negative performance of divers and manipulator operators.

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INTRODUCTION

A major consideration in the development, operation, and maintenance of subsurface installations is the type of implementation methodology selected to perform the work. Examples include surface-controlled rigging, a direct diver deployed in any of serveral configurations, and submersibles equipped with manipulators.

Experience with the performance capacities of these methodologies varies from a great deal of experience in surface-controlled rigging to somewhat less experience in the diver area, to marginal experience with submersible manipulator systems. A selection from among these approaches would consider many variables, including depth, environment, cost, and personnel. The objective of our research is to improve the level of experience and, therefore, to increase the information available for decision making on one of these variables - performance ability of the operator. The research, in addition to accessing fixed performance levels, has compared the skills and abilities of an operator employed as a diver with his role as a submersible manipulator operator. The comparison

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References and illustrations at end of paper.

concerns performance as a function of such variables as the type of manipulators used, the characteristics of the work to be performed, and the conditions of well-anchored submersibles using manipulators versus usage at sea under more reactive conditions.

The bulk of the previous research concerning the evaluation of manipulator control systems had been single-task oriented rather than multi-task oriented. The approach used in this study was to examine several levels of task complexity and show which task and behavioral task elements were most suited to a particular type of manipulator control system. The most salient result of our research is that the general statements found in the literature concerning the relative value of various rate-control systems for manipulator control should be treated cautiously when extrapolated to submersible work systems. This is because the results are generally based on single, relatively simple applied tasks. Our results indicate task complexity to be a key variable with regard to control system selection.

APPROACH

Initially, the work involved an overview of previous operational applications and research in the areas of underwater diver performance, remote manipulators developed for handling radioactive materials, and NASA research concerning both EVA and manipulator applications.

In conjunction with this review of previous work, we obtained data on the ability of Electric Boat division's manipulator-equipped STAR vehicles to perform fairly simple recovery tasks and a certain amount of tool work. This data indicated a large discrepancy between underwater and laboratory (in-air) data on the same manipulator arms, and between data reported in remote-handling literature. One of the key problems identified was viewport distortion and its effect on visual judgments of depth and alignment (22). A second problem was the typical location/position of the operator in a cramped submersible sphere, especially as a function of task duration (22). A third problem was the general level of visibility, light, and empty visual field conditions in which the work was performed. A fourth problem was the mobile and reactive interface between the submersible and the manipulator work place (21). Despite improvements such as corrective optics, glass spheres, better operator layout design, laser and pulsed light and image intensifiers, and vehicle anchoring systems, these problems still exist with current systems. We reasoned therefore that research regarding quantified capabilities of undersea manipulators should be performed in that context.

We performed this research with the first three problem areas simulated in a wet tank facility; all four problem conditions were researched at sea using the AUTEC vehicles.

The wet simulation facility consisted of a tank 15 feet in diameter and 18 feet deep, containing 22,500 gallons of water. The tank wall was penetrated with a conventional 5-inch diameter submersible viewport, and a mockup of the forward portion of a small submersible was attached to the outside wall. This interface was designed to simulate the STAR II submersible and its lower forward viewport. Figure 1 shows this design translation. The operator assumed the conventional "Moslem at Prayer" position to view the manipulator task through the viewport. Figure 2 is the view when looking into the tank through the viewport. Figure 3 shows the same view with the tank filled with water for the experimental condition. The reader should note the effects on visibility. Figure 4 is a view from the top of the tank showing the relative locations of the work task, the manipulator, the operator's viewport (top, just above stand framework), and the test observer's viewport (top, right). (The last two figures show the tank drained of water for the sake of clear photography.)

Work Task

The overall task studied was to salve a large valve, obstructed by framework connected to the valve, and raise the valve to the surface through use of an available flotation device. The individual tasks involved:

a. collecting two small sponge-like samples of interest, located in the general area of the valve,

b. hooking a J hook, attached by a chain to the flotation device, into a padeye located on the valve,

c. unbolting two bolts which held the valve to the wreckage,

d. drilling a 1/2-inch hole in the flotation device buoyancy area,

e. pipe tapping the drilled hole,

f. inserting a pipe nipple, with one half (male end) of a Hansen quick-disconnect air coupling, into the tapped hole for airtight fit,

g. connecting the other half (female end) of the quick-disconnect coupling, fitted with an air supply hose, to the male fitting on the pipe, and,

h. opening a valve to fill the self-venting flotation device with air to raise the structure, to the surface.

We attempted to design a work task which consisted of various subtasks that varied in complexity and requirements. This allowed us to describe the performance differences between divers and manipulators in terms of increasing levels of complexity of work requirements.

Manipulator Control Systems

A major variable in this type of comparison is the type of manipulator used and the control system used to activate the manipulator. Since the majority of underwater manipulators are of the simple, rugged, rate-control type, we chose a representative arm of this class for our first study. (See Figures 2 and 4.) To control the arm, we selected four different control systems to evaluate relative to each other. These control systems were:

1. pushbutton with a fixed rate for each arm joint,
2. pushbutton with an option for the operator to continuously adjust the rate of arm movement,

3. joystick with a fixed rate for each arm joint, and

4. joystick with an option for the operator to continuously adjust the rate of arm movement.

The pushbutton and joystick controllers are shown in Figures 5 and 6.

Additional Conditions

The divers wore SCUBA rigs and boots (no fins) and were tethered only for the drilling task. Visibility was maintained at about 12 feet for both the diver and the manipulator tests. The light level was maintained at an average of 15 foot lamberts. A total of four subjects was used for the manipulator portion of the research and two subjects for the diver portion. Each of the subjects was a well-trained, experienced operator. For example, two of the manipulator operators were pilots of small submersibles and had operated similar arms at sea and in the laboratory. The divers included a qualified Navy diving officer and a commercial diver.

RESULTS

Our major findings are summarized in Table 1. The data is presented in the form of a diver/remote manipulator (D/R) ratio of performance time. The ratio is presented for a diver versus four different manipulator control modes to perform a specific task. The table is organized such that manipulator complexity increases from left to right across the top of the table and task complexity from top to bottom down the side of the table. For example, for a relatively simple task such as Sample Collection, a diver under fairly ideal conditions could perform the task in 0.18 minutes. A rate-controlled manipulator with a pushbutton, fixed-rate control (PBFR) system performed the same task in 2.59 minutes, or 14.4 times slower than the diver.

The blank areas under position and computer-controlled manipulators represent research in progress at Electric Boat. The objective of this current research is to compare the increase in work effectiveness of these more complex manipulator systems with the rate-controlled manipulators, as described in this paper.

Discussion by Task

The following is a discussion of the results by each task (rows of the Matrix) studied and the conclusions drawn from the research.

Sample Collection – This task was representative of the type of task generally found in the literature and represented our lowest level of task complexity. The task involved collecting two sponge-type samples which were relatively easy to grasp from almost any approach angle and dropping them into a large retrieval basket.

A pronounced effect was noted with the addition of variable rate (VR) to the joystick (JS) and the pushbutton (PB) conditions: performance increased by approximately 20 percent. This effect was statistically supportable.

The sample collection task required a good deal of simple movement and travel behavior. The addition of variable rate allowed the operator to speed up these simple motion patterns which he could coordinate at higher speeds without overcontrol (overshoot, etc). With variable rate, the joystick showed a slight advantage due to simultaneous motion coordination; however, this effect was not statistically supportable.

The ratios for this task are somewhat in agreement with general conclusions offered by others (19) with respect to rate-controlled manipulators versus divers.

In addition to the time analysis for this task, a qualitative performance index was collected from the test observer's comments. This index indicated superior performance for joystick control over pushbutton control in terms of dropped samples and overall apparent coordination.

In summary, for this particular task, the optimal manipulator control was a joystick with variable rate (JSVR); the D/R ratio was about 1/11.

Valve Manipulation - This was a comparatively simple task requiring the operator to close a 90-degree lever handle ball valve. The task was performed equally well by all of the control systems. This finding is closely allied with the results for sample collection, an equally simple task. Performance records of the test observer did not indicate that any system possessed an apparent advantage or limitation.

The D/R ratio is also similar to that for the sample collection task (1/11).

Rigging Chain, Hooks - This task involved picking up a standard 3-ton capacity "J" hook and chain, and hooking it into a padeye on the valve to be salved. The task was more difficult than the sample collection task in the travel, grasp, and alignment phases. For example, one travel motion required the handling of the hook and chain together, resulting in chain snags if the travel path was not carefully controlled. Similarly, grasp and alignment functions were more precise in relation to the approach to the hook and the padeye.

Performance improved as a function of variable rate and pushbutton control systems. The joystick, fixed rate (JSFR) was significantly different from pushbutton, fixed rate (PBFR) and pushbutton, variable rate (PBVR). Joystick, variable rate was significantly different only from pushbutton, variable rate.

This trend is supported in previous research with regard to the value of variable rate; however, it contradicts the assumed superiority of the joystick. The principal reason postulated for the better performance of the simple pushbutton control system was the task requirement for deliberate control. This was especially noted when travelling with the hook and chain without snagging the chain, which was almost 30 percent faster for the pushbutton, variable rate control. Deliberate alignment and grasp of the hook was similarly improved by approximately 20 percent. These aspects of the task primarily accounted for the superior performance of pushbutton control.

Inspection of the test observer's notes also indicated that the pushbutton system's deliberate control ability facilitated accuracy in the task. This increase was observed especially when variable rate control was used, permitting the operator to slow down the arm for more accurate alignment and grasp control. This increase in accuracy was not indicated in the time data because, from a time standpoint, slowing the arm decreased performance. The increase in accuracy was observable, however, in the smaller number of snags and aborted runs caused by dropping the hook. The D/R ratio increased over that for the sample collection task by about 35 percent, indicating increased difficulty for the manipulator arm when compared to the diver.

Bolt Removal with Power Tool - This task required the operator to remove two 3/4-inch 10 threaded bolts from a framework in order to free a valve to be salved. This was a fairly easy task; the only critical portion involved the alignment of a socket wrench with the hex head of the bolts. This aspect of the task resulted in poor performance for the fixed rate joystick control, compared to all other forms of control. This difference was statistically supportable.

The major conclusion drawn from this task analysis is that for combined motion control, a manipulator system with very slow rates is optimal for precisely controlled alignment.

As shown in Table 1, the D/R ratio for this task was approximately 1/10 overall. The primary difference between manipulator and diver performance was, again, due to the alignment requirements of the task. We postulate that the manipulator's lack of tactile or force feedback is the main reason for its relatively poor performance in comparison to the drilling and tapping tasks.

Tapping with the Power Tool - This task involved using a power tool to tap a 23/32-inch drilled hole in a 1/2-inch aluminum plate. The task consisted of travel to the hole, alignment, tap use, and withdrawal. The most critical segments of the task were alignment and use of the tap. As the data in Table 1 indicates, no real difference existed between the control systems; statistically speaking, the points were the same. The major difference between this task and drilling occurred in the alignment and use portions of the task. Alignment was less critical: the tap point often "walked" into the hole, thus acting as a guide to align the arm. Because of its threading action, the tap also tended to draw itself into the hole during the use segment. This is a good example of task requirements actually favoring the manipulator/tool system.

As shown in Table 1, the D/R ratio is the lowest of any of the tasks studied. In addition to the D/R time measure, the performance data comparison showed that the accuracy of the divers' performance was substantially poorer than that of the manipulator control systems. While tapping, the divers broke off the tap in the hole in approximately 20 percent of the trials, as against no tap breakage for the manipulator trials. Figure 7 shows the relative tapped hole angle error for divers and manipulators; Figure 8 shows a subjective rating of the holes made by both manipulator control systems and a diver. In both cases, the divers' performance was inferior to that of all manipulator control systems.

The divers' tap breakage problem resulted from poor initial alignment and high stress loads applied to the tap when the hole caused the tap and the tool to center themselves. The major problem of initial alignment does not show up in the tap angle results because the drilled hole tended to center the tap.

A third performance measure was the depth of tap as measured by a thread gage. The results of this measurement are shown in Figure 9 which shows thread error as a function of the control system. The divers' performance was again shown to be inferior to that of all manipulator control systems.

Threading with Power Tool - This task required the operator to insert a threaded pipe into the tapped hole for an airtight fit. The results of this task were fairly uniform and statistically insignificant with respect to the differences between manipulator control systems. Good threading was observed in 80 percent of the trials, and cross threading in 20 percent of the trials for the manipulators. The performance measures, consisting of the number of cross-threaded holes and the test observer's comments on goodness of fit, were generally equal across all control systems. The most interesting result of the trials for this task is that although it was essentially the same as the tapping task in motion pattern and alignment requirements, the D/R ratio returned to about 1/10. The performance scores similarly shifted in favor of the diver with respect to cross threading. The manipulator operator spent the bulk of the time aligning the pipe with the hole and attempting to match the threads. This aspect of the task was most difficult for the manipulator operator without tactile or force feedback, and probably accounts for the major difference.

Drilling with Power Tool - This task involved the drilling of a 23/32-inch hole in a 1/2-inch aluminum plate. The plate was set at a 30-degree angle to the vertical, and the operator was required to align the drill to the plate in terms of X and Y planes perpendicular to the plate, and feed the drill in the Z axis. This task is most important in illustrating the advantages of pushbutton over joystick control, and in showing a dramatic change in the D/R ratio in favor of manipulators.

The major finding is an approximate 40 percent improvement in performance for the pushbutton type of control over the joystick control. This was statistically supportable. The task involved travel, perpendicular alignment, drill use and feed, and withdrawal of the drill from the finished hole. The key element of this task was the use of the drill, especially the holding of the drill perpendicular to the plate and feeding it in a straight line. This aspect of the task severely penalized the joystick control and contributed most to the differences shown in Table 1.

The drilling task is distinctly different from the previous tasks in its requirements for controlled use of a tool. This controlled use is almost analogous to the use of a drill press control system; a stable manipulator having a linear extension feature gives the operator the equivalent of a drill press setup. When the joystick is attached, the operator is given the logical opportunity to use more than one motion at a time; more importantly, he can inadvertently activate a motion and bind the drill in the hole.

A major change in the D/R ratio occurred with this task. As previously mentioned, a typical D/R for this type of comparison is 1/10; however, for this task, the ratio for pushbutton control was 1/1.6. This is a departure by a factor of 7 from the previous conclusions reported in the literature, and supports our contention that any general statement concerning diver/

manipulator system comparisons must be made based on specific tasks or task complexity.

In addition to the performance time comparison offered, data was collected regarding the accuracy of drilling performance. The qualitative data recorded by the test observer showed the joystick to be a poor control device: poor alignment and difficulty in the application of uniform pressure existed. The arm was moved often during the drilling of the hole, resulting in binding of the drill. These problems did not occur with the pushbutton control system. Figure 10 shows the amount of drill angle error for the manipulator control systems and a diver. Drill angle is the mean error in both axes. This histogram shows that pushbutton performance was better than joystick control performance and that the diver was slightly better than either control. Of interest are the small angle errors made when using any of the control methods in a visually distorted field.

Figure 11 shows a histogram of judged hole condition. Experienced machine shop personnel judged the holes, taking into consideration angle, shape, finish, and general suitability for tapping. This measure may have suffered from the 3-point scale used (1 = poor, 2 = fair, 3 = good); however, the personnel performing the scaling resisted a more elaborate rating procedure. The data tends to align with the results of the quantitative measure of drill angle error, showing the diver as best and pushbutton control second; joystick control produced the least acceptable holes. (Note the Y-axis performance inverted from previous figures.)

Connect/Disconnect - This task involved picking up a female quick-disconnect fitting with a special tool (shown in Figure 12, an in-air view) and connecting the fitting to a male quick-disconnect fitting. The tool used was specially designed by Electric Boat division and manufactured by Stanley Tool Works for use with our STAR vehicle manipulators. This proved to be the most difficult task for the manipulator to perform; an untrained operator often required between 30 and 45 minutes to accomplish the task. The major problem was the actual connecting of the two fittings. An extremely close tolerance was required, necessitating near parallel alignment. This task was beyond the general working range of a rate-controlled device. The technique used by the operators was to continually reposition the manipulator in the near mating area and repeatedly try to connect the fittings. In short, they tried until, by chance, the fittings mated. This operational technique caused the high variability in the data, resulting in non-significant statistical differences between control systems.

A secondary problem for the operator was making sure of the final fit of the connectors. At least one operator spent a great deal of time testing the fit before actually removing the tool. This is a particularly difficult task for a manipulator without force feedback.

The main value of the matrix (Table 1) is that it allows specific tasks to be compared; this is true for all tasks as well as within tasks. Of interest is the lack of a clear trend in the ratios as a function of task complexity or manipulator complexity. In fact, as a function of an increase in task complexity, column 2, pushbutton,variable rate results in the lower D/R ratio. When compared to column 4, only the simple tasks show equivalent or improved performance. For variable rate, columns 1 and 2 show a direct improvement on almost every task. This value is even greater when the performance evaluations are observed in combination with these time measures. A time comparison of fixed rate to variable rate is also biased by the use of variable rate to slow down the manipulator rate for positive control. On the other hand, the deliberate control results in more positive control which, in turn, hastens the task.

A note of caution should precede an extrapolation of the results of the experiment based on the use of the D/R table. The reader should recognize that he cannot quickly mentally add the ratios of Table 1 to obtain an overall ratio. This can only be done with a common denominator of raw data. (See diver time under each task.) For example, the overall ratio between diver and manipulator performance over all tasks and conditions, or specifically, for all forms of manipulator rate-controlled devices and divers in warm shallow water is 1/4.15. A quick look at Table 1 would lead the reader to another conclusion however. In short, the performance times must be viewed as individual times taken to perform specific tasks and relative only within tasks. The ratio can possibly be used to find the amount of time either a diver or manipulator will require if one value is known and the conditions are similar to those of our research. The subsequent time value can then be treated on an additive basis to calculate total task times for new tasks.

MAJOR CONCLUSIONS AND RECOMMENDATIONS DIRECTLY RESULTING FROM THE STUDY

The overall performance time D/R ratio for divers versus several forms of rate-controlled manipulators was 1/4.1; i.e., divers were four times faster than manipulators. Of more importance than the overall ratio is the fact that the ratio is very task specific: ratios for specific tasks ranged from 1/31 for a close tolerance connect/disconnect task to 1/1.3 for the tapping of holes. Our recommendation, therefore, is that instead of citing overall D/R ratios, as done by previous investigators, more concern should be devoted to a series of D/R ratios which reflects the requirements of specific applied tasks. In this manner tasks can be identified and redesigned to augment the capabilities of the manipulator device and the operator's ability to effectively control the device. The reader should note that this data was collected on highly trained manipulator and diving operators.

The addition of variable rate to either the joystick or pushbutton controller generally improved performance; however, the actual benefits of variable rate control were, again, task-specific.

The relatively poor performance of the manipulator, for the work element of alignment in the tasks studied, points out the need for designers to develop improved task designs for the manipulator work place.

A finding of the study was that a stable manipulator could actually use a tool for drilling or tapping almost as fast as a diver, and usually more accurately. The problems for a manipulator were in the pre-use elements such as alignment and travel.

A major problem of underwater manipulator work is the need for slow, deliberate control under conditions of poor visibility and optical distortion. These factors may have contributed to the general superiority of pushbutton control over joystick control.

Previous studies have suggested that rate-controlled manipulators are limited to position accuracy of 1/2 to 1 inch. This study showed that, given time, the operator can work with very tight tolerances (0.015 inch) by cancelling and re-cancelling his error. The essential difference, again, is "can do" versus "can do well rapidly." The previous work provides a good point at which the designer should consider providing self-aligning, self-guiding features.

A major point concerning the D/R ratio is that diver performance will degrade as a function of at-sea conditions of stress (depth and temperature). Variables such as visibility and submersible motion will degrade manipulator performance. The potential effects of these factors should be considered when extrapolating from the data presented in this paper.

The data described in this paper can be used by manipulator system designers as a preliminary aid in selecting the best control system for a selected set of task requirements. Additional data of a more detailed nature can be found in reference 24.

GENERAL CONCLUSIONS

Several conclusions regarding the application of underwater manipulators were arrived at through the course of our work which are not direct experimental results. These conclusions are opinions of the authors and should be viewed as such. They are also primarily applicable to simple rate-controlled manipulators although some do translate to more complex manipulators such as position or computer-controlled devices. These conclusions are offered in terms of the design of underwater structures and underwater manipulators.

1. Most manipulators have a problem in aligning perpendicularly square to large numbers of surfaces in the same task area. In short, when designing the task area, designers should consider reducing the requirement to perpendicularly align a tool or the hand of the manipulator. Alternatively, consider the specific manipulator, and its mounting (fixed or mobile) in terms of its ability to square up to all the required surfaces. In addition to the mechanical alignment, the designer should be aware of the difficulty which the operator has in judging when the manipulator is aligned as a function of both optical distortion and empty visual field conditions.

2. The designer should consider keeping the size of the task area within the working envelope of the manipulator to be used in order to avoid time-consuming movement of the submersible itself.

3. Placement of specific tasks should consider the line of sight to the viewport and the position of the arm when it performs the task. Too often the operator cannot see the task because the manipulator itself blocks his view.

4. The visual aspects of design should also consider effects of air/water refraction, size distortion (22), effects of displaced vision on the operator as a function of mobile television camera placement (28), and the distance from the task to the viewport (2).

5. The color selected for the manipulator should afford moderate contrast with the background or task area. For example, a white arm (generally high contrast) often provides too much backscatter and washes television reception, while a dark arm cannot be seen against the background. We have generally used a color with a Munsel value of about 5 and a reflectance of about 20 percent. Some International Oranges fit these requirements (23).

6. In both the design of rate-controlled manipulators and work tasks to be performed by this type of arm, designers should avoid requirements for simultaneous controlled movement of two or more joints. This is especially true where close tolerances are present, e.g., for a connect/disconnect function.

7. Practices common in many machine shops could profitably be applied to manipulator tool design. These include self-alignment, self-tool feed, torque-limiting clutches, step drills for pilot holes, spot-facing drills for drilling on curved surfaces or flat surfaces poorly aligned to the drill, and tools with built-in compliance. Each of these items overcomes the operator's inability to monitor force, visually guide, or control precisely when using a tool with a simple rate-controlled manipulator.

8. Self-locking actuators are desirable; however, provisions should be made to permit specific joints to comply with external loading at the discretion of the operator. This feature is especially useful when releasing a bound tool. This compliance feature should be designed in any tool which can be expected to experience extreme forces. Furthermore, selective compliance in the manipulator allows flexibility for unforeseen task situations.

9. A review of the nuclear handling and NASA manipulator tool development literature would be beneficial to designers. Direct extrapolation, however, should consider the underwater conditions which are more severe than either of the above applications. Some of these conditions which affect the operator are described in the Approach section of this paper.

10. To perform an underwater task in which the submersible movements and manipulator operation interact, it is best to provide both operators the same field of view.

11. An overall conclusion is that for any specific underwater application, manipulator and task designers

should perform a joint detailed task analysis of the type of work to be performed. Examples of important questions to ask are: What is the operator required to do? What does he need in terms of feedback (visual force, etc)? How can we simplify the task or minimize tool changes? This should be followed by a mockup of the task, the manipulator, and the optics to be used and tested under shallow water conditions. The advantages include preliminary performance predictions, operator training, and a thorough testing of the feasibility of the design. While this recommendation appears academic, it is rarely followed.

ACKNOWLEDGEMENT

The authors wish to thank Mr. Gerald Malecki, Dr. Martin Tolcott, Dr. Charles Harsh, and Dr. James Miller of the Office of Naval Research for their guidance in the course of this research program.

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TABLE 1 - DIVER/REMOTE MANIPULATOR PERFORMANCE TIME RATIO AS A FUNCTION OF TASK COMPLEXITY AND MANIPULATOR COMPLEXITY

	RATE CONTROL				POSITION CONTROL					COMPUTER CONTROL		
	Discrete Actuator Switches, Buttons		Combined Actuator Joystick		Discrete Position	Combined Position		Bilateral		Man in the Loop		Computer Alone
TASK COMPLEXITY	PBFR Fixed Rate	PBVR Variable Rate.	JSFR Fixed Rate	JSVR Variable Rate	Knobs, Dials	Pantograph	Anthropomorphic Harnesses	Force Feedback	Space Correspondence	Learned Task Segments	Supervisory Control	Artificial Intelligence
Sample Collection Diver = 0.18 min	1/14.4	1/11.8	1/13.6	1/11.1								
Valve Manipulation Diver = 0.09 min	1/10.5	1/9.2	1/9.3	1/9.2								
Rigging Chain, Hooks Diver = 0.15 min	1/16.2	1/15.7	1/19.9	1/18.6								
Bolt Removal With Power Tool Diver = 0.20 min	1/8.8	1/8.6	1/12.5	1/9.7								
Tapping With Power Tool Diver = 2.47 min	1/1.5	1/1.3	1/1.4	1/1.4								
Threading With Power Tool Diver = 0.18 min	1/10	1/9.1	1/8.4	1/9.9								
Drilling With Power Tool Diver = 2.12 min	1/1.6	1/1.6	1/2.8	1/2.5								
Connect/ Disconnect Diver = 0.21 min	1/26.8	1/29.2	1/24.3	1/31.4								

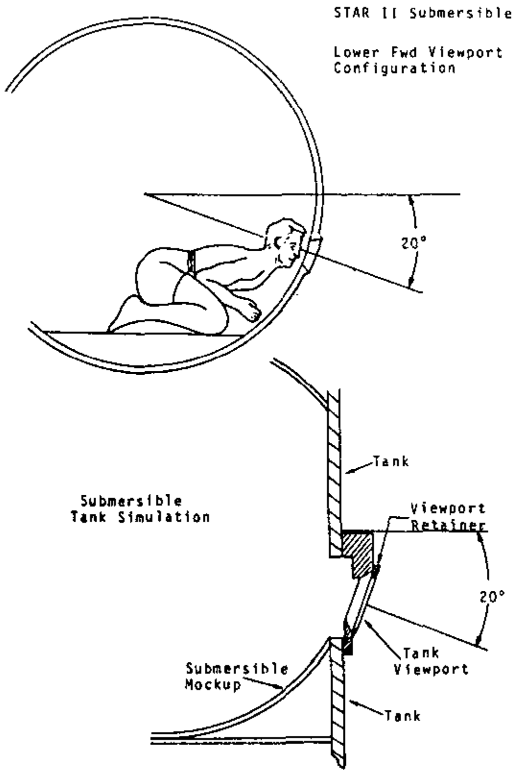

Fig. 1 - Submersible viewport mockup.

Fig. 2 - View looking into tank through mockup viewport (in-air condition).

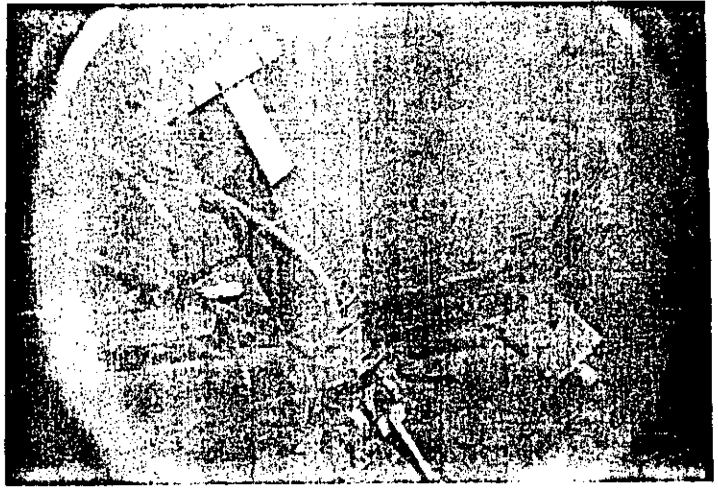

Fig. 3 - View looking into tank through mockup viewport (actual in-water operating conditions).

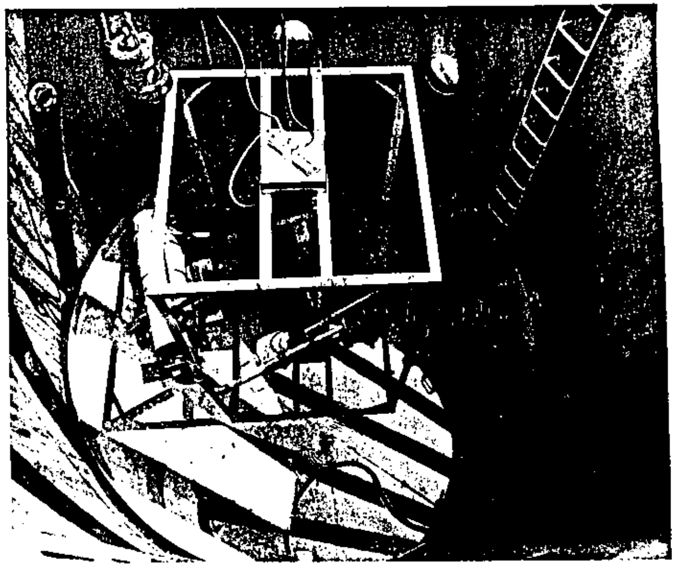

Fig. 4 - View of work area as seen from top of test tank.

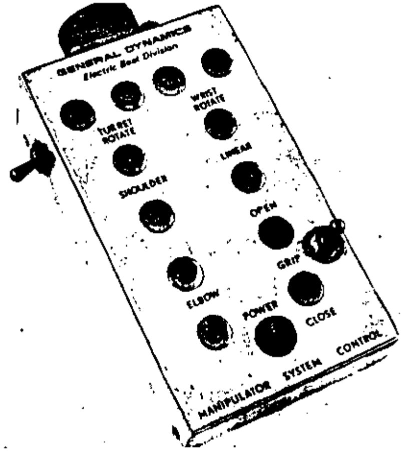

Fig. 5 - Pushbutton controller (pushbutton, fixed rate and pushbutton, variable rate).

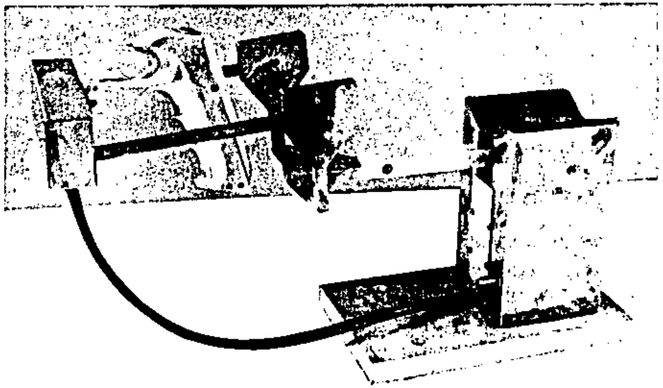

Fig. 6 - Joystick controller (joystick, fixed rate and joystick, variable rate).

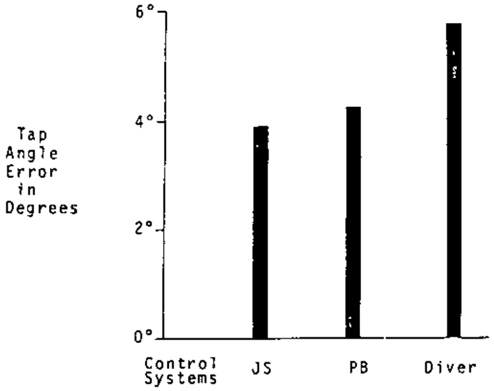

Fig. 7 - Tapped hole angle error (X,Y) as function of control system used.

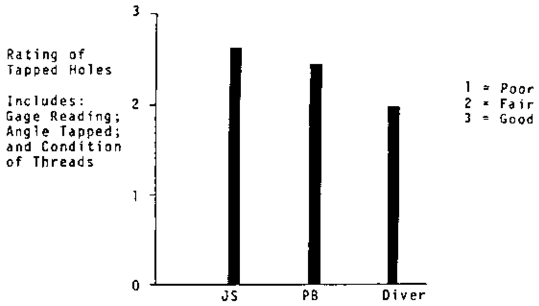

Fig. 8 - Tapped hole rating as function of control system used.

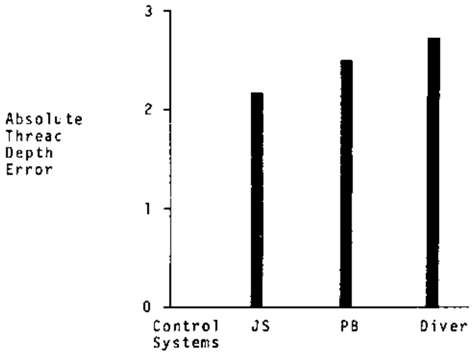

Fig. 9 - Absolute tap depth error as function of control system used.

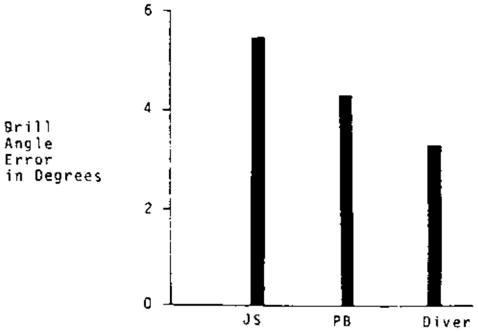

Fig. 10 - Drilled hole angle error (X,Y) as function of control system used.

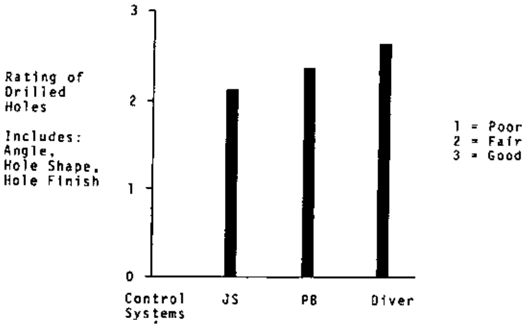

Fig. 11 - Drilled hole rating as function of control system used.

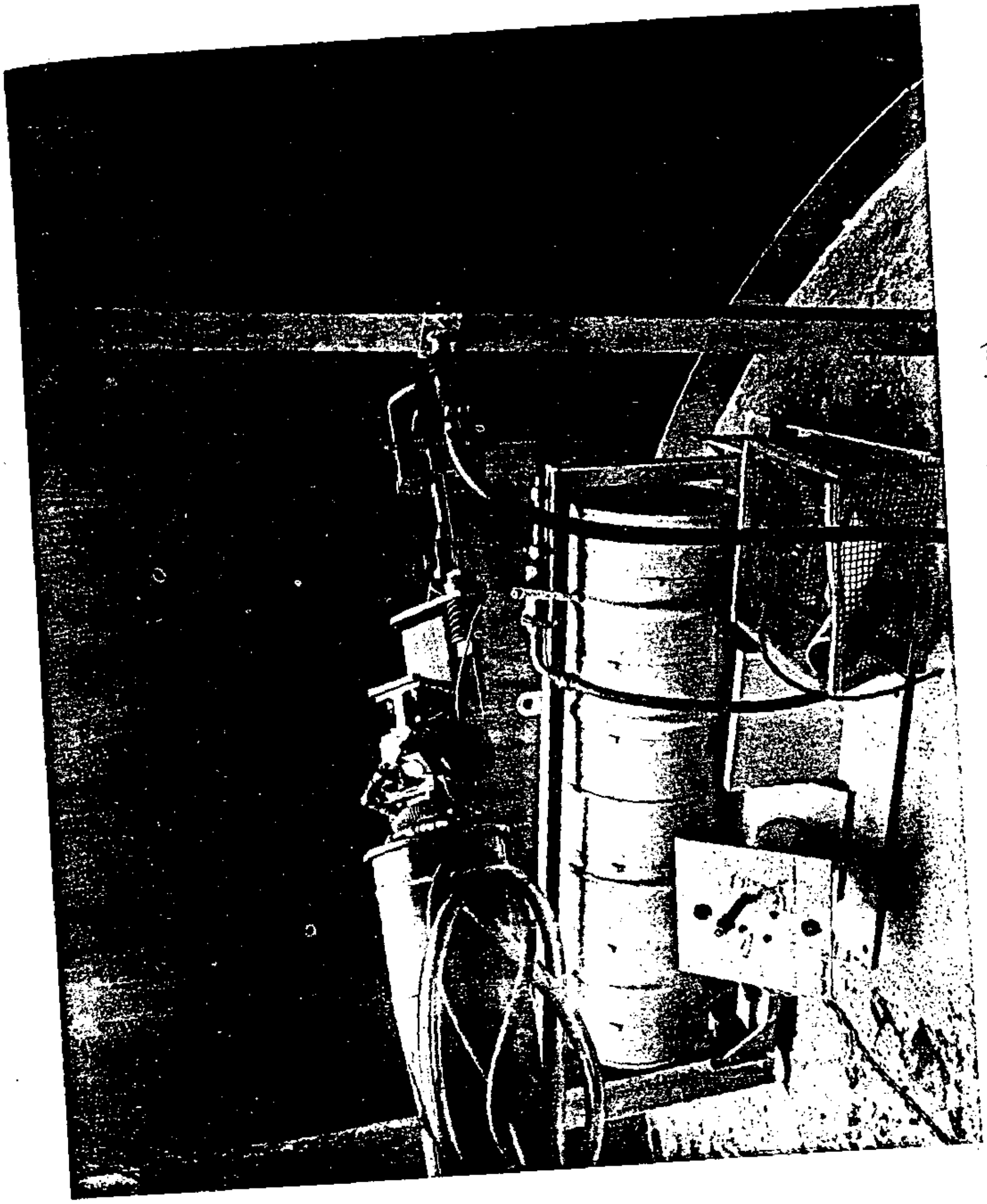

Fig. 12 - Quick-disconnect task (in-air view).

AN INTEGRATED MEASUREMENT SYSTEM FOR THE STUDY OF HUMAN PERFORMANCE IN THE UNDERWATER ENVIRONMENT

by

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ABSTRACT

As man's role in the sea continues to expand, the need increases for basic information concerning his ability to function in the hostile undersea environment. This need in turn requires the development of performance testing equipment and techniques appropriate for high pressure underwater conditions. Further, the tests and measures employed must bear a definite relation to the kinds of operational tasks performed by divers.

In response to these research needs, a program was undertaken for the Navy Experimental Diving Unit to identify relevant performance dimensions and to develop an integrated measurement system for efficient acquisition of performance data. This report describes the resulting system designed to measure human mental and perceptual-motor functions at ambient pressures of up to 444 lb/in^2, equivalent to a depth of 1000 feet.

The system provides for remote administration and scoring of 26 specific tests ranging from simple reaction time to complex manual tracking, and from monitoring a simple display to solving difficult mental arithmetic and symbolic problems. Test problems are presented to the diver on a rear-projection screen located inside the chamber. A slide projector placed just outside the chamber at a porthole illuminates the testing screen. Coded answers on the slides are intercepted by a small mirror and reflected onto an array of photocells. Solid-state logic circuitry monitors and stores the number of responses made by the diver and scores performance by comparing the diver's responses with signals from the photocells.

To register his answers, the diver operates a magnetically actuated keyboard by inserting a permanent magnet probe into appropriate letter or digit positions on the keyboard. Each keyboard entry is displayed to the experimenter outside the environmental chamber. In many tests, performance is automatically scored and displayed to the experimenter.

To perform various manual tracking tests, the diver views an oscilloscope located at a porthole and controls a target dot by using one or both manual control sticks provided. The experimenter, by merely setting a few switches, can establish a series of tracking tasks of varying difficulty and complexity. Performance is scored automatically. Separate readings for the vertical and horizontal display axes are given.

An additional item used by the diver is an 8.5" long stylus. A photocell at the tip of the stylus senses variations in light intensity and can operate either a counter or a timer at the experimenter console. By projecting appropriate patterns on the underwater testing screen, to be used in conjunction with the stylus, it is possible to measure such functions as arm-hand tremor and speed of arm movement.

While the system was designed as an integrated battery of tests, it was also intended as a highly versatile research tool. The slide projection system and alphanumeric keyboard permit considerable latitude in test development or modification. The investigator is not restricted as with the conventional test battery where each item of equipment serves only one purpose.

As a formal test battery and as a general research tool, the system is expected to have extensive application in the areas of (1) specification of human underwater performance capabilities, (2) delineation of factors of the diving environment which affect performance, and (3) development of diver selection criteria.

FOREWORD

This report, submitted in compliance with contract requirements, describes the design and construction of a comprehensive test battery for the measurement of diver performance in wet and dry hyperbaric environments.

The project is supported jointly by the Naval Ship Systems Command, the Navy Experimental Diving Unit, the Deep Submergence Systems Project Office (PM-11), and the Office of Naval Research.

ACKNOWLEDGMENTS

The authors wish to extend their appreciation to the individuals who have contributed to this project.

LT Thomas E. Berghage, MSC, USN, of the Navy Experimental Diving Unit, played a dominant role in the initiation of the effort and has given valuable guidance throughout the project as Technical Monitor.

LT Robert J. Biersner, MSC, USNR, of the Navy Experimental Diving Unit, Dr. James W. Miller and Mr. Gerald Malecki of the Office of Naval Research, Mr. Charles Irwin and Mr. Frank Romano of the Naval Ship Systems Command have given their attention to various aspects of the program, thereby contributing to its successful performance.

Drs. Edwin A. Fleishman, Harold Van Cott, and Albert Zavala of the American Institutes for Research participated in the development of the test selection rationale and formulative thinking during the initial phase of the project.

Mr. Billy R. Lanier and the engineering staff of BioTechnology, Inc., provided invaluable ingenuity and technical expertise in the design and construction of system hardware.

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INTRODUCTION

Man has barely begun to explore the immense frontier represented by the oceans, which occupy some seventy percent of the surface of the earth. Although there are abundant resources within the sea which can be used for man's benefit, their development requires that he be able to live and work productively for extended periods of time beneath its surface. Accordingly, the Navy has begun an intensive program of research and development to extend man's operational capability at great depths and to specify man's role as a direct element in undersea exploration.

Man-In-The-Sea Program

The Navy Man-In-The-Sea Program was given formal direction through Specific Operational Requirement (SOR) No. 46-19, "Deep Submergence, Man-In-The-Sea, Continental Shelf," which was issued by the Chief of Naval Operations in October 1964. This SOR directed the Navy to develop a capability for free-swimming divers to accomplish useful work at ocean depths to 600 feet for periods of time from minutes to as long as several weeks or months.

The broad goals of the Man-In-The-Sea Program, as defined by Workman (1966), are to establish man's ability to work in the open ocean down to the continental shelf for as long as desired, and to determine the ultimate depth-time limits to man's ability to work on the ocean bottom, provided he has available to him all the ancillary equipment, gas mixtures, pharmacological agents, etc., that can be of help.

As a first step toward solving the many medical, physiological, psychological, and technological problems associated with the Man-In-The-Sea objectives, the SeaLab I experiment was conducted in Bermuda in 1964. In that project, four divers operated from a sea floor habitat and were maintained at a depth of 192 feet for 11 days. This work was continued and expanded in the conduct of SeaLab II in 1965. The SeaLab II shell was located at a depth of 205 feet on the edge of the Scripps Canyon about 3,000 feet off the pier of the Scripps Institution of Oceanography, La Jolla, California. Additional studies will be made under SeaLab III, the preparations for which are under way at this time.

Navy Experimental Diving Unit

A key facility in the Navy's research and development program is the Navy Experimental Diving Unit located at the Washington Navy Yard, Washington, D. C. The mission of this facility has been described by Leibold (1966) as follows:

> At the present time, the Navy Experimental Diving Unit is a Bureau of Ships field activity and is charged with the responsibility to perform experimental work in connection with diving and other related matters, conduct development and testing of diving suits, face masks, and associated equipment, and to develop methods and procedures relative to diving.

One of the two diving chambers in use at the Diving Unit is shown in Figure 1. This facility is capable of simulating depths up to approximately 1,000 feet, a pressure of 444 pounds per square inch. These pressure vessels are thus admirably suited not only to test life support equipment but also to provide the degree of environmental control necessary in the systematic study of human performance.

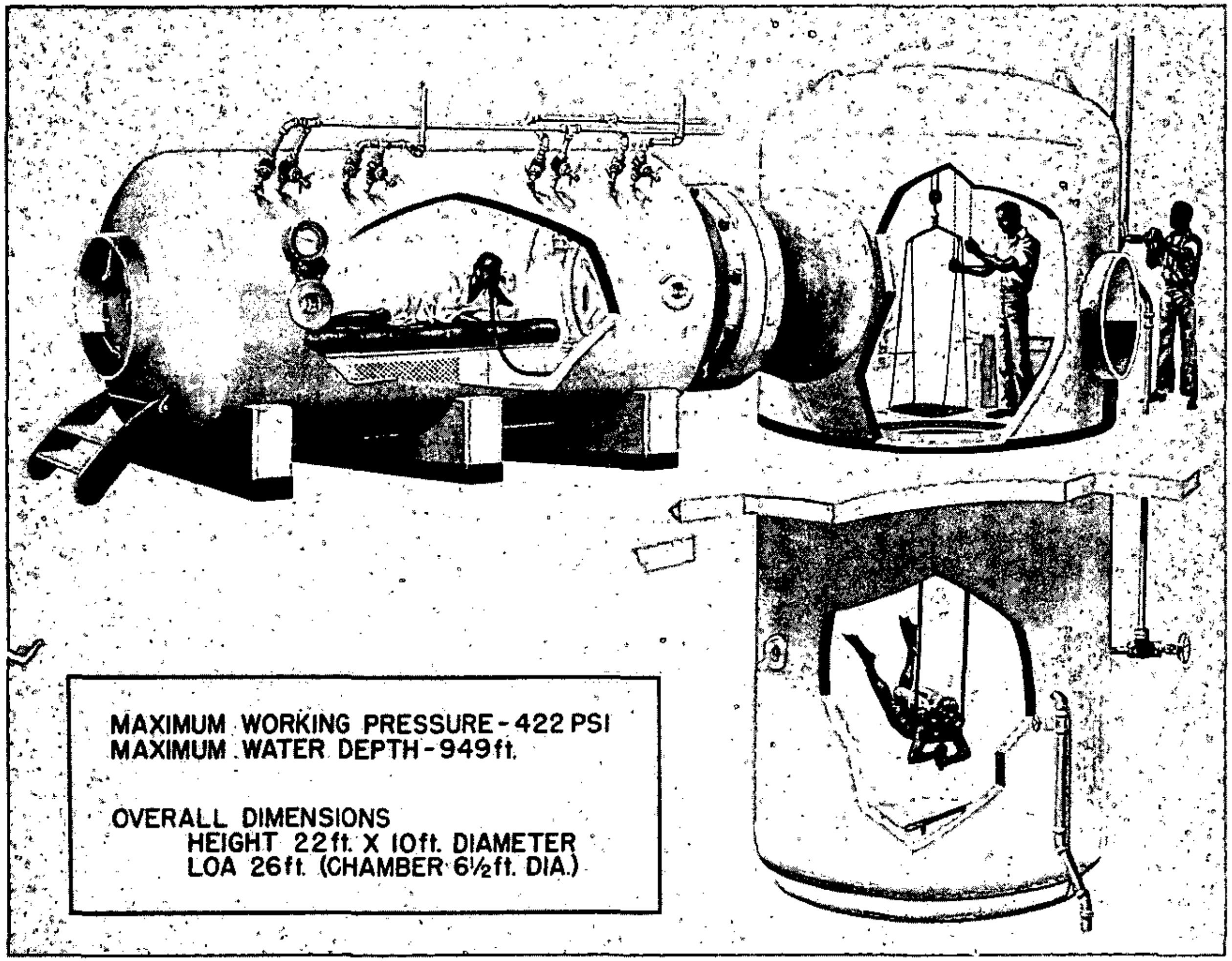

Fig. 1. Diving chamber at Experimental Diving Unit.

From an experimental standpoint, human performance research conducted at the Diving Unit has many advantages over that conducted in the open ocean due to the greater control which can be maintained over significant variables. This facility clearly plays a vital role in determining the needs and capabilities of aquanauts in present and projected operating environments. Research conducted at the Experimental Diving Unit should contribute much to the Man-In-The-Sea Program.

Need for Human Performance Measurement System

To date, there has been no systematic attempt to study the effects of the undersea environment on a broad spectrum of human performance. There are a limited number of studies of man's undersea performance which focus on psychomotor and cognitive aspects of human behavior as a function of gas mixture and pressure for varying amounts of time. Kiessling and Maag (1962) found a 6.9 percent decrement in performance on a modified Purdue Pegboard, a 20.8 percent decrement in performance on a choice reaction time task, and a 33.5 percent decrement on a cognitive reasoning task. These findings were based on a comparison between performance at sea level and at 100 feet during a 12-minute dry dive in a pressure chamber. Baddeley (1966) found a 49 percent decrement on the Purdue Pegboard in a wet dive at 100 feet. These two studies were performed using atmospheric air, and the results imply that the effects were due to nitrogen narcosis. However, such an interpretation is open to question.

For example, Bowen, Anderson, and Promisel (1966) reported that Baddeley and Flemming compared divers on a manual dexterity test at 200 feet, where one group was on a helium/oxygen mixture, and the other group was on air. The former group showed a 32 percent decrement and the latter a 47 percent decrement, when compared to the performance of both groups at 10 feet. These studies illustrate the difficulty of obtaining unequivocal results where environmental and physiological factors may combine to affect even simple types of performance, and, indirectly, lend support to the case for a comprehensive measurement approach.

In SeaLab II, more than one type of psychomotor test was used. In that study, performance on dry land, in shallow water (15 feet), and in SeaLab conditions was compared. Three teams of 10 men each took 15-day turns living and operating from an underwater habitat at a depth of 205 feet. The SeaLab II breathing mixture contained about 85 percent helium, 11 percent nitrogen, and 4 percent oxygen. Tests conducted in the water were: a strength test, a two-hand coordination test, an assembly test, a group assembly test, a visual test to detect and recognize targets of various colors and shapes, and a test of mental arithmetic. The mental arithmetic test was performed inside the habitat. The results of the study suggested that performance on short-term, simple tasks showed little impairment. Performance on long-term, complex tasks showed greater impairment. These decrements were attributed to stresses and hindrances of operating in water, rather than to the effects of the gas mixtures used (Bowen et al., 1966; Miller, 1966). These studies emphasize the importance of assessing divers' psychomotor, cognitive, and sensory performance. Furthermore, performance measurement requirements are not restricted to the problem of breathing gas mixtures. A recent study of work measurement techniques conducted for the Office of Naval Research by the University of California, Los Angeles (Weltman, Egstrom, Elliot, & Stevenson, 1968) states:

> Early in the study, it became apparent that "response" measurements on the diver (i.e., psychophysiological measurements) are probably at least as important as

> "procedural" measurements of the time-and-motion type in properly describing underwater task performance. Further work has reaffirmed this viewpoint. The working diver is generally stressed to some extent and frequently stressed severely. Any technique of work measurement which neglects his compensatory responses gives a distorted picture of the situation. Some form of procedural recording is necessary for overall work evaluation and we plan to continue our investigations in this area. But procedural recording, no matter how fine, should be augmented by psychophysiological measurement. This is perhaps the more difficult problem, and we plan to continue to emphasize it in our subsequent research.

Thus it appears that a systematic evaluation of human performance is needed. In order to provide an overall picture of man's undersea abilities, it is necessary to obtain useful data over a wide spectrum of performance capabilities and to determine how these are affected in systematically simulated combinations of deep-sea environment characteristics. One objective of the Navy Experimental Diving Unit is to conduct such a research program. Because of extreme environmental stress, restricted access to and communication with the divers whose performance is to be measured, and the need to administer a wide range of tests rapidly, special equipment and techniques are required.

It was determined by the Experimental Diving Unit that an integrated measurement system having substantial scope and flexibility in assessing cognitive, perceptual, and psychomotor performance would best fill this need. The objective of the present research and development program was to design and build such a system.

Problem Approach

Through initial interactions between the Experimental Diving Unit and BioTechnology, Inc., the following general requirements were established.

1. The testing system would be designed to measure rather basic components of performance. These primary abilities would be identified through consideration of present and anticipated diver activities in the operational environment.

2. From a pool of test alternatives, selection of specific measures would be made on the basis of their relevance to diver performance, amenability to modification for use underwater, and engineering constraints attending the development of a unified system.

3. The system developed would have sufficient flexibility in terms of stimulus presentation, subject response modes, and performance data readout to permit its use beyond the specific tests which comprise the test battery.

Accordingly, the program was organized into two phases:

Phase 1. Identification and selection of relevant primary abilities and associated performance measures.

Phase 2. System development.

PHASE 1: IDENTIFICATION AND SELECTION OF RELEVANT PRIMARY ABILITIES AND ASSOCIATED PERFORMANCE MEASURES

Given the objective of identifying basic cognitive and perceptual-motor abilities relevant to present and anticipated diver performance requirements and the selection of appropriate measures amenable to incorporation into an integrated measurement system, efforts were directed along the following lines:

1. Consideration of the nature and scope of human undersea activities to develop a listing of generic performance categories.

2. Examination of the basic classes of diver performance as elements of a man-machine-environment system.

3. Analysis and description of diver activities in terms of fundamental cognitive and perceptual-motor functions.

4. Review of technical literature on measurement of cognitive and perceptual-motor performance.

5. Identification of relevant ability dimensions and specific measures of these dimensions.

6. Survey of the state of the art in engineering and equipment design with regard to program objectives and constraints.

7. Development of test selection criteria.

8. Selection of tests for inclusion in the battery.

To provide a comprehensive attack on the initial problem of delineating the measurement content of the system, the services of Drs. Edwin A. Fleishman, Harold P. Van Cott, and Albert Zavala of the American Institutes for Research were enlisted.

Steps 1-4 above were guided by the requirement to establish a rationale for the identification and selection of particular abilities and measures. In this regard, two approaches were used.

Personnel of the American Institutes for Research were oriented principally toward identification of abilities and tests primarily on the basis of factorial purity, test reliability and validity, and general relevance to program objectives.

BioTechnology, Inc., in addition, addressed the problem of ability and test selection within the context of known and anticipated diver activities, and the practical requirements of constructing an integrated measurement system which would permit remote test administration and scoring under the constraints imposed by the state of the art in engineering and the implementation alternatives provided by the Experimental Diving Unit facility.

Through coordination of these two approaches, a listing of recommended abilities to be measured and associated tests was developed and formally submitted for review by the Experimental Diving Unit and other cognizant Navy personnel.

General Areas of Diver Activity

As technological advances extend the operating duration and depth of tethered and free-swimming divers, the number and complexity of tasks to be performed under water increase rapidly. In view of the rate of progress in this area, few would care to speculate on the ultimate limits of performance requirements to be placed on the diver. An example of certain expectations in this regard is provided in a recent report (Propst, 1965) which states that, "Operation and maintenance of future manned sea floor habitats will require that divers possess technical skills and knowledge which go beyond present-day diving operational requirements.

These projected skill requirements are expected to include operation and maintenance of sophisticated electronic equipments, advanced life support systems...and autonomous underwater power sources."

When one adds to these considerations the diverse demands for "normal living" within the habitat, which cut across the spectrum of social and psychological parameters, and the dynamic vehicular control skills required in the use of swimmers' propulsion units such as the Mark I, it becomes clear that there is very little in the way of performance which will not be required of future aquanauts.

Although foreseen diver activities are virtually without limit, it is apparent that present activities will continue for some time and may be expected to proliferate along dimensions already in evidence. The following illustrates general types of activities in which divers are presently engaged.

Salvage

Salvage operations include raising sunken ships, repairing damaged ships, refloating grounded ships, and clearing harbors. Knowledge and use of simple and complex pneumatic tools, cutting and welding techniques, and explosives may be required.

Rescue

Rescue operations involve those activities concerned with freeing trapped men from undersea craft, structures, and equipment of all types.

Search and Recovery

These missions include locating and recovering undersea objects (practice torpedoes, anchors), verifying contacts made by drags, sonar gear, and electromagnetic detection systems, and devising and implementing techniques for raising the objects.

Inspection and Repair

This area involves the conduct of ship-bottom surveys for suspected damage, leakage, sea suction problems, checks of sonar equipment, and search for underwater ordnance. The diver may be required to clear fouled propellers, straighten bent blades, replace zincs, or repair damaged sonar equipment.

Construction and Maintenance

The diver is frequently a major component in the building and maintenance of tunnels, bridges, wharves, piers, and pipelines.

Tactical Diving

Representative missions might include bottom reconnaissance, location and demolition of underwater obstacles, primary approach to enemy beaches, direct attack on ships, inactivation of underwater ordnance, destruction of bridges, or providing defense against individual attacks on shipping.

Science Support

This area includes those activities concerned with subsea exploration and charting, environmental research, geophysical testing, and aquaculture.

The foregoing activities are of course quite general and diverse. Viewed with respect to requirements placed on the individual diver, however, it is possible to delineate certain categories of human performance which are common to the majority of these operational settings. These are:

Visual Surveillance
Navigation
Information Retrieval
Information Processing
Decisionmaking
Work Production

The above categories are relatively abstract representations of diver activities which may be further analyzed into specific performance dimensions. These classes of performance, however, do not function independently or in isolation in the operational world or in the laboratory. Each type of performance is in fact one facet of a dynamic process involving interactions among the human, his vehicle (or equipment), and the environment.

In regard to this, Weltman et al. (1968) identify four major categories of limitations to effective performance toward which assessment must be directed: structural, physiological, methodological, and psychological. These investigators observe further:

> It is interesting to note, however, that an operator could be highly qualified in the three previous categories, and remain relatively ineffective as a result of an inadequate psychological adaptation to underwater surround. The effect of psychological state upon underwater effectiveness is virtually unknown. It must be recognized that underwater work requires a specific adaptation to the demands of the work environment and that this adaptation is, unfortunately, highly individual. Consequently, generalizations can be made only with extreme caution, and a prime objective of underwater performance research is to establish a solid data base independent of theoretical interpretation.

The foregoing remarks establish a basic premise on which the present effort is founded--namely, that the testing system to be developed should be based on a fundamental approach to human performance as it may be affected by the diving environment. In this regard, a consideration of specific diver activities is of value in the sense that it provides a point of departure within a real-world context and permits one to trace through the various levels of performance complexity in moving from operational tasks to the laboratory situations designed to measure the basic components of those operational performance requirements.

In developing the conceptual framework for the measurement system, the various types of operational performance of concern were considered within the context of a typical man-machine-environment configuration as discussed below.

The Diver as a System Component

A system may be defined as a collection of interacting components whose organization is designed to achieve particular outputs or end products in response to specific inputs. Although a system may be composed entirely of hardware, most contain one or more human operators who play vital roles as system components.

The diver is clearly one element of a system which at any point in time has well-defined objectives. It is appropriate, therefore, in studying various aspects of diver performance, to view such activities within a system context. Further, a system-analytic approach lends structure and organization to the problem by delineating the various man-machine-environment interfaces and loops within the total situation.

A typical man-machine-environment system is shown in Figure 2. Various energy sources acting upon the human operator may be traced

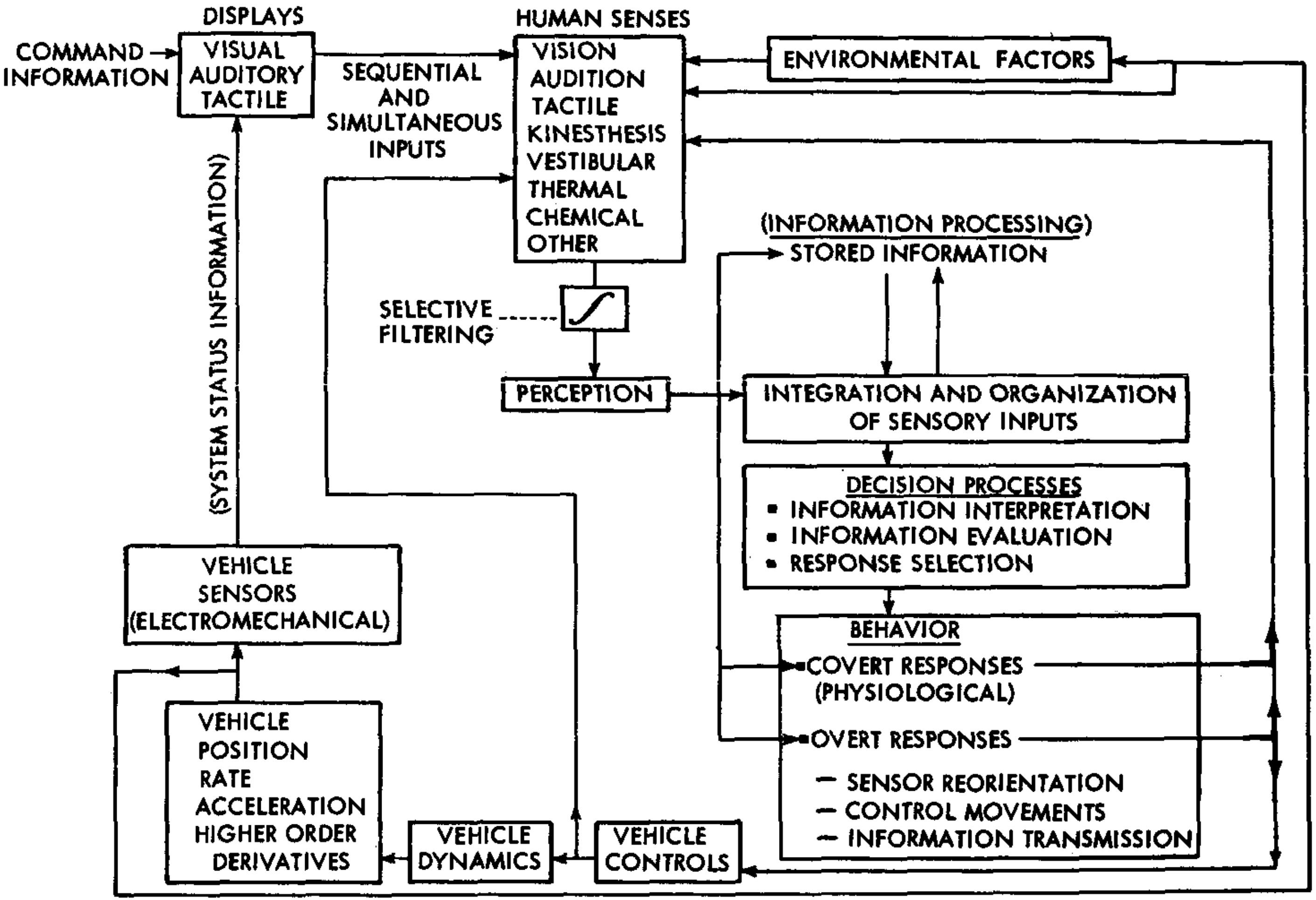

Fig. 2. Simplified representation of man-machine-environment interaction.

from initial stimulation of receptor mechanisms through the perceptual and cognitive stages to termination in the form of physiological and motor responses.

Major feedback loops are shown to illustrate interactions among human, vehicle, and environment. The term "vehicle" as used here refers to surface and submersible craft as well as to equipment requiring adjustment of controls to achieve a desired output function or change in status.

Consistent with the objectives of the present program, attention is focused on those aspects of the system concerning human cognitive and perceptual-motor functions. As seen in Figure 2, these functions are an integral part of a more complex scheme. Ultimately, all aspects must be studied and coordinated to arrive at a comprehensive understanding of the total system.

With respect to the simplified system diagram, it is possible to classify various types of diver performance of concern into relatively basic categories such as perception, information processing, etc. These categories may then be considered in terms of more fundamental ability components, which in turn are associated with specific measurement techniques and testing procedures. In this regard, representative diver activities as they relate to primary performance abilities are discussed below.

Diver Tasks and Basic Performance Components

The various types or stages of behavior as depicted in Figure 2 may be related to both real-world tasks and to typical laboratory arrangements used to measure these abilities under controlled conditions. In indicating these relationships below, one further step was taken toward identifying performance dimensions and testing procedures of relevance to the present system.

Information Processing

This function has at various times been defined to include perception, short- and long-term memory, and decisionmaking. However, studies conducted under the general heading of "information processing" have been concerned in large measure with specifying the rate and complexity of messages which an operator can reliably recieve, store, and transmit under specified conditions. An applied parallel may be found in the process of information transfer among free-swimming divers working in teams, to and from men in submerged vehicles and shelters, as well as to and from the surface. Within this category, those activities are included which relate directly to the diver's ability to acquire, assess, and report information with sufficient accuracy, clarity, and discrimination to insure its maximum utility.

Laboratory studies of information processing (e.g., Teichner, 1963; Teichner, Reilly, & Sadler, 1961) typically involve the presentation of discrete (e.g., alphanumerics, flashes of light) signals which are varied in terms of number of stimulus categories and presentation rates to one or more sensory modalities.

Information Retrieval

For present purposes, information retrieval is considered as synonymous with the capacity and function of human memory. Information is retrieved in the sense that it has previously been learned and stored, subject to recall in the presence of specific stimuli.

As a matter of convention, the ability to remember or recognize previously learned material is divided into "short-term" memory and "long-term" memory; the essential distinction between the two is the amount of elapsed time between acquisition and recall.

Many diver tasks require short- and long-term memory as a matter of course. The diver receives certain instructions and/or information regarding operations to be performed at depth. Alternatively, he may be required to descend in order to acquire information which he must remember and report later.

In performing routine duties, the diver must draw upon knowledge acquired months, or even years, before. While accomplishing specific tasks, he must also acquire data which will be used seconds or minutes later, perhaps with other mental or perceptual-motor activities occurring during the intervening period.

In laboratory situations, short-term memory is frequently measured in terms of the length of a series of digits which can be correctly reproduced immediately after presentation. Measurement of long-term memory often employs paired associates. The subject is presented with a list of stimuli pairs, e.g., a noun followed by a number, which, through repeated exposures, he learns to associate. At a later time he is presented only with the first member of each pair and asked to recall the second member. Both long- and short-term memory effects are described in considerable detail by Estes (1962).

Perception

If perception is to be considered as a relatively separate psychological process, it may be thought of as that stage of the human input-output function where diverse temporal and spatial stimuli become integrated or organized on the basis of innate capacities and previous experience to form meaningful analogs of the real world. An example would be the process whereby patterns of light energy falling upon the surface of the retina (essentially in two dimensions) are integrated to permit an appreciation of three-dimensional space, i.e., distance, solid objects, depth.

Diver performance which may be classified as "perceptual" includes a wide range of visual surveillance activities connected with undersea reconnaissance and exploration. Terrain evaluation, search, location, and recovery missions; inspection of damaged equipment, and detection, recognition, and identification of natural and manmade objects of varied shapes and sizes all fall within this category. Research in this area emphasizes the relationship between spatial/temporal stimulus patterns, and responses made to them, on the basis of learned and unlearned mental processes.

Decisionmaking

In general, it is difficult to separate perception, information processing, and decisionmaking, since these functions are not directly observable but are inferred on the basis of stimulus-response relationships derived under rather similar conditions. Human decisionmaking, however, generally implies the assessment of a situation and the selection of a response from a pool of possible alternatives.

One aspect of this function concerns routine decisionmaking which relates directly to work activity--for example, a diver's response to not having appropriate equipment on hand to perform a task because the problem is different from what had been anticipated.

A second aspect involves the diver's response to emergency situations such as sudden deprivation or degradation in gas supply, rapid change in buoyancy, or entanglement. In these instances, the diver is required to select rapidly among various previously learned procedures or to improvise some solution to the problem.

In more abstract form, decisionmaking is concerned with the manner in which humans make predictive or anticipatory responses on the basis of previously acquired information. If, for example, one must predict which of several events might occur, factors such as the previously observed relative frequency of each event are considered along with the risk involved (cost) in making an erroneous prediction, and the benefit (payoff) of selecting a particular event and being correct (Myers, Reilly, & Taub, 1961). Thus, current laboratory studies of decisionmaking investigate human ability to assemble data and assign probabilities of occurrence to events as a basis for the selection of appropriate responses.

Perceptual-Motor Responses

Perceptual-motor responses concern the manner in which the human operator applies force to his tools, equipment, or controls, once a response has been selected and the decision to act has been made. Depending upon the circumstances, this may involve only a discrete response such as closing a valve where time is the critical factor, or an integrated, continuous response involving visual, auditory, and/or kinesthetic feedback information as in manual guidance of vehicles. Since all overt responses are considered reactions to some signal (of external or internal origin), performance of this type is termed "perceptual-motor" rather than simply "motor," and its investigation must involve specification of the "input" variables. The emphasis, however, is on the speed and accuracy of execution of responses rather than on the manner in which these actions are selected. Perceptual-motor performance thus is concerned with how well certain reactions are carried out separately and as segments of larger behavior patterns.

Characteristic perceptual-motor responses are those associated with work-production requirements. Included within this category are the common manual functions involved in salvage and rescue operations, assembly, maintenance, and damage repair. Mosby (1967) has identified representative diver action tasks as shown in Table 1.

Visual-Spatial Functions

Abilities within this category relate to appreciation of one's position and orientation in space and in relation to other objects. Diver performance requirements falling under the general heading of "navigation" are of this type.

Mosby (1967) has described this category by stating that the diver must be prepared to "navigate from point to point and be able to keep track of his position with respect to surface, bottom, shelter, other workers, etc., in spite of currents and limited visibility." The performance dimension of interest here involves the diver's ability to establish physical orientation, spatial position, and rate of position change on the basis of vestibular, visual, auditory, kinesthetic, and cutaneous cues.

The research literature concerning perception of verticality, real and apparent motion, relative position and velocity, and associated phenomena is voluminous. (See, for example, Day, 1964.) As a

Table 1

Representative Diver Action Tasks (after Mosby 1967)

Minimum Skill

- Hammering
- Packing
- Collecting
- Manual Operations
    - Lifting
    - Pulling
    - Pushing
    - Communicating
- Chipping
- De-Embedding
    - Raising
    - Dislodging
    - Unencumbering
- Connect/Disconnect
- Punching

Moderate Skill

- Cutting
    - Sawing
    - Shearing
- Torquing
    - Zero Reaction
    - Reacting
- Drilling
- Stud Driving
    - Riveting
    - Fastening
    - Stud Placement
- Sealing
    - Crimping
    - Vacuumizing
- Coring
- Guiding/Positioning
- Inspection
- Photography

Complex Skill

- Cutting
    - Pyrotechnics
    - Burning
    - Arc/Ox
    - Ox/Hydrogen
- Detection
- Welding
    - Electronic Beam
    - Metal/Arc

practical matter, however, testing situations requiring manipulation of the spatial environment and/or the subject are not consistent with present requirements and constraints. The most reasonable approach to this problem would appear to be through measurement of the ability to discriminate among visual stimuli which vary with respect to designated spatial references.

Ability Factors Recommended for Inclusion in the Testing System

Drawing upon the foregoing discussion of diver activities and components of human behavior, and information from the technical literature on performance measurement, the following list of abilities and factors was developed for further consideration. Associated tests and measurement techniques are presented in the Appendix.

Basic Abilities and Associated Behavior

Cognitive Abilities	Description of Behavior
Information Retrieval	
Memory Span	Recall sequences of digits presented visually.
Associative Memory	Recall second element of previously learned paired associates when presented with first element of each pair.
Information Processing	
Perceptual Speed	Make rapid comparisons of items of visual information.
Number Facility	Mentally solve addition, subtraction, multiplication, and division problems.
Induction	Discover rule by which specific binary sequence is generated.
Flexibility of Set	Detect change and make adaptive response to changes in pattern of binary stimulus sequence.

Decisionmaking

Time Interval Estimation	Estimate prescribed intervals of time.
Time Sharing	Divide attention among two visual displays to detect occurrence of critical event(s).
Stress Sensitivity	Make appropriate response to conflicting visual stimuli.

Visual-Spatial Functions

Response Orientation	Make directional control responses to nondirectional stimuli.
Spatial Scanning	Visually trace components of a complex visual field.
Visualization	Recognize relationships between two-dimensional and three-dimensional representations of stimulus figures.
Spatial Orientation	Discriminate rotation of figures in one axis as opposed to a different axis.

Perceptual Abilities

Detection

Visual Monitoring	Attend to continuously changing visual display to maintain cognizance of system status.

Vigilance	Attend to information source for prolonged period to detect occurrence of infrequent event(s).
Recognition	
Flexibility of Closure	Identify specific figures within complex visual surround.
Length Estimation	Discriminate difference in distance of two stimulus points from a given reference point in the presence of visual distractors.

Perceptual-Motor Abilities

Fine Manipulative Abilities	
Arm-Hand Steadiness	Hold arm and hand steady while fully extended.
Wrist-Finger Speed	Make rapid repetitive tapping movements.
Finger Dexterity	Manipulate small objects with fingers.
Manual Dexterity	Manipulate large objects with hand.
Gross Positioning and Movement Abilities	
Multilimb Coordination	Use hands and/or feet simultaneously.
Speed of Arm Movement	Make discrete, rapid arm movement.

Position Reproduction	Repeat discrete arm-hand movement without aid of vision.
Reaction Time Ability	
Visual Reaction Time	Respond as rapidly as possible to discrete signal.
System Equalization Abilities	
Manual Tracking	Use of hand controller(s) to control one or more axes of motion in system having:
Position Control	Zero-order dynamics
Rate Control	First-order dynamics
Acceleration Control	Second-order dynamics

Test Selection Criteria

For a given performance dimension or ability factor there are usually several tasks or tests which may be employed. A number of considerations are relevant to determining the particular measure to be used. In selecting specific tests for modification and inclusion in the battery, three types of criteria were applied. These were: (1) methodological considerations, (2) engineering factors, and (3) practical considerations. Specific items within each category are indicated below. The listing, however, is illustrative rather than exhaustive.

Methodological Considerations

1. Factorial purity.
2. Amount of evidence supporting identification of the factor. *
3. Range of ability levels covered.
4. Face validity--relationships between test configuration and kinds of tasks divers are known or anticipated to perform.
5. Sensitivity--does the test appear likely to reflect the influence of stresses associated with the diving environment?
6. Transformability--is it possible to alter the test so as to make administration compatible with the diving environment without seriously altering the measurement capability of the test?

Engineering Factors

1. Feasibility of test transformation/instrumentation.
2. Effect of environment on test stimuli or response components.
3. Suitability for remote administration and automatic scoring.
4. Feasibility of integration into testing system.
5. Availability of appropriate fabrication materials.

Practical Considerations

1. Estimated labor and cost to achieve desired end product.
2. Importance of test's contribution to overall battery with respect to cost, time, and effort of implementation.
3. Freedom from complications concerning copyrighted materials.
4. Ultimate economy and ease of test administration, scoring, and interpretation.

After extensive review of candidate measures, twenty-six tests were selected for implementation. These are listed in Table 2.

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*Detailed and extensive information on evidence supporting identification of those factors eventually selected for measurement may be found in French, Ekstrom, & Price (1963) and Parker, Reilly, Dillon, Andrews, & Fleishman (1965). The former deals with cognitive factors; the latter with perceptual-motor factors.

Table 2

List of Factors and Tests Included in Measurement System

Factor	Test
Arm-Hand Steadiness	Arm Tremor
Associative Memory	Word-Number
Control Precision	Position Control
Finger Dexterity	Key Insertion
Flexibility of Closure	Hidden Patterns
Flexibility of Set	Binary Set Persistence
Induction	Letter Sets
Length Estimation	Shortest Road
Manual Dexterity	Wrench and Cylinder
Memory Span	Visual Digit Span
Multilimb Coordination	Two-Hand Tracking
Number Facility	Addition
	Subtraction
	Multiplication
	Division
Perceptual Speed	Number Comparison
Reaction Time	Visual Reaction Time
Response Orientation	Choice Reaction Time
Spatial Orientation	Card Rotations
Spatial Scanning	Choosing a Path
Speed of Arm Movement	Horizontal Arc
System Equalization	Acceleration Control
	Rate Control
Time Interval Estimation	Interval Reproduction
Time Sharing	Track and Monitor
Vigilance	Visual Signal Detection
Visualization	Surface Development
Visual Monitoring	Terminal Digits
Wrist-Finger Speed	Tapping

The form of each test as it is employed in the battery is described in the following section pertaining to system development.

PHASE 2: SYSTEM DEVELOPMENT

Having selected an array of 26 tests for inclusion in the battery, the initial requirement concerning system development was an overall conceptualization of the device. Specifically, it was necessary to determine (1) the manner in which analog and digital test information should be presented to the diver, (2) the type of response apparatus which the diver would use inside the chamber, and (3) the extent and form of test automation which could be accomplished within the scope of the project.

Within the framework established by meeting the above requirements, test materials, circuitry and procedures were developed for each test. Design concepts were verified at the breadboard level and then an extensive analysis and design integration was carried out to achieve the required degree of system compactness while retaining functional flexibility.

Finally, the system was rendered in production form, tested and modified as necessary. The end result is described below.

System Configuration

Figure 3 shows an artist's rendering of the system (SINDBAD I*) as it will appear in operation at the Experimental Diving Unit. The system consists of four elements: (1) an experimenter console, (2) an electronics package containing digital and analog control circuitry, (3) a visual display system, and (4) a subject console with ancillary equipment.

From his station, the experimenter selects the test to be administered, manipulates his controls to achieve the required system functions, monitors system status, and extracts performance data from digital and analog displays on his console.

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*System for Investigation of Diver Behavior At Depth

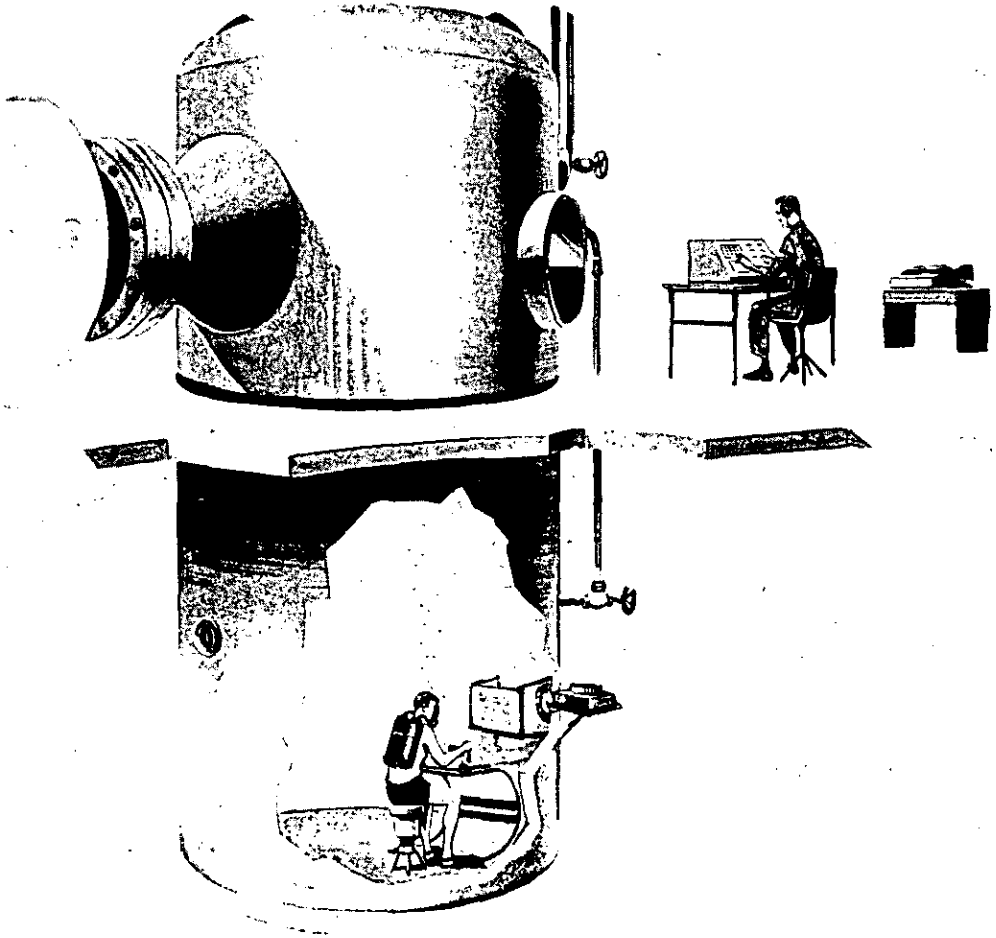

Fig. 3. Artist's rendering of SINDBAD I system in operation.

Experimenter Console and Electronics Package

All tests are selected and administered from the experimenter console shown in Figure 4. Additional circuitry is contained in a separate enclosure 22" wide x 13" high x 15" deep.

Programming and scoring are accomplished almost entirely by solid-state integrated circuits. Subject responses and scores are presented to the experimenter by means of optical digital displays, three electromechanical counters, and a single microammeter.

At the upper left of the console is a six-unit display which shows the output of the digital clock. The clock (or timer) reads in one-hundredth of second intervals to a total of 9999.99 seconds. This device records elapsed time as a performance measure and is used to sequentially program stimuli and activate or deactivate the subject's controls as appropriate.

The second six-unit optical display (just below the digital clock) serves three basic functions. As seen from left to right, the first four units display subject responses such as answers to arithmetic problems, multiple-choice selections, etc. The fifth unit allows the experimenter to monitor numerical information presented to the subject on a parallel display. The sixth unit reacts whenever the subject makes a response on his own alphanumeric keyboard, giving the experimenter continuous feedback from subject activity. This sixth unit also permits manual recording of discrete responses, if desired, while the system may be automatically scoring responses and accumulating totals.

Below the optical displays are three electromechanical counters. These show respectively, from left to right, total correct responses, total errors, and total responses made. They also record response frequency (e.g., number of "taps" made by subject in Wrist-Finger Speed; number of operations performed in Manual Dexterity, Finger Dexterity, etc.).

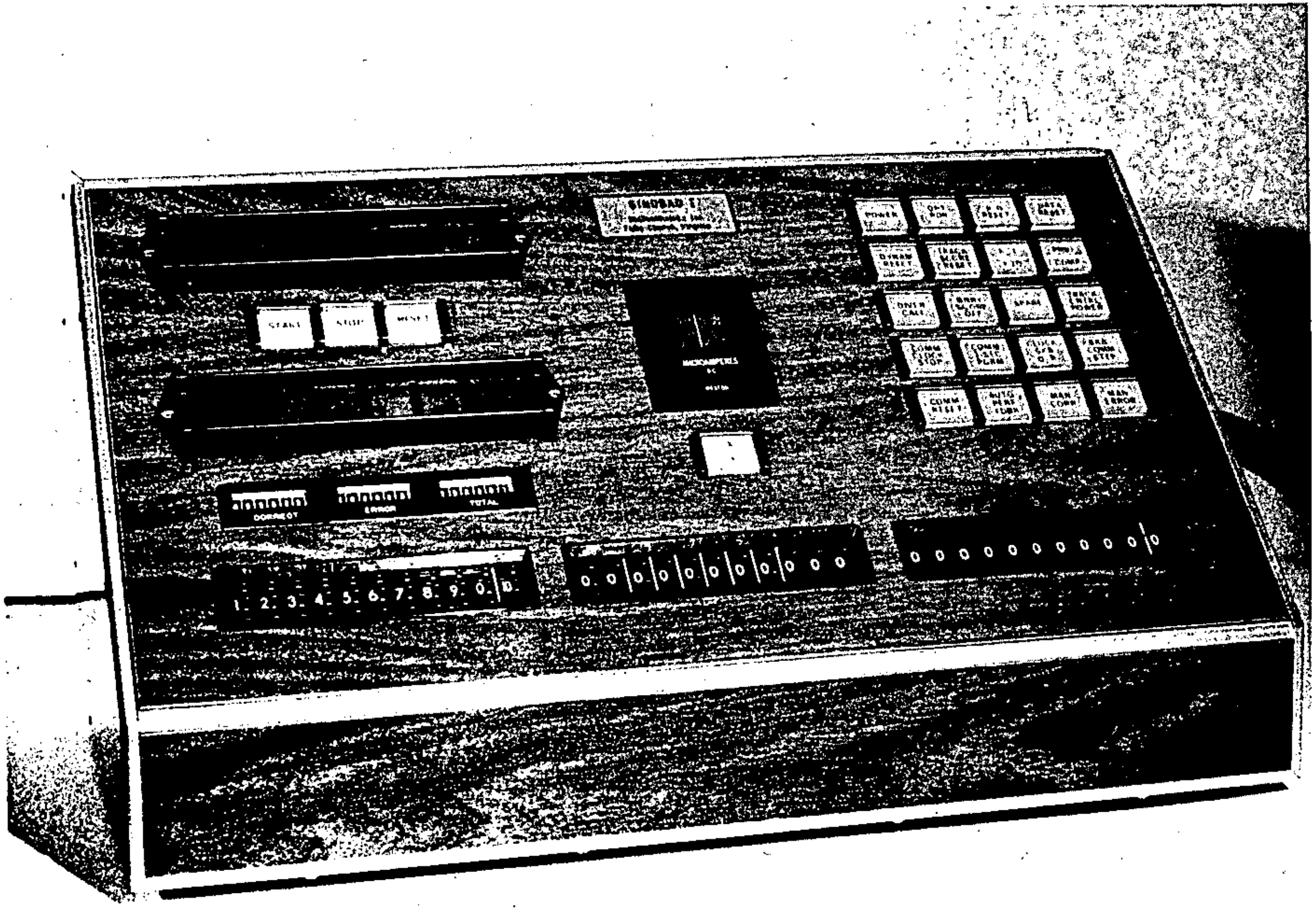

Fig. 4. Experimenter console.

At the center of the console is a meter which displays integrated absolute error voltage scores associated with manual tracking performance. The system scores performance separately in the horizontal and vertical axes. Using the switch immediately below the meter, the experimenter may view either score at any time.

Across the bottom of the console are three units, each containing eleven detented thumbwheel switches (Digiswitches). Each switch has two poles and eleven positions. The unit on the left is used to program number sequences in the test of Digit Span and to determine the automatic reset position of a ten-position commutator within the system which programs sequential stimulus events.

The center set of Digiswitches controls tracking circuitry setup, programming inputs, digital clock control function, and control of the electromechanical counters.

The right-hand set of Digiswitches receives and channels signals coming from the subject's response apparatus. It also establishes routes for internal scoring and display circuitry.

At the upper right of the console is a matrix of 20 back-illuminated microswitches. These cover a range of functions in establishing circuitry for the various tests and system functions. Two switches are used to flash "error" or "correct" signals on the subject's keyboard at the discretion of the experimenter. (This function can also be set to occur automatically when desired.)

The experimenter also operates a small remote control unit for the slide projector described later.

A single, 16-lead cable runs from the experimenter console through a penetration site in the chamber bulkhead to the subject's apparatus.

Subject Visual Display Apparatus

The visual display system which presents the subject with various tasks consists of three basic elements: (1) a slide projector with rear-projection screen and appropriate slides, (2) an oscilloscope, and (3) a digital display.

Slide Projector. A random-access Kodak Carousel slide projector (Figure 5) under control of the experimenter is located at a porthole outside the test chamber. Test problems and information are viewed on a rear-projection screen mounted inside the chamber. The screen is 1/4-inch-thick plexiglass with a special (Polacoat) surface designed for rear projection.

Any of a total of 80 slides can be selected in sequence forward or backward, or in random order, using a control unit at the experimenter station. Approximately 200 stimulus slides were prepared as part of the test equipment.

On certain tests, the stimulus slides contain a binary code (obscured from subject's view) which is reflected by an interposed mirror outside the chamber to an array of photoconductor cells. Photocell outputs are scanned by a commutator and the subject's responses are compared and scored automatically as the test progresses. This device also permits automatic starting and stopping of the digital clock when a slide image appears or is removed.

Oscilloscope. When measuring manual tracking performance, the slide projector is replaced by a cathode ray oscilloscope which is viewed directly through the porthole. Figure 6 shows the oscilloscope, a Hewlett-Packard Model 120B.

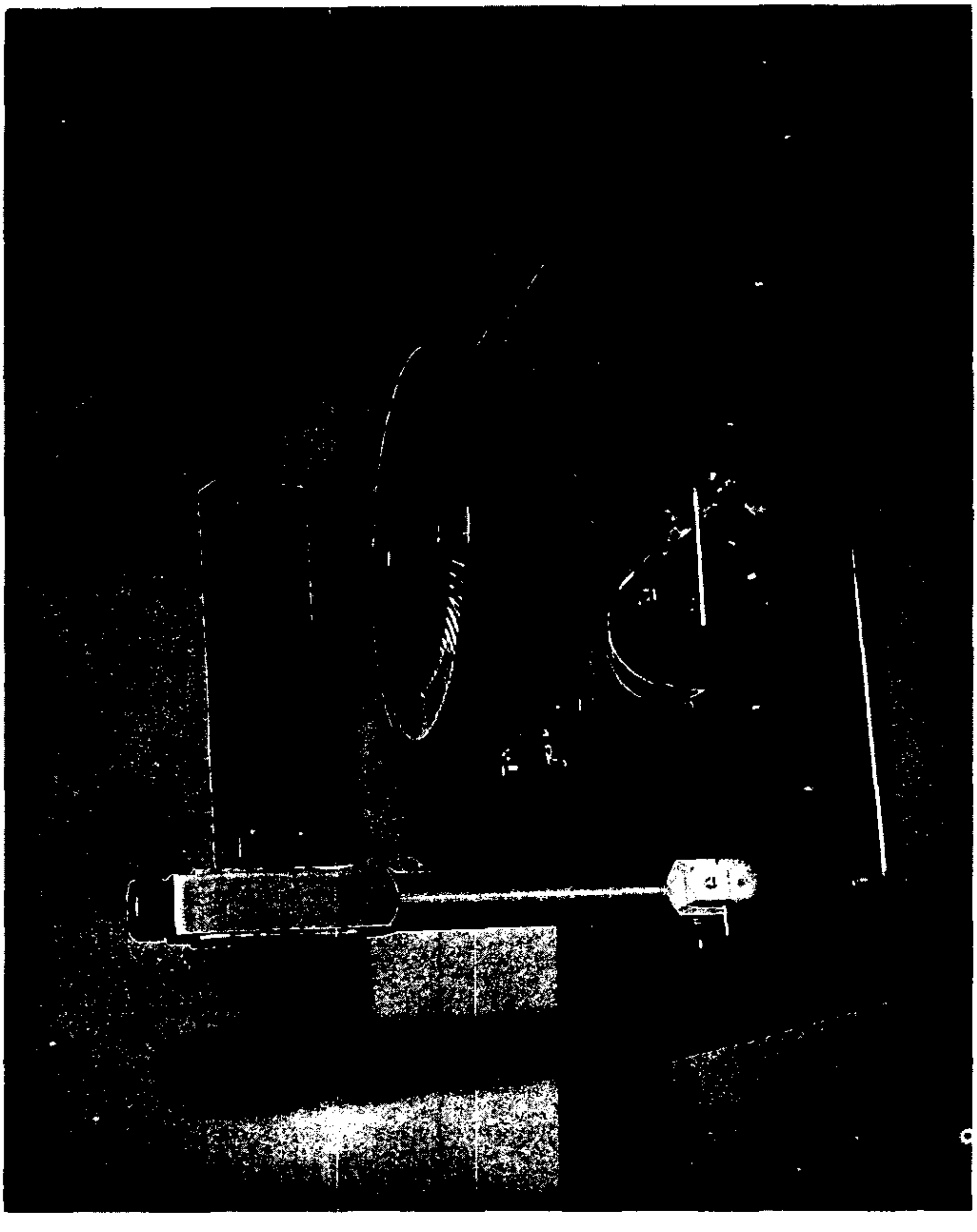

Fig. 5. Random-access Kodak Carousel slide projector.

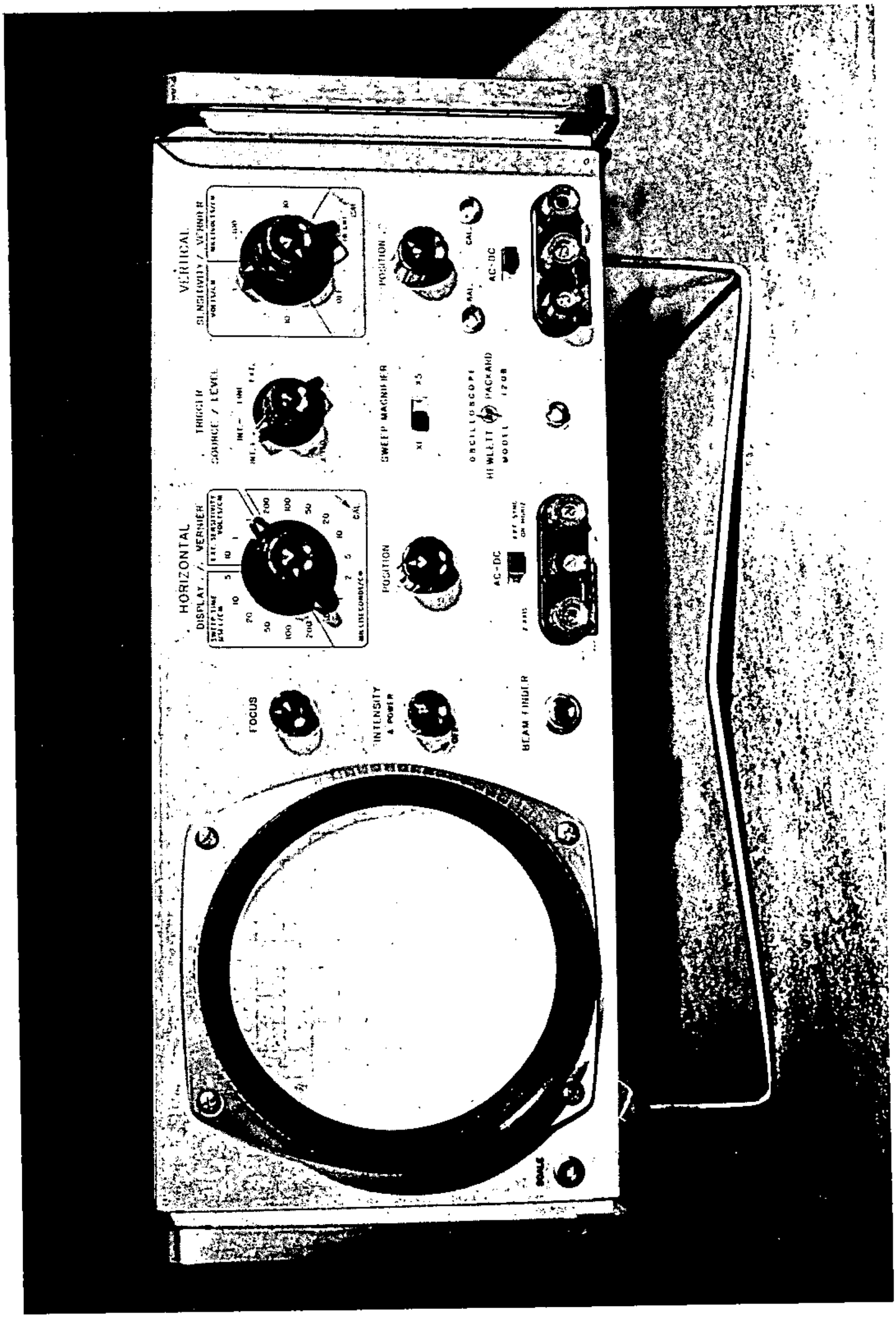

Fig. 6. Oscilloscope.

Digital Display. An "online" optical display (Figure 7) is used at the porthole to present series of digits to the subject as in the test of Digit Span. This display presents 1"-tall, luminous characters against a dark surround.

Display Mountings. Special supports were designed and constructed for the slide projector and the oscilloscope to facilitate the placement and exchange of displays at the subject's viewing port.

Shown in Figure 8 is the oscilloscope support arm and platform which differs only in minor detail from that of the projector support. The arm swivels at two points and the tray is free to rotate 360° giving ample flexibility for display positioning. The lower portion of the figure shows the support arm with the tray removed.

Figure 9 shows the oscilloscope in place on its support.

Subject Response Apparatus

Figure 10 shows the subject keyboard, magnetic stylus (upper right corner of keyboard), photocell stylus (at left), and dual tracking controls. The tracking controls are not physically attached to the keyboard.

The keyboard enclosure and tracking control housings are made of aluminum. With the exception of the top surfaces, the housings are all seamless, having been formed from blocks of solid aluminum.

In addition to stainless steel structural supports within the enclosures, each is filled with inert, nonconductive silicone fluid. The enclosures are, thus, virtually incompressible.

Protruding from either tracking control housing, two pistons may be seen. These communicate external pressure to the inside of the housing and compensate for expansion and contraction of the silicone fluid due to changes in ambient temperature. The keyboard is also equipped with a

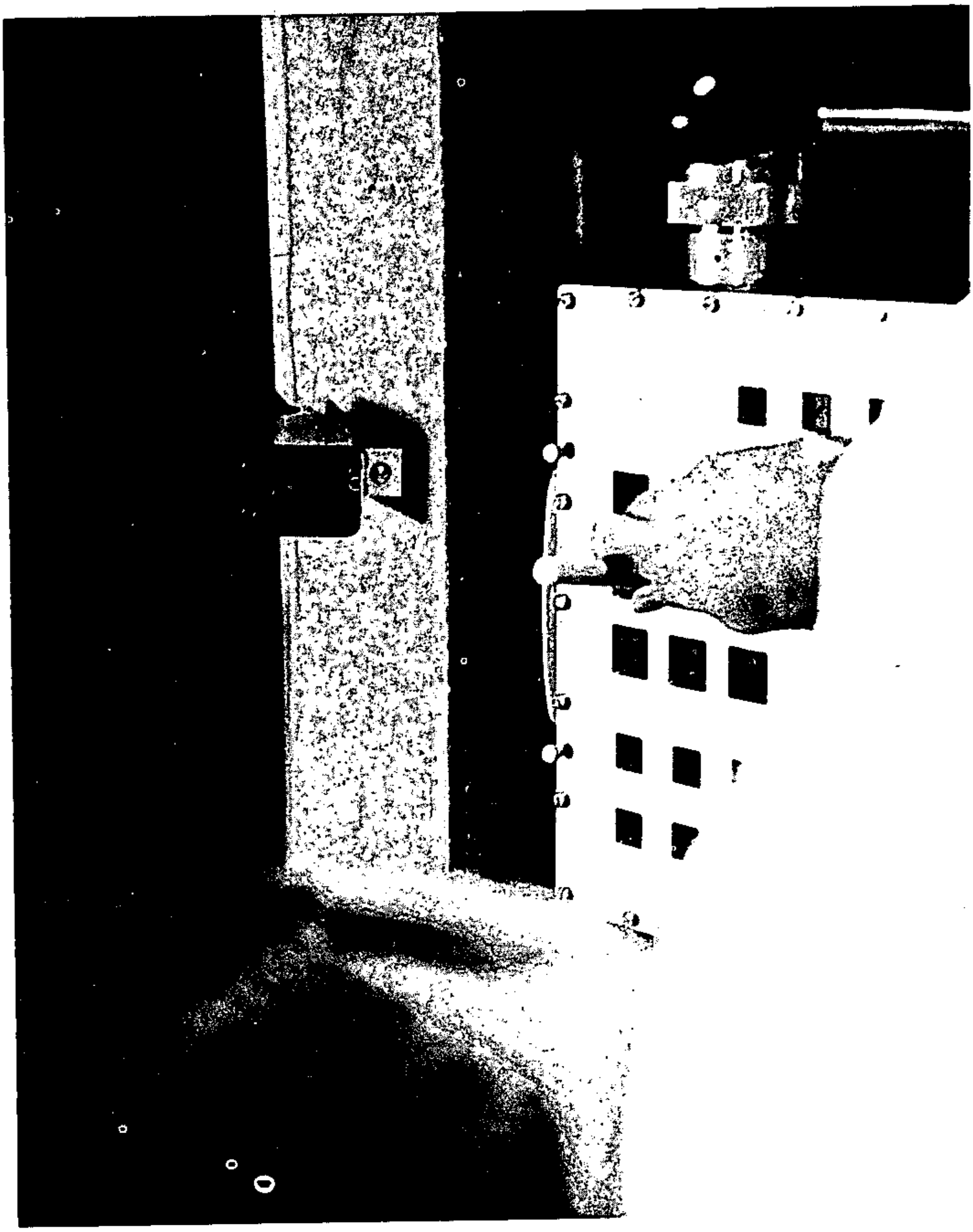

Fig. 7. Digital display in operation.

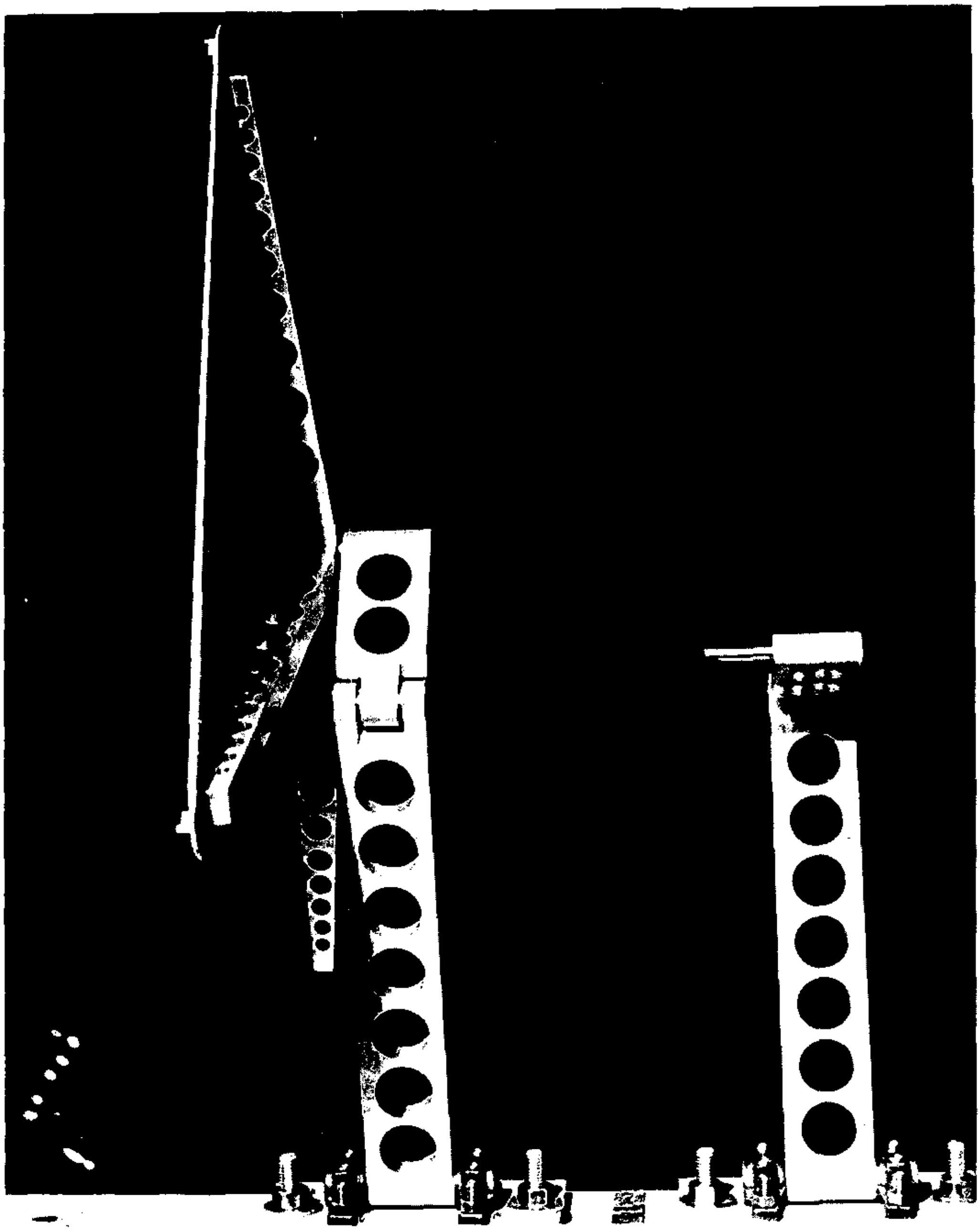

Fig. 8. Oscilloscope support arm and platform.

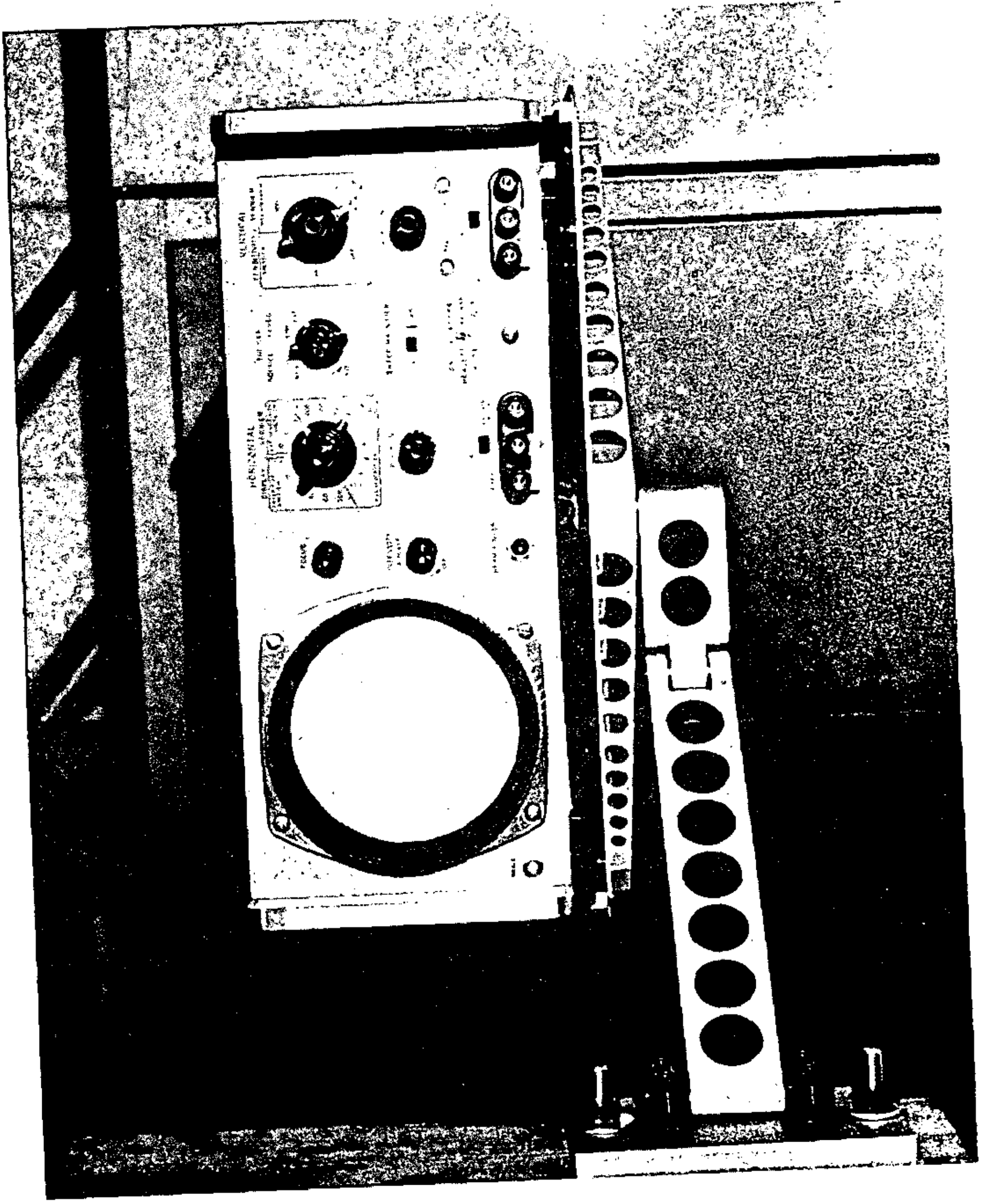

Fig. 9. Oscilloscope in place on its support.

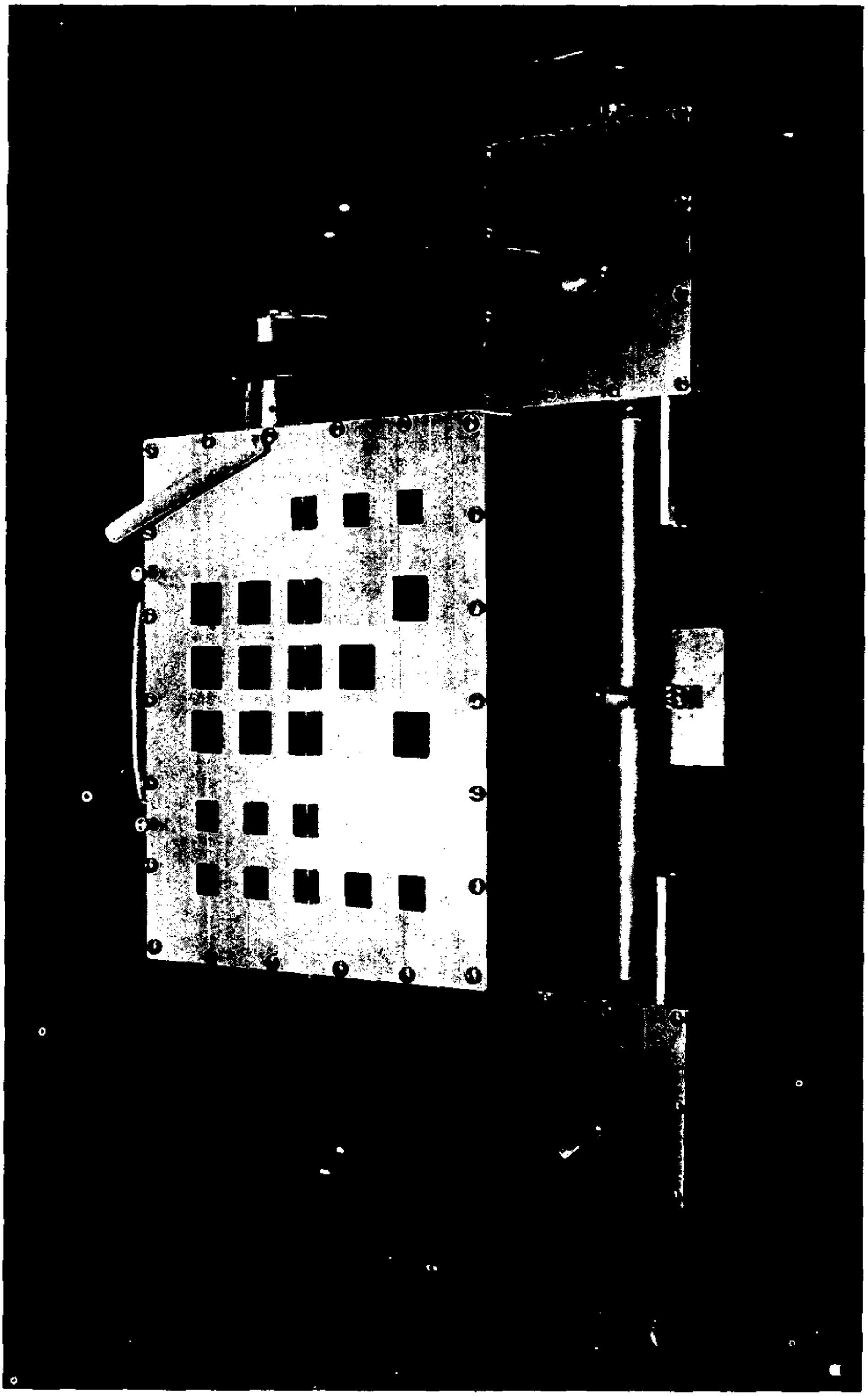

Fig. 10. Subject response apparatus.

piston, which is mounted at the back and underneath. Since no pressure differential of any magnitude is permitted to exist across the enclosure walls, there is no danger of implosion at high ambient pressures.

Response Keyboard. The letters A through F and digits 0 through 9 are used to generate numerical and alphabetic responses to various cognitive and perceptual tests.

At the lower left of the keyboard are two display lamps. These are actuated manually (or set to automatic) by the experimenter to provide the diver with knowledge of results as "correct" or "error."

A reaction time stimulus light and response key are located at the lower right side of the keyboard. Beneath these is a key marked with an asterisk (*). When actuated by the diver, a tone or light (or both) occurs at the experimenter console. This serves as a general-purpose communication signal whereby the subject may indicate "ready," "test completed," etc.

Through use of an overlay template, keyboard positions are exposed or masked as appropriate for tests such as Manual Dexterity, Finger Dexterity, and Response Orientation. Ancillary objects (containing permanent magnets) are used with the keyboard in performing these tests.

Tracking Controls. The dual-axis hand controllers are used in conjunction with the oscilloscope display. Either unit may be used individually to control vertical and horizontal motion of the display dot, or both units may be used, each controlling a single axis of motion.

Photocell Stylus. This device is 8.5" long and contains a small photoconductive cell at one end. It is used with the underwater projection screen to measure Speed of Arm Movement and Arm-Hand Steadiness.

Illustrations of Equipment in Use

The manner in which the subject display and response apparatus is used in various tests is indicated below.

Rear-Projection of Test Stimuli. Figure 11 shows a test problem rear-projected onto the screen. The subject is using his keyboard to register answers. Note that the previously mentioned binary code along the top of the slide which permits automatic scoring is not visible on the subject's screen.

Use of Photocell Stylus. Use of the photocell stylus in the test of Arm-Hand Steadiness is demonstrated in Figure 12. With arm extended, the subject tries to keep the tip of the stylus in line with the small spot of light projected on the screen. Tremor of the arm and/or hand causes misalignment of the stylus and target light. Each light-to-dark excursion is registered on a counter. The test is scored as the number of impulses (tremors) accumulated in 20 sec.

In testing Speed of Arm Movement, the subject holds the stylus as above and swings his arm back and forth across the front of the screen as rapidly as possible. With the screen fully illuminated by the slide projector, and control circuitry switches properly set, the digital timer runs as the stylus moves across the screen. Speed of Arm Movement is scored indirectly as time to traverse the screen. The test score is the mean of four trials (two movements left to right; two, right to left).

Example of Keyboard Overlay

Figure 13 shows the arrangement of the subject apparatus for the test of Response Orientation. The subject holds his magnetic stylus at the center of the four template apertures. The template, thus, provides for a "directional" response, forward, backward, left, or right.

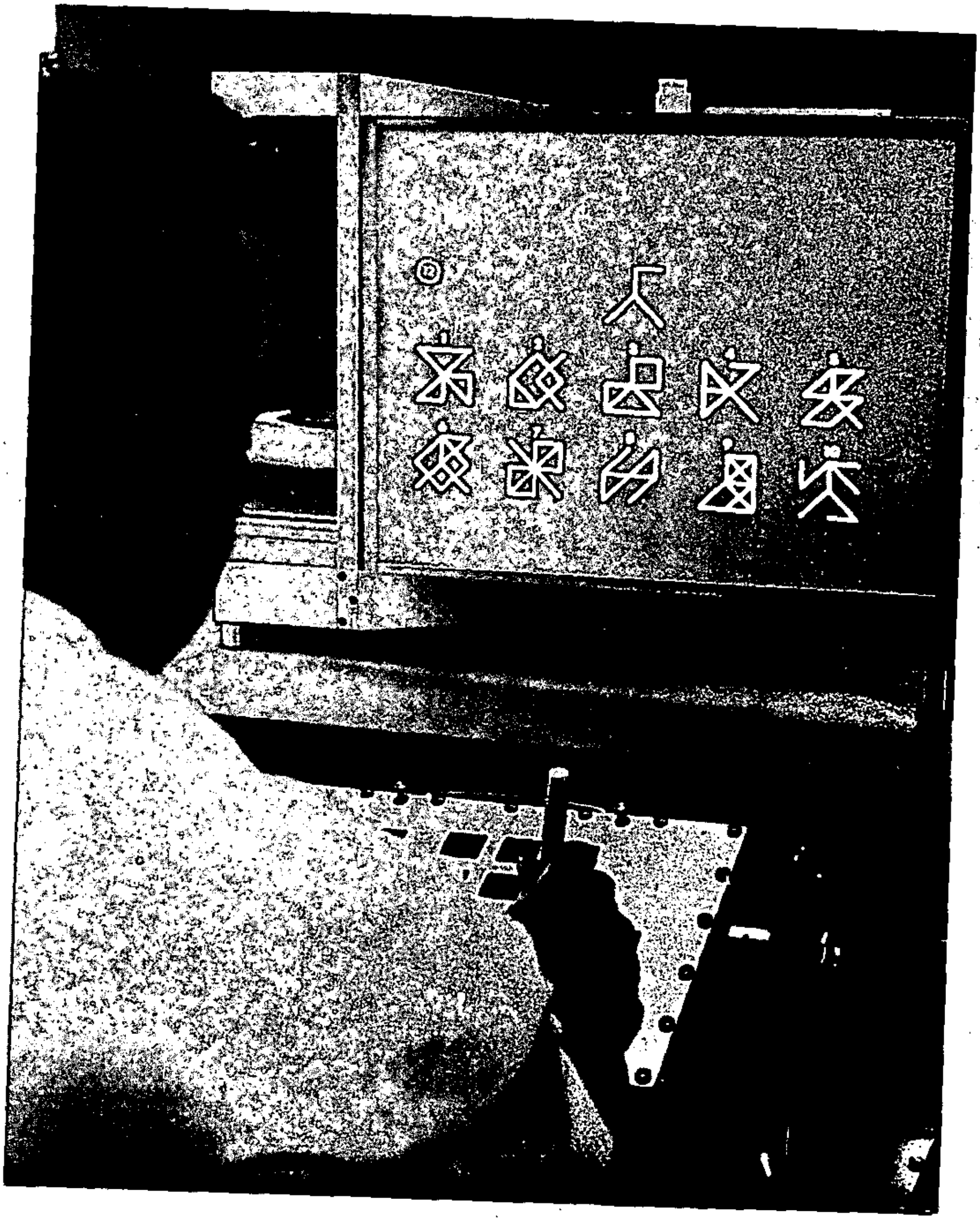

Fig. 11. Solving a test problem rear-projected on underwater screen.

Fig. 12. Photocell stylus being used in Arm-Hand Steadiness test.

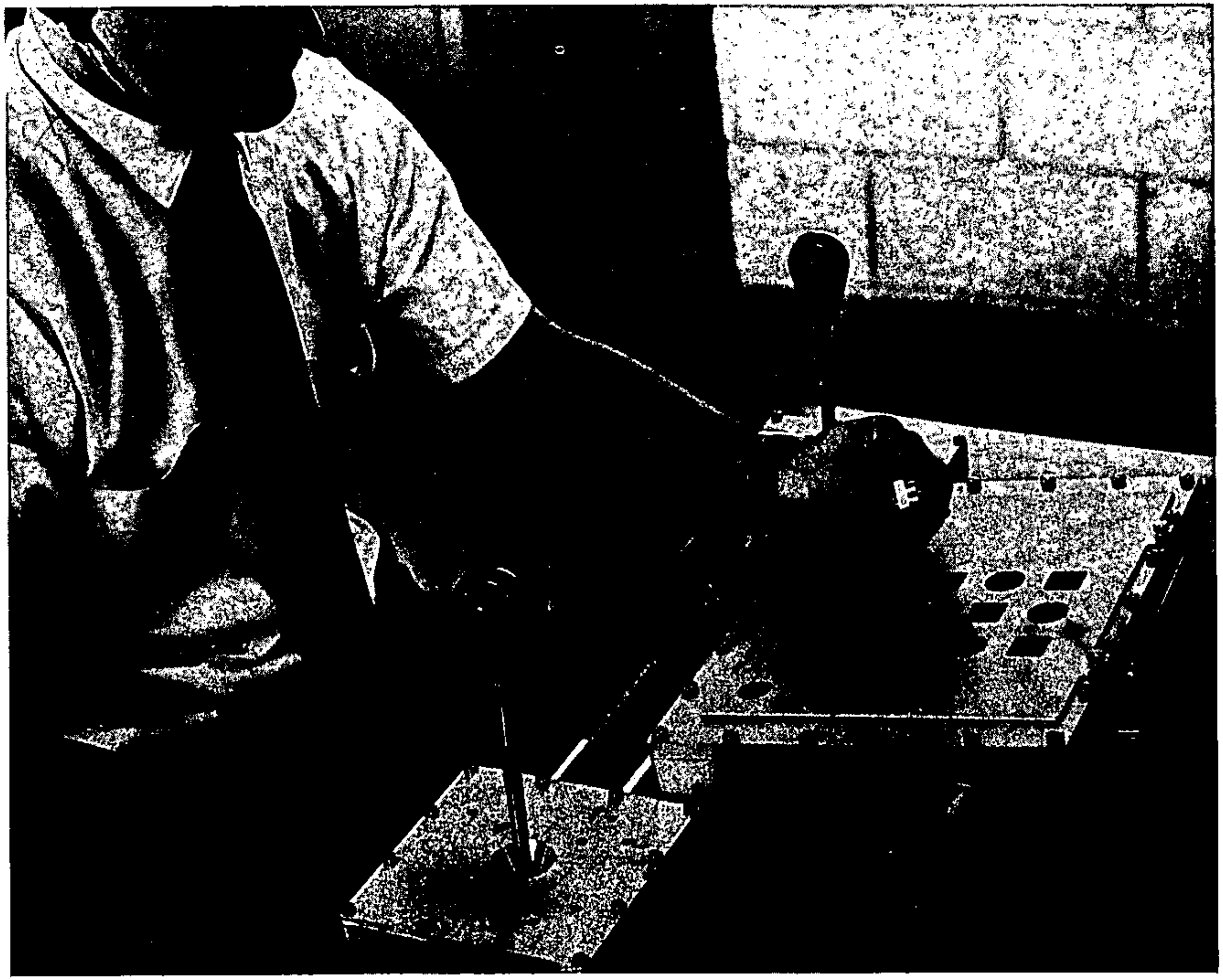

Fig. 14. Finger Dexterity test apparatus in use.

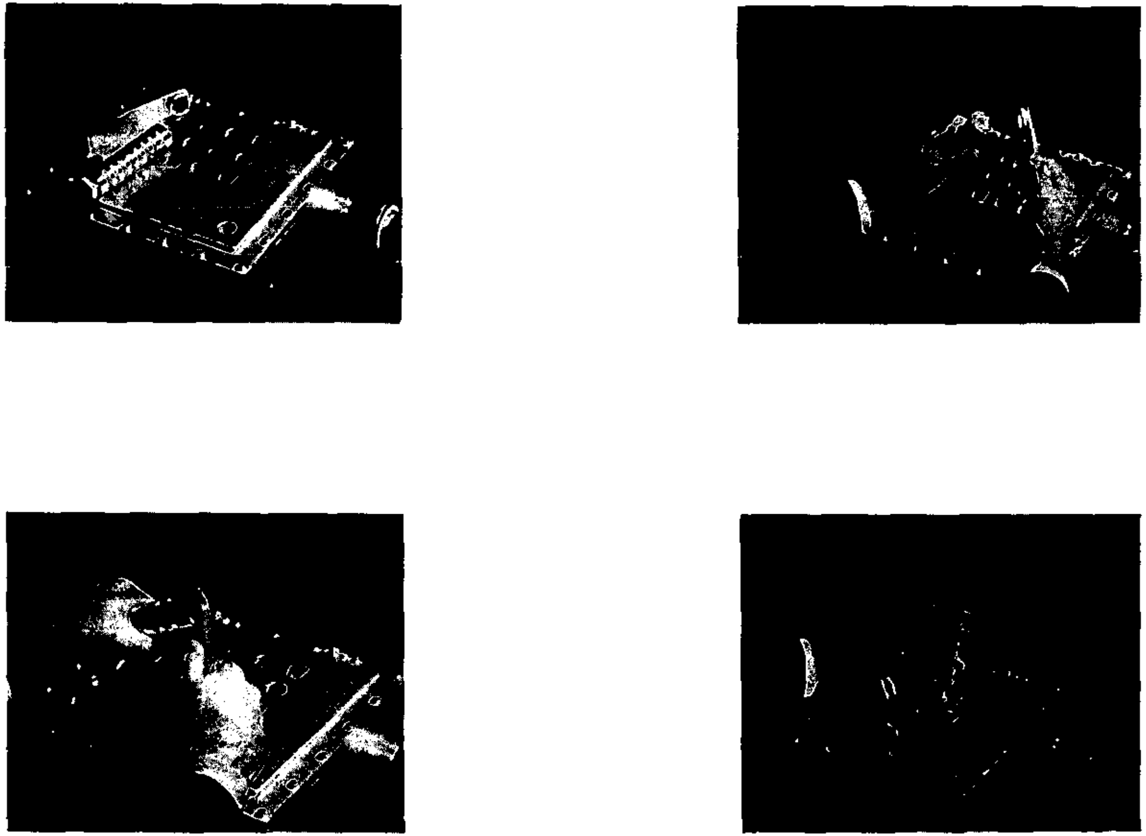

Fig. 15. Manual Dexterity test (Wrench and Cylinder)

The outer portion of the cylinder is a sleeve which, by means of internal threads, can be moved to expose one or the other end of the inner component. The ends of the inside portion of the cylinder are shape coded (square and round) and magnetic.

Using the wrench to stabilize the inner component, the outer sleeve is rotated to expose first one end, then the other. As each end is exposed it is inserted into a correspondingly shaped opening on the keyboard. Each complete operation is thus registered and accumulated for scoring at the experimenter console.

The test is scored as the total operations (keyboard registrations) performed in a 60 second period.

Tracking Apparatus. Figure 16 shows a Two-Hand tracking test in progress. In this particular test configuration, the subject is using his left-and-right-hand sticks to control, respectively, the horizontal and vertical axes of motion of the control dot as he attempts to superimpose the dot on a moving target dot. Either stick may be used individually to control vertical and horizontal motion, or both may be used with each controlling a single axis, as is being done here.

Summary Information

Physical data for the major system components are given in Table 3 .

Table 4 lists each test and the manner in which it is administered and scored.

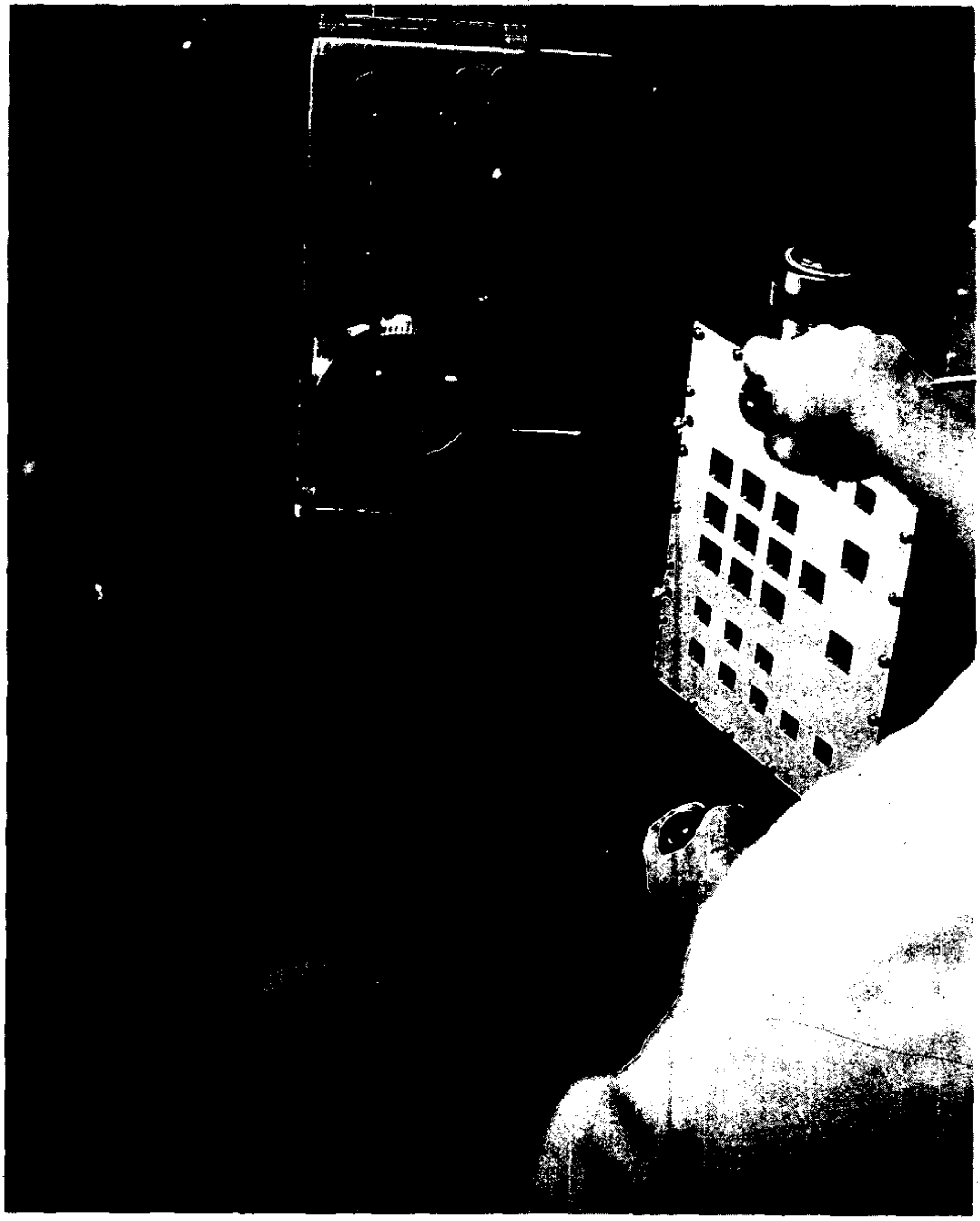

Fig. 16. Two-Hand Tracking test in progress.

Table 3

Size, Weight, and Power Requirements of Principal Components

Component	Dimensions (in)	Weight (lb)	Power
Subject Keyboard	12.5 x 10.0 x 5.5	41 (16 in water)	
Internal lamps (total)			2 amp @ 1.5 vdc (via experimenter console)
Tracking Controls			
Max overall	24.6 x 6.0 x 10.0	16 (9 in water)	
Each unit	6.0 x 6.0 x 2.6		
Control handle	7.4 long		
Distance between control handles	18.6		
Projection Screen		11	
Viewing area	15.0 x 19.0 x 0.25		
W/support frame	18.0 x 24.0 x 0.75		
Support arm length (adjustable)	11.0 to 17.0		
Oscilloscope (HP120B)	16.8 x 18.4 x 7.3	32	95 w @ 115 vac
Projector (Kodak 950)	13.5 x 11.0 x 4.0	15	600 w @ 115 vac
W/BTI optical reader (overall max)	17.3 x 14.0 x 12.4		
Experimenter Console	22.8 x 14.0 x 12.3	44	2 amp @ 115 vac
Electronics Package	21.6 x 14.8 x 13.5	48	via experimenter console
Photocell Stylus	8.5 x 0.56 diameter	6 oz (dry)	
Magnetic Stylus	5.0 x 0.5 diameter	3 oz (dry)	

Table 4

Summary of System Test Configurations

Cognitive Abilities

Test	Stimulus/(Source)	Programming	Response Mode	Scoring System	Performance Measure
Digit Span	Sequence of digits (Online display)	Manual entry of sequence for storage Automatic presentation	Numerical answer (Keyboard)	Automatic Number of digits produced correctly in sequence	Length of series reproduced correctly
Associative Memory	First member of paired associates (Slide)	Manual slide advance	Numerical answer (Keyboard)	Manual entry of correct answer(s) Automatic scoring	Number of correct responses
Perceptual Speed	Column of pairs of numbers (Slide)	Manual slide advance	Binary answer (Keyboard)	Automatic Count	Total correct minus incorrect
Number Facility	Arithmetic problem +, -, x, ÷ (Slide)	Manual slide advance	Numerical answer (Keyboard)	Visual display of answer (Manual scoring)	Total correct
Induction	Sets of letter groups (Slide)	Manual slide advance	Single response, numerical designation (Keyboard)	Automatic Count	Total correct minus incorrect
Flexibility of Set	Digit series (Online display)	Manual entry of series Automatic presentation	Numerical answer (Keyboard)	Automatic Count	Trials to learn new sequences

Table 4--Continued

Cognitive Abilities (cont'd)

Test	Stimulus/(Source)	Programming	Response Mode	Scoring System	Performance Measure
Time Interval Estimation	Discrete signal (light source) (Slide projector or *online display*)	Manual	Single response (Keyboard)	Automatic Elapsed time	Time error
Time Sharing	Random discrete events (Online display and pilot lamp on subject console)	Automatic cycling Manual programming of critical events	Binary response (Keyboard)	Automatic Time	Detection time Detection frequency
Response Orientation	Colored light (four colors) (Slide)	Manual slide advance	4 Keys - one per color (Keyboard)	Automatic Time	Cumulative response time
Spatial Scanning	Visual pattern (*Slide*)	Manual slide advance	Response is one of six letters (Keyboard)	Fully automatic Count	Total correct
Visualization	Visual pattern (Slide)	Manual slide advance	Letter-number pairs (Keyboard)	Automatic Count	Total correct minus part of incorrect
Spatial Orientation	Set of geometric figures (Slide)	Manual slide advance	Number (Keyboard)	Fully automatic Count	Total correct minus incorrect

Table 4--Continued

Perceptual Abilities

Test	Stimulus/(Score)	Programming	Response Mode	Scoring System	Performance Measure
Visual Monitoring	Continuous digit series cycle (Online display)	Manual interruption of cycle	Numerical answer 0 - 9 (Keyboard)	Automatic Manual entry of test digits	Total correct
Vigilance	Discrete signal (visual) Online display or x-y indicator	Manual actuation of critical events	Single Key (Keyboard)	Automatic Time	Detection time Detection frequency
Flexibility of Closure	Geometric patterns (Slide)	Manual slide advance	Binary response (Keyboard)	Fully automatic Count	Total correct minus incorrect
Length Estimation	Visual pattern (Slide)	Manual slide advance	Number (prob. ident.) plus Letter A or B (Keyboard)	Fully automatic Count	Total time minus incorrect

Table 4--Continued

Perceptual-Motor Abilities

Test	Stimulus/(Source)	Programming	Response Mode	Scoring System	Performance Measure
Arm-Hand Steadiness	Target grid (Slide)	Preset time interval	Tremor (Photocell stylus)	Count of tremor (pulses)	Total pulses over prescribed interval
Wrist-Finger Speed	Warning signal "Go" signal (Contact switches)	Preset time interval	Tap back and forth between two keys (Keyboard)	Automatic Count	Total contacts
Finger *Dexterity*	Warning signal "Go" *signal* Test object and board	Preset time interval	Manipulation of test object	Automatic Count	Total responses
Manual Dexterity	Warning signal "Go" signal Test object and board	Preset time interval	Manipulation of test object	Automatic Count	Total responses
Multilimb Coordination	CRT target dot x-y indicator	Preset time interval	Left- and right-hand control stick	Automatic Count	Time integral of error voltage
Speed of Arm Movement	Illuminated screen (Slide projector)	N/A	Sweep photocell stylus across screen	Automatic Time	Time to traverse screen
Reaction Time	Discrete signal (visual) Slide or pilot lamp	Manual start; automatic stop	Actuate or release key (Keyboard)	Automatic Time	Reaction time

Table 4--Continued

Perceptual-Motor Abilities (cont'd)

Test	Stimulus/(Source)	Programming	Response Mode	Scoring System	Performance Measure
Control Precision	Two dots (pursuit tracking) x-y indicator	Preset time interval	Tracking (Control stick)	Automatic Error	Time integral of error voltage
Rate Control	Single dot (compensatory tracking) x-y indicator	Preset time interval	Tracking (Control stick)	Automatic Error	Time integral of error voltage
Acceleration Control	Single dot (compensatory tracking) x-y indicator	Preset time interval	Tracking (Control stick)	Automatic Error	Time integral of error voltage

System Utilization

There would appear to be three major areas of application of the human performance measurement system: it should provide a means of specifying performance capabilities on a wide range of tasks in deep water and dry hyperbaric environments; it should represent a well defined technique for studying the differential effects of the variables comprising much of the diver's operational sphere; and, it should afford a comprehensive and stable method in the development of diver selection criteria.

Human Underwater Performance Capabilities

Ideally, one would like to have a complete set of functional relationships between diver performance and combinations of all relevant physical (and psychological) variables at all levels of magnitude.

The acquisition of such information requires a comprehensive and systematically executed program of research which in turn utilizes well-defined performance measures. Such a program is clearly a long-term venture. Results from this program, however, should provide a basis for responding to specific operational questions which arise and which must be answered quickly.

It is anticipated that SINDBAD I coupled with the facilities of the Navy Experimental Diving Unit, should represent a powerful research vehicle through which general laws of underwater performance may be derived. This combination also will provide a unique facility for obtaining information rapidly for specific questions. For example, one may readily provide an answer to questions such as: "To what extent does a particular type of diving gear improve or impair performance at a given depth?" "What is the effect of a particular gas mixture at a given pressure on those abilities required in the operation of certain complex underwater equipment?"

Thus, limited studies may be conducted to determine what effects are present for specific circumstances.

Differential Effects of Factors Comprising the Diving Environment

In studying the influence of the diving environment on human performance, a basic distinction must be made between effects which are due essentially to mechanical or physical encumbrances such as resistance of water and diving gear to movement of limbs, locomotion, etc., or reduced vision due to turbidity, low light levels, or fogged face mask, and those effects which are mediated by psychophysiological changes produced within the human, e.g., nitrogen narcosis, loss of dexterity due to vasoconstriction, thought-disrupting anxiety due to the hostile environment, etc.

The two types of factors may operate separately or in combination to reduce performance effectiveness. However, if one is to obtain information necessary to develop successful countermeasures, these variables must not be confounded in the experimental data. In this regard, the integrated measurement system as it is envisioned for use at the Navy Experimental Diving Unit appears to have great potential. Unlike research conducted in the sea where several parameters (e.g., level of illumination, pressure, turbidity) vary concomitantly with depth, and adequate experimental control is virtually impossible, these factors may be independently varied in the laboratory and their relative effects evaluated. Such information in itself would be of value while also providing guidance in the planning of research which ultimately must be carried out in the sea.

Development of Diver Selection Criteria

The objective of any personnel selection program is to assess the potential of aspirants to achieve a prescribed level of competence in the performance of required tasks. To meet this goal it is necessary to develop a set of tests or measures which permits an estimate of future performance on certain operational or criterion tasks. This in turn requires the demonstration of a strong relationship (e.g., high correlation) between test performance scores and criterion performance scores.

One significant advantage of SINDBAD I is its capability to provide rather comprehensive individual performance profiles on a select population of divers of varying experience.

Through appropriate statistical procedures, the relationship between test and criterion performance scores can be determined and expressed as a probability, in answer to the question: "Given a test performance profile of known characteristics, what is the likelihood that an individual will achieve a prescribed performance level on the criterion task(s)?" Normative test data may thus be obtained and criterion tasks identified and specified in terms of the constellation of underlying abilities.

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APPENDIX

DESCRIPTION OF ABILITY FACTORS AND ASSOCIATED TESTING PROCEDURES

This section presents the pool of factors or basic abilities identified as appropriate for inclusion in the test battery. Only certain of these items were finally selected.

For each factor, reference is made to one or more standard or conventional measurement techniques which were considered for modification and incorporation into the testing system.

Of particular value in the area of cognitive testing was the Kit of Reference Tests for Cognitive Factors published by the Educational Testing Service, Princeton, N. J., 1963. Many of the tests eventually modified for inclusion in SINDBAD I were drawn from this source.

Cognitive Abilities

Information Retrieval

Ability/Factor: Memory Span

Definition: The ability to recall and reproduce a series of items after only one presentation of the series.

Conventional Measure(s): (1) Auditory Number Span Test, (2) Visual Digit Span Test, (3) Auditory Letter Span Test.

Description of Representative Measure:

The Visual Digit Span Test involves recall and reproduction of series of digits immediately after they have been presented and removed from view. Series of numbers of increasing length are shown one digit at a time. The task is to reproduce the series after it has been completed.

The subject is shown a number of cards, one after the other, at one-second intervals. Each card has a different digit on it, thus:

$\boxed{7}$ then $\boxed{2}$ then $\boxed{4}$ then $\boxed{9}$ then $\boxed{6}$

When the series has been completed, the subject writes it down.

Number series range from three to ten digits in length; score is length of longest series remembered correctly.

Ability/Factor: Associative Memory

Definition: The ability to remember bits of unrelated material.

Conventional Measure(s): (1) Picture-Number Test, (2) Object-Number Test, (3) First and Last Names Test.

Description of Representative Measure:

On the Object-Number Test, the subject is presented series of words. Each word is paired with a two digit number. Later, the words are presented in a different order, and the task is to respond with the appropriate number.

The test item below shows five words and the numbers that go with them. They would be exposed for one minute, then removed from view. The words by themselves are then reexposed and the subject writes down the associated numbers. Score is number of items remembered correctly.

Word	Number
window	73
desk	41
carpet	19
door	84
glass	90

Information Processing

Ability/Factor: Perceptual Speed

Definition: The ability to compare one pattern with another under speeded conditions.

Conventional Measure(s): (1) Finding A's Test, (2) Number Comparison Test, (3) Identical Pictures Test.

Description of Representative Measure:

In the Number Comparison Test, pairs of multidigit numbers are inspected. The task is to determine whether the numbers in each pair are the same or different. If the numbers are different, the subject puts an X on the line between them. Score is items marked correctly minus items marked incorrectly. The items below are marked correctly.

7343801 ________ 7343801

18824 ________ 18824

705216831 ___X___ 795216831

55179 ___X___ 55097

5173869 ________ 5173869

63216067 ___X___ 63216057

658331 ________ 658331

4821459 ___X___ 4812459

Ability/Factor: Number Facility

Definition: The ease with which abstract symbols can be mentally manipulated.

Conventional Measure(s): (1) Addition Test, (2) Division Test, (3) Subtraction and Multiplication Test.

Description of Representative Measure:

Addition, Subtraction, Multiplication, and Division Tests measure how quickly and accurately an individual can mentally perform a basic computational operation. Test items are illustrated below. Score is number of items computed correctly.

$$\begin{array}{rrrrr} 34 & 17 & 45 & 31 & 80 \\ 81 & 50 & 41 & 52 & 78 \\ +\underline{51} & +\underline{74} & +\underline{89} & +\underline{19} & +\underline{15} \end{array}$$

$$\begin{array}{rrrrr} 76 & 59 & 90 & 46 & 56 \\ -\underline{40} & -\underline{46} & -\underline{31} & -\underline{29} & -\underline{23} \end{array}$$

$$\begin{array}{rrrrr} 37 & 81 & 86 & 43 & 69 \\ \times\underline{\ 8} & \times\underline{\ 4} & \times\underline{\ 3} & \times\underline{\ 6} & \times\underline{\ 7} \end{array}$$

$$546 \div 6 \qquad 376 \div 8 \qquad 153 \div 3 \qquad 415 \div 5 \qquad 117 \div 9$$

Ability/Factor: Induction

Definition: The ability to find general concepts that fit sets of data, and to form and test hypotheses.

Conventional Measure(s): (1) Letter Sets Test, (2) Locations Test, (3) Figure Classification.

Description of Representative Measure:

Each problem on the Letter Sets Test consists of five groups of letters with four letters in each group. Four of the groups are alike in some way. The fifth is different from the others. The task is to determine which of the groups does not fit some general rule that links the other four.

In example (1) below, four of the groups have letters in alphabetical order; therefore an "X" has been drawn through "DEFL." In example (2) an "X" has been drawn through "THIK" because the other four groups contain the letter "L." Score is number marked correctly minus a fraction of items marked incorrectly.

(1) NOPQ ~~DEFL~~ ABCD HIJK UVWX

(2) NLIK PLIK QLIK ~~THIK~~ VLIK

Ability/Factor: Flexibility of Set

Definition: The ability to institute an adaptive response pattern to changed conditions; and to discard a previous response pattern when it is no longer appropriate.

Description of Representative Measure:

The subject is presented with the successive onset of two lights in basic patterns of simple alternation or double alternation. Prior to each onset of a light, the subject indicates which of the two will illuminate; and with its illumination receives feedback as to the correctness of his prediction. After it has been established that the subject can correctly predict the sequence, the pattern changes, e.g., from units of two reds and a green to units of two greens and a red. Performance may be scored as number of trials required to adopt correct response pattern.

Decisionmaking

Ability/Factor: Stress Sensitivity

Definition: The ability to persist in and complete a predetermined response pattern in the presence of competing stimuli.

Description of Representative Measure:

The Stroop Word-Color Test consists of three cards, A, B, and C. Card A contains the words "red," "green," and "blue" printed in random sequence across its face. The subject's task is to read the card as rapidly as possible. Card B contains 1/4" x 1/2" colored rectangles (red, green, and blue) displayed in random order across its face. The subject's task is to name the colors as rapidly as possible. Card C contains the words "red," "green," and "blue" printed in colors different from what the word reads; e.g., "red" is printed in blue ink, "green" is printed in red ink. The subject's task is to name the color in which the word is printed. The competing responses induced by Card C represent a powerful cognitive stress situation.

Ability/Factor: Time Sharing

Definition: The ability to divide one's attention among two or more information sources through temporal/spatial sampling.

Conventional Measure(s): Time sharing is customarily measured by presenting the subject with two or more displays which cannot be attended to simultaneously.

Description of Representative Measure:

A representative situation is one where the subject is presented with two or more visual displays, separated in space in a manner which prohibits their being viewed simultaneously. The subject's task is to scan the displays continuously to detect the occurrence of some specified event. Usually the subject reports detection of an event by operating a switch. Performance is measured as the cumulative response time between onset of events and occurrence of detection responses.

Ability/Factor: Time Interval Estimation

Definition: The ability to estimate intervals of elapsed time or to discriminate differences between two or more time intervals.

Conventional Measure(s): In direct estimation of elapsed time, the subject is signaled as to the start of the test duration. He may be asked to indicate when a specified period (e.g., five minutes) has passed. Or, after a certain period, he may be signaled that the interval has terminated and asked to state the amount of time which has elapsed.

In some circumstances (e.g., sensory deprivation studies) the subject is simply asked to estimate how long it has been since the start of the experiment.

Description of Representative Measure:

The ability to discriminate among time intervals may be tested by presenting three short signals of known temporal separation. The subject then reports which interval (between first and second signal, or between second and third signal) was longer (or shorter). Alternatively, two pairs of temporally spaced signals may be presented, each pair defining a time interval. The subject reports any difference between the two intervals. Performance is usually scored as accumulated discrepancies between actual and estimated or judged events.

Ability/Factor: Response Orientation

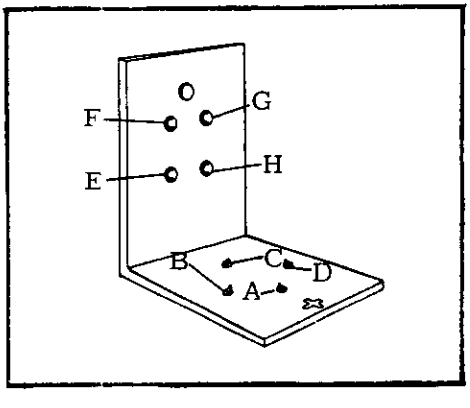
Definition: The ability to choose and perform the appropriate movement or direction of movement from several alternatives.

Conventional Measure(s): (1) Discrimination Reaction Time, (2) Complex Multiple Reaction, (3) Signal Discrimination.

Description of Representative Measure:

On the Discrimination Reaction Time Test, the subject manipulates one of four toggle switches as quickly as possible in response to a series of visual stimulus patterns differing from one another with respect to the spatial arrangement of their component parts, e.g., position of a lighted red lamp relative to a lighted green lamp.

The apparatus illustrated below shows four toggle switches (A, B, C, D) and four lamps (E, F, G, H). The subject's task is to throw the appropriate toggle switch to extinguish the lamps as they light in a previously learned red-green sequence, e.g., E-H, switch A; E-F, switch B; F-G, switch C; G-H, switch D. A warning light provides the subject with a ready signal before each light stimulus is presented. Score is accumulated response time for four series, each series containing 20 reactions for each stimulus pattern.



Ability/Factor: Visualization

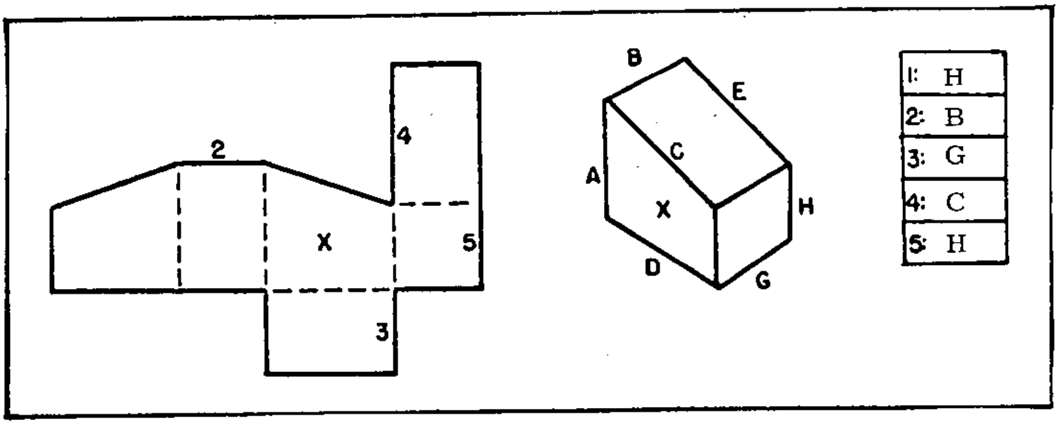
Definition: The ability to understand relationships involved in performing imaginary movements in three-dimensional space.

Conventional Measure(s): (1) Form Board Test, (2) Paper Folding Test, (3) Surface Development Test.

Description of Representative Measure:

On the Surface Development Test, drawings are presented of solid forms that might be made with sheet metal. With each drawing, a diagram shows how a piece of metal might be cut and bent to make the solid form. The task is to indicate which lettered edges in the drawing correspond to numbered edges in the diagram.

In the item below, the drawing on the left represents a piece of metal which can be bent on the dotted lines to form the object at the right. Imagine bending the metal, and determine which of the lettered edges on the object are the same as the numbered edges on the metal. The side of the flat piece marked with the X is the same as the side of the object marked with the X. The metal must be bent so that the X is on the outside of the object. The items are marked correctly. Score is number of correct items minus a fraction of the number of incorrect items.



1:	H
2:	B
3:	G
4:	C
5:	H

Ability/Factor: Spatial Orientation

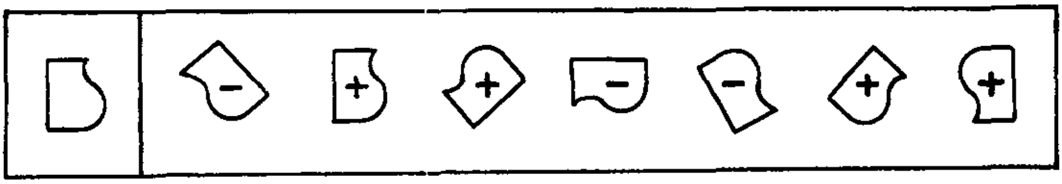
Definition: The ability to identify a particular kind of spatial alignment or pattern, and not be distracted by alignments or patterns in a different spatial position.

Conventional Measure(s): (1) Card Rotation Test, (2) Cube Comparisons Test, (3) Guilford-Zimmerman Spatial Orientation Test.

Description of Representative Measure:

Each item on the Card Rotation Test shows a drawing of an irregularly shaped object. To its right are seven other drawings of the same object. Sometimes the object is rotated; sometimes it is turned over onto its other side. The task is to indicate which drawings show the object not turned over.

In the sample item below, the object to the left of the vertical line is to be matched with those to the right.



Among those on the right, objects marked with a plus (+) are the same as the object shown on the left; they have merely been rotated into different positions on the page. Objects marked with a minus (-) are not the same as the object on the left; the object on the left would have to be flipped over or made differently in order to be like them. Score is number of objects marked correctly minus number marked incorrectly.

Ability/Factor: Spatial Scanning

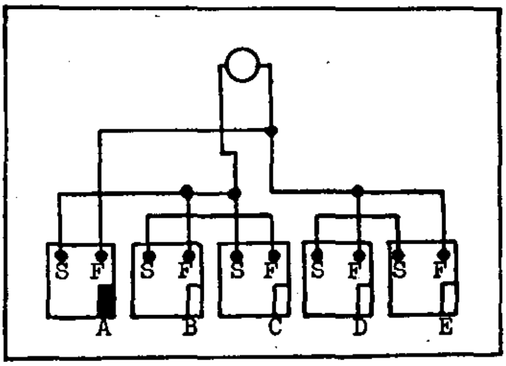
Definition: Speed in visually exploring a wide or complicated visual field.

Conventional Measure(s): (1) Maze Tracing Speed Test, (2) Choosing a Path Test, (3) Map Planning Test.

Description of Representative Measure:

Each item in the Choosing a Path Test consists of a network of lines as in an electrical-circuit diagram having many intersecting and intermeshed wires with several sets of terminals. The task is to visually trace the lines and to determine for which pair of terminals, marked S (start) and F (finish), there is a complete circuit through a circle at the top of the diagram.

In the item illustrated below, only one box has a line from the S, through the circle, and back to the F in the same box. Dots on the lines show the only places where connections can be made between lines. If lines meet or cross where there is no dot, there is no connection. Box A is the correct choice. Score is number of correct items.



Perceptual Abilities

Detection

Ability/Factor: Visual Monitoring

Definition: The ability to attend to a continuously changing visual information source and report system status on request.

Description of Representative Measure:

A distinction between visual monitoring and vigilance is not generally made in the experimental literature. However, it would appear useful for present purposes to distinguish between monitoring and vigilance in the following manner: Vigilance is considered as that task requiring the detection of infrequent events which occur at random intervals over prolonged periods. Monitoring is that task which requires attention to a continuously changing display to maintain cognizance of its status at all times. Emphasis is not on the detection of a critical event.

A configuration which provides measurement of the dimension of interest is one in which a continuously changing series of digits is presented one at a time in an "online" visual display. At predetermined intervals, the display sequence is interrupted, at which time the subject reports the last digit displayed. Score is number of correct recalls.

Ability/Factor: Vigilance

Definition: The ability to attend to one or more information sources or situations for relatively long periods to detect specified events which occur at random, or unpredicted intervals. Often the event to be detected is a discrete signal (visual or auditory) occurring against a noisy surround.

Conventional Measure(s): (1) Mackworth Clock Test, (2) Fraser Projected Circles.

Description of Representative Measure:

On the Mackworth Clock Test, the subject is required to view a clock-type display whose pointer rotates continuously in uniform step increments. Occasionally the pointer jumps by a double increment. The subject attempts to detect this event and responds by pressing a key. Performance is scored as discrepancy between actual and reported number of double increment jumps during periods ranging from one-half hour to two hours.

Recognition

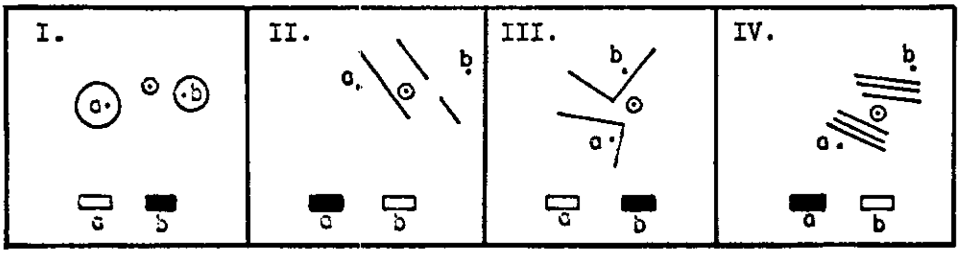
Ability/Factor: Length Estimation

Definition: The ability to judge distances.

Conventional Measure(s): (1) Estimation of Length Test, (2) Shortest Road Test, (3) Nearer Point Test.

Description of Representative Measure:

The stimulus items on the Nearer Point Test consist of two dots, "a" and "b," a reference point (⊙), and some distracting lines or figures. The subject's task is to select the dot that is nearer the reference point. Score is number of items marked correctly minus number marked incorrectly. The items below are marked correctly.



Ability/Factor: Flexibility of Closure

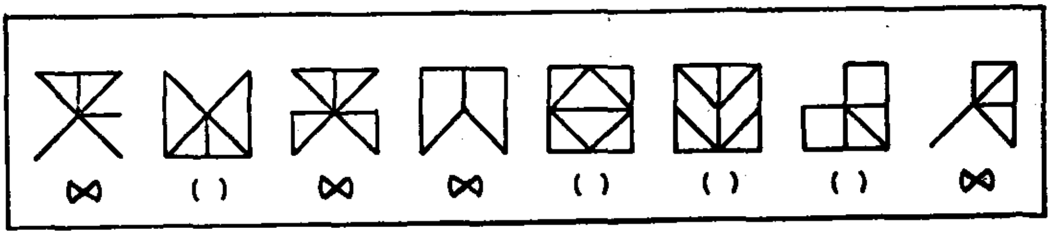
Definition: The ability to keep one or more definite configurations in mind so as to make identification in spite of perceptual distractions.

Conventional Measure(s): (1) Hidden Figures Test, (2) Hidden Patterns Test, (3) Copying Test.

Description of Representative Measure:

The stimulus items on the Hidden Patterns Test consist of geometrical patterns, some of which contain a particular figure. The task is to identify those patterns in which the figure is present.

For example, in which of the patterns shown below does the following figure appear ? The figure will always be in the position shown. It will not be on its side or upside down.



Patterns marked with an "X" contain the figure. Score is the number right minus the number wrong.

Fine Manipulative Abilities

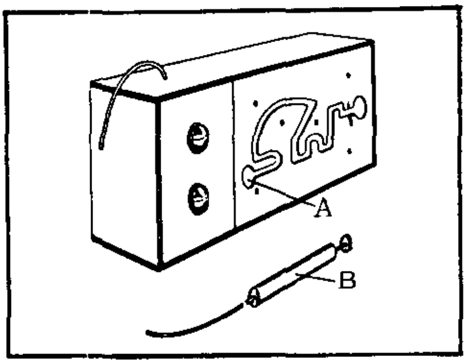
Ability/Factor: Arm-Hand Steadiness

Definition: The ability to make precise and steady arm-hand movements of the type which minimize strength or speed.

Conventional Measure(s): (1) Arm Tremor, (2) Steadiness Precision, (3) Track Tracing.

Description of Representative Measure:

On the Track Tracing Test, the subject is required to negotiate an irregular slot pattern (A) with a T-shaped stylus (B) held at arm's length. Score is number of errors (contacts with the back, top, or sides of the slot) during four attempts to negotiate the channel.



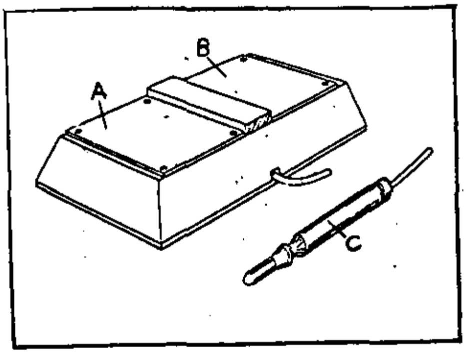
Ability/Factor: Wrist-Finger Speed

Definition: The ability to make pendular and/or rotary wrist movements; movements involve rapid, repetitive jabbing in which accuracy is not critical.

Conventional Measure(s): Usually the test consists of a printed form on which the subject taps back and forth between two circles for a specified amount of time. Performance is measured by counting the number of dots produced within the circles.

Description of Representative Measure:

On Two-Plate Tapping, the subject is required to strike two adjacent metal plates (A, B) with a stylus (C) as rapidly as possible. He strikes the plates successively, i.e., first one, then the other, making as many taps as possible on the plates in the time allowed. The number of taps is recorded on counters. Score is accumulated number of taps in three 30-second trials.



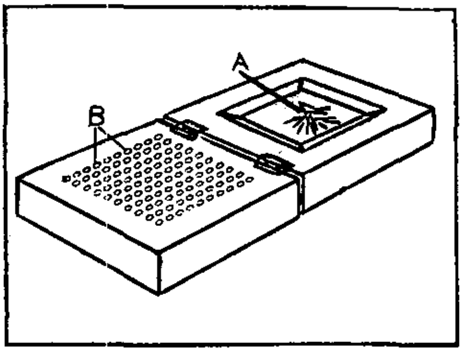
Ability/Factor: Finger Dexterity

Definition: The ability to make rapid, skillful, controlled movements of small objects where the fingers are primarily involved.

Conventional Measure(s): (1) Purdue Pegboard, (2) Santa Anna Dexterity Test, (3) O'Connor Finger Dexterity.

Description of Representative Measure:

On the O'Connor Finger Dexterity Test, the subject is required to pick up three small pins at a time from a tray of pins (A) with the preferred hand and place them three at a time in a small hole. A series of holes (B) must be filled in this manner as rapidly as possible. Score is the number of pins placed in one 5-minute trial.



Ability/Factor: Manual Dexterity

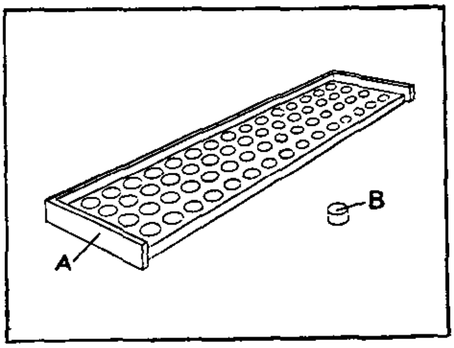
Definition: The ability to make skillful, controlled arm-hand manipulation of relatively large objects.

Conventional Measure(s): The Minnesota Rate of Manipulation--Turning is the standard measure of manual dexterity.

Description of Representative Measure:

On the Minnesota Rate of Manipulation Test, a placing task involves putting sixty cylindrical blocks in the proper holes as rapidly as possible. A turning task involves removing the blocks from the holes with one hand, turning them over with the other hand, and replacing them in the same holes, moving from block to block as rapidly as possible.

The device illustrated below shows a form board (A) and one cylindrical block (B). In placing, score is number of blocks placed in two 35-second trials. In turning, score is number of blocks turned in two 40-second trials.



Gross Positioning and Movement

Ability/Factor: Multilimb Coordination

Definition: The ability to coordinate the movements of two hands, two feet, or combinations of hands and feet simultaneously.

Conventional Measure(s): (1) Rudder Control, (2) Plane Control.

Description of Representative Measure:

In one type of test configuration, the subject sits in a mock airplane cockpit which he attempts to keep aligned with one of three target lights as they come on in front of him. His own weight throws the seat off balance unless he applies and maintains proper correction by means of foot pedals. He must also utilize appropriate pedal control to shift the cockpit from one light to another as these come on at random intervals. Score is the total time the cockpit is lined up with the proper light during three 112-second trials.

Ability/Factor: Speed of Arm Movement

Definition: The speed with which a subject can make discrete, gross, arm movement.

Conventional Measure(s): (1) Rate of Movement, (2) Ten Target Aiming.

Description of Representative Measure:

One type of test configuration involves two switches, 24 inches apart laterally, 12 inches in front of the subject. The subject's task is to place his hand above the left switch and, at his discretion, strike this switch and then move his arm horizontally as rapidly as possible to strike the second (right) switch. A timer starts as the first switch is touched and stops when the second is struck. Score is time required to traverse the distance between switches.

Ability/Factor: Position Reproduction

Definition: The ability to reproduce, on the basis of proprioceptive cues, the direction and extent of a previous movement.

Conventional Measure(s): (1) Direction Tracing, (2) Knob Positioning, (3) Control Movement, (4) Stick Positioning.

Description of Representative Measure:

A common feature of position reproduction tasks is that the subject moves his arm (or the control on which his arm rests) to a given position, removes it, then returns his arm to the original position. In certain instances, e.g., when the subject is blindfolded, the experimenter moves the subject's arm to the position which is to be reproduced.

Reaction Time Ability

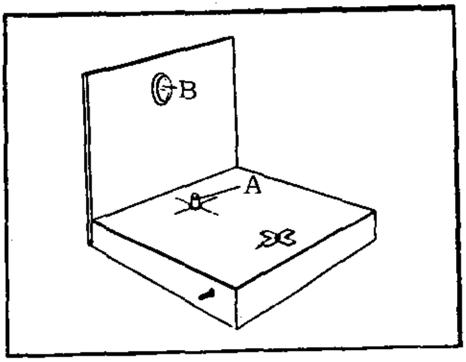
Ability/Factor: Reaction Time

Definition: The speed with which an individual can react to a stimulus.

Conventional Measure(s): (1) Visual Reaction Time, (2) Auditory Reaction Time, (3) Jump Visual Reaction Time, (4) Jump Auditory Reaction Time.

Description of Representative Measure:

On the Visual Reaction Time Test, the subject keeps his finger on a button (A), depressing it as rapidly as possible in response to the onset of a single amber light before him (B). A click provides him with a ready signal before each light stimulus is presented with the period between click and light varying in a random order from .5 to 1.5 seconds. Score is accumulated reaction time for a series of twenty reactions.



System Equalization Abilities

Ability/Factor: Manual Tracking

Definition: Use of hand controller(s) to control one or more axes of motion in system having zero-order dynamics, first-order dynamics, or second-order dynamics.

Conventional Measure(s): (1) Position Control, (2) Rate Control, (3) Acceleration Control.

Description of Representative Measure:

Manual tracking tasks typically consist of mechanical hand crank and pulley arrangements whereby rotary motion of the crank is translated into linear movement of a cursor along an irregular course or track.

More sophisticated devices are employed to vary the relationship between control movement and system output. An oscilloscope display, hand controller, and interposed analog circuitry permit a vertically unlimited number of transfer functions to be established. The most commonly encountered arrangements in studies of human tracking performance use either a simple gain amplifier (zero-order dynamics) or a series of integrators to achieve rate, acceleration, and higher-order dynamics.

IN: Human Factors, 1966, 8:499–506.

Perceptual Narrowing in Novice Divers[1]

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It was hypothesized that in diving, danger-induced stress may contribute to performance decrement by narrowing perceptual scope. A study was conducted to examine the effect of task load and type of underwater exposure on response time to a signal light in the visual periphery. Novice divers monitored a peripheral light alone, or while simultaneously performing a central addition or dial-watching task. Each subject was tested on the surface, in a diving tank, and in the open ocean. It was found that the central tasks did not interfere with peripheral vigilance on the surface. During diving, a distinct subgroup of the dual-task subjects exhibited markedly increased response times to the peripheral light while maintaining near constant performance on the central tasks. Their behavior appeared more closely related to diving risk than to other environmental factors. The remaining dual-task subjects, and the light alone group, were almost uneffected by underwater exposure. The hypothesis was considered partially validated.

INTRODUCTION

The diver is subject to manifold stresses during ocean activity. Such factors as gas narcosis, cold, restriction in visibility, movement and respiration, bouyancy change, and lack of communication, serve to impair his performance capability. Although these stresses act in consort, their adverse effects are for the most part amenable to separate attack along familiar biotechnical lines. (See, for example, Goldman et al., 1966; or Bennet, 1966.) There is in diving, however, the additional stress of dangerous exposure; that is, of operating under risk of injury of death (MacInnis, 1966). This psychological stress has been recognized as a probable factor in performance decrement underwater (Baddeley, 1966; Bowen et al., 1966). But even though it occurs in many other situations of interest to the human factors community, it is more difficult to isolate and define, its effects are less clearly understood, and the approach to its compensation more obscure than for the other, specific stresses.

The lack of precise information on the effects of danger-induced stress is understandable. Ethical considerations generally prevent the exposure of subjects to actual danger for purely experimental purposes. Moreover, Berkum (1964) has pointed out that no matter how dangerous a contrived situation actually is, subjects will tend to assume it safe, reasoning that the experimenter would not otherwise permit their participation. One way around this difficulty is to stage elaborate simulations, such as the "war games" employed by Berkum in his studies of performance during life-threatening military exposure; another is to make use of ongoing dangerous activities such as jet aircraft operations (Roman, 1965; Warren, et al., 1966) or auto racing (Vinson, 1966). The present study fits the second category; it rests on the observation that on any dive there is an element of real danger, not completely mitigated by the experimenter's presence. In fact, this element has been stressed in the diver's training. Although voluntarily undertaken, ocean diving is frequently approached with apprehension, particularly by beginners. The major drawbacks to diving experimentation are the somewhat select nature of the participants, the uncontrollability of the ocean environment, and the restrictions imposed by the diver's gear. However, these drawbacks are no different than those encountered in other field situations. Accordingly, it was felt that data obtained from divers would apply to the general question of human performance under risk, as well as to the specific problem of undersea performance.

The present study focused on one apparent con-

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[1] This study was supported by funds from NASA Grant NSG 237-62.

commitant of psychological stress, termed "perceptual narrowing," which involves a reduction in the individual's ability to assimilate sensory information. Berkum (1964) described the occurrence of such behavior in his simulated life-threat situations. He stated "... subjects underwent a severe restriction of the perceptual field. Relevant stimuli were not noticed, and inadvertant cues which the experimenters feared would compromise the deception failed to register with the subjects." Teichner (1966) reported that the detection of a light signal in the visual periphery was adversely affected by sleep deprivation. Analogous results have been contributed by Brown (1962) and Vinson (1966) for automobile driving, and by Flinn (1965) for flying. Our informal observations revealed similar responses in divers, who frequently do not "see" things in the water, such as fish, rocks, misplaced objects, etc., which are readily perceived by their more practiced partners. We concluded that whatever the genesis of this phenomenon, it seemingly occurs under varied conditions of psychological stress, including that induced by danger, and may relate to performance in the diving situation.

Our study objective was to examine quantitatively perceptual narrowing in beginning divers, using test environments of decreasing security. These were: on the surface, in an enclosed diving tank, and in the open ocean. We adopted as a measure of perceptual scope the response time to a small light fixed in the visual periphery. That is, longer response times were assumed to indicate perceptual narrowing. Response time was examined for subjects who attended to the peripheral light alone, and for subjects who attended to the peripheral light while performing an additional task involving the central visual field. No attempt was made to equate visual centrality with psychological primacy, but it was felt that the subjects would in fact favor the task in front of them. We reasoned that if the psychological stress associated with risk caused a reduction in overall perceptual capability, the effect would be more evident if some portion of that capacity were already committed. Thus we hypothesized that response time to the peripheral light would increase underwater, particularly in the ocean, and that this increase would be greater for the subjects performing central tasks.

METHOD

Tasks and Apparatus

Three standard oval diving masks were prepared with a small light source on the left side, approximately 60° into the periphery at a polar angle of 300° (see Weltman, et al., 1965, p. 427). The light sources were pieces of ¼ inch Plexiglass tubing, backlit by a miniature incandescent bulb. The peripheral light was lit at random-appearing intervals of 25 to 65 seconds, at an average rate of 75 signals per hour. The light remained on for 10 seconds, unless extinguished sooner by the subject with a water-proof switch held in his left hand. Two central tasks were used, an addition task and a dial monitoring task. The addition task required the subject to add a row of digits, and circle the digit which brought the sum to a given reference value. The addition problems were presented 50 to a side on 10 × 10-inch roughened Plexiglass sheets, which were written on directly with a lead pencil. The dial monitoring task utilized a 2⅝-inch diameter, blank-faced voltmeter enclosed in a water-proof plastic case. The pointer deflected 47° clockwise at a regular rate of one deflection per second. The signal was a single 75° deflection. The subject held his right hand on a spring-loaded toggle switch under the meter case, and acknowledged detection of a signal by briefly activating the switch. The dial signal rate and intervals were the same as for the peripheral light. Dial signals were scored a miss after 10 seconds without a response.

A portable programmer automatically provided simultaneous peripheral light signals to the three masks, and noncoincident signals to the voltmeter dial. Response times were displayed on a set of electrical stop clocks. Electrical cables led from the programmer to three test stations. On the surface, these stations were standard desks. Underwater, they were canvas camp stools attached to a tubular aluminum framework which supported the addition sheets or voltmeter case at optimum work heights. Underwater connectors on the diving masks allowed the subjects to move to and from the submerged test stations free from cabling. For all underwater runs the subjects wore standard open-circuit SCUBA gear employing a one-hose regulator, and were stabilized by weight belts placed across their laps.

Design

Male and female subjects were recruited from the current UCLA SCUBA diving class. They ranged from 20 to 36 years old. Each subject was tested first on the surface, then in a diving tank, and last in the open ocean. The ocean run closely followed the final class "check-out," and represented the second or third ocean diving experience. The subjects were separated at random into three task groups, Table 1 describes the groups, shows the number of subjects tested in each environment, and indicates the division by sex in each condition. Of the 27 subjects who began the experiment, 15 finished all three exposures. The attrition was due to subjects leaving the Los Angeles area after completing the SCUBA course. Each experimental run lasted 24 minutes, and was divided into three 8-minute intervals for subsequent analysis. The performance measures recorded in each interval were (1) mean peripheral response time for all subjects; (2) the number of addition problems worked; (3) the percent of addition problems in error for subjects in Group II; and (4) the percent of dial signals detected for subjects in Group III. Interval scores for the addition task were obtained by handing the subject a fresh problem sheet at the 8-minute and 16-minute times.

TABLE I
Task Group Classification and Composition

TASK GROUP		No. of Subjects (No. of Females) Completing Test Runs		
		Surface	Tank	Ocean
I	Peripheral Light Alone	9 (2)	8 (1)	4 (0)
II	Peripheral Light and Addition	9 (2)	6 (2)	6 (2)
III	Peripheral Light and Dials	9 (3)	8 (2)	5 (1)
TOTAL		27 (7)	22 (5)	15 (3)

Procedure

The surface tests were administered in cubicles within a large room. The tank runs were conducted in the UCLA Underwater Research Facility, a 15-foot deep, 15-foot diameter tank partitioned into three sections by transluscent plastic sheets for this study. Tank water temperature was 90–91° F, so that thermal protective suits were unnecessary. Two ocean locales were used, one off Catalina Island, the other adjacent to the pier at Marineland of the Pacific, on the Palos Verdes Peninsula, Los Angeles. The water at both ocean sites was from 20 to 25 feet deep, fairly clear, with a moderate-to-pronounced surge, and a temperature of about 65–70° F. The subjects wore neoprene wet suits, with hoods and gloves optional. Each ocean site had sandy bottom. Work stations were placed on it in a semicircle, facing out to sea. Worksite illumination on the surface, in the tank, and in the ocean was about 35 to 50ft-candles. Subjects were run by one's, two's and three's on the surface and in the tank, and by two's and three's in the ocean. For the tank and ocean trials, one or more safety divers assisted the subjects into their work stations, and remained with them, out of sight, during the course of the run. The beginning and end of the test periods were announced over an underwater loudspeaker system.

RESULTS

Peripheral Vigilance: Initial Analysis

In Table 2, mean response times to the peripheral light are shown for the largest subject groups available for comparison over the various combinations of tasks and environmental conditions. The group means on the surface (Comparison 1) reflected the effect of addition and dial monitoring tasks on response to the peripheral light in a non-stressful situation. The mean scores for the three 9-man groups were quite close, and a Kruskal-Wallis analysis of variance by ranks (Siegel, 1956) revealed no significant differences among them. The overall mean response time in the tank was longer than that on the surface (Comparison 2), but the difference was not statistically significant when the entire 22-man group was tested by a Wilcoxon signed-ranks test (Siegel, 1956), or when this test was applied to each of the three groups individually. In the tank, it appeared that the mean response times for the dual-task groups were considerably higher than that of the light-alone group. A Kruskal-Wallis analysis, however, revealed no significant differences among them.

TABLE 2
Response Time to Peripheral Light as a Function of Task Group and Environment

Subject Group and Comparison		MEAN RESPONSE TIME (SECONDS)		
		SURFACE	TANK	OCEAN
1	I (N=9)	0.95		
	II (N=9)	1.08		
	III (N=9)	0.92		
	Mean (N=27)	0.98		
2	I (N=8)	0.93	1.12	
	II (N=6)	1.24	1.85	
	III (N=8)	0.95	1.50	
	Mean (N=22)	1.04	1.49	
3	I (N=4)	0.97	0.79	0.96
	II (N=6)	1.24	1.85	2.55
	III (N=5)	0.97	1.65	2.11
	Mean (N=15)	1.06	1.43	1.87

Comparison over the three environmental conditions could only be made with the 15-man subject group (Comparison 3). For this group as a whole, response time to the peripheral light in the ocean was significantly longer than in the tank ($P < 0.005$; one tailed) and than on the surface ($P < 0.02$; one tailed) on the basis of the Wilcoxon Test. Examining the task groups separately, it appeared that the means of Group II and III increased markedly in both underwater conditions. While the mean response time for Group I remained about the same over the three environments. Separate Friedman analyses of variance by ranks (Siegel, 1956) confirmed that there was no significant differences over environments for Group I, and indicated only marginally significant differences for Group II ($P < 0.18$) and Group III ($P < 0.18$). The observed differences among groups means were not statistically significant in any environment.

Peripheral Vigilance: Steady and Unsteady Subjects

It was somewhat surprising that such large differences in means yielded so few statistically significant results, even in view of the small sample sizes. Closer analysis of the data provided an explanation. Apparently, Groups II and III contained two distinct subgroups: one composed of subjects whose peripheral response times remained virtually unchanged over the three environments, the other of subjects whose response times showed a marked increase underwater. The subgroups themselves seemed undifferentiated between the addition and dials case. We termed the first group the dual-task "Steady" Group and the second the dual-task "Unsteady" Group. Five of the 11 dual-task subjects were placed in the Unsteady group on the basis of elevated mean response time in the ocean. Figure 1 illustrates the mean response time data organized in terms of these new groups, and includes the group ranges in the ocean environment.

There was a clear difference in reaction to

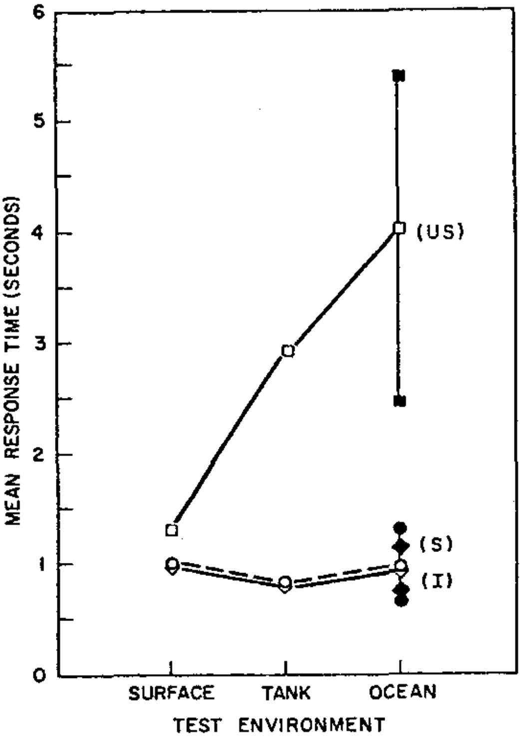

Figure 1. Mean Response Time to Peripheral Light for Group I (I), Dual-Task Steady Group (S) and Dual-Task Unsteady Group (US), Showing Response Time Range in Ocean.

diving between the Unsteady Group on the one hand, and Group I and the Steady Group on the other. For the latter two groups, mean response times were nearly the same in each environment, and the changes over environment were small and not statistically significant. In contrast, the response time differences over environments for the Unsteady Group were striking, and statistically significant ($P < 0.04$) when tested by the Friedman analysis of variance by ranks. The mean increase over surface scores was 226% in the tank, and 310% in the ocean. Individuals showed corresponding increases as high as 440% and 610%; and the actual changes were probably underestimated because of the arbitrary 10-second limitation on response times. The Unsteady Group had been selected on the basis of their high ocean response times, so that statistical comparison with the other groups was meaningless in that environment. But, in the tank also the Unsteady Group response times proved significantly higher than those of the other subjects ($P < 0.05$, two-tailed) when analyzed by the Mann-Whitney U-Test (Siegel, 1956). The Unsteady Group exhibited a slightly longer mean response time on the surface, but the difference was not statistically significant. It appeared then, that while the Unsteady subjects were about the same as the others on the surface, they were unable to maintain peripheral vigilance when performing two tasks underwater.

Central Task Performance

Table 3 summarizes the addition and dials task performance scores for the Group II and Group III subjects who completed all three test environments. Mean scores for the addition task differed hardly at all in the three cases. Although the Steady and Unsteady subgroups of Group II were too small for statistical comparison, their scores appeared quite similar, particularly in the ocean. Mean performance on the dial task deteriorated in the tank and ocean. The change over environments was significant ($P < 0.02$) when tested by a Friedman analysis of variance by ranks. Again, there was no apparent difference between the Steady and Unsteady subjects of Group III in the quality of their response to the dials task. There were also no significant correlations between the peripheral response times and any central task performance scores.

TABLE 3
Summary of Central Task Performance Scores

MEASURE AND GROUP		ENVIRONMENT		
		SURFACE	TANK	OCEAN
No. Addition Problems per 8-min Interval	II Steady (N=3)	48.8	49.8	55.8
	II Unsteady (N=3)	58.3	57.8	54.3
	II Mean (N=6)	53.6	53.3	55.1
% Addition Problems in Error	II Steady (N=3)	2.7	3.2	1.8
	II Unsteady (N=3)	1.6	1.9	1.8
	II Mean (N=6)	2.2	2.6	1.8
% Dial Signals Detected	III Steady (N=3)	82.3	82.3	71.0
	III Unsteady (N=2)	98.5	92.0	77.0
	III Mean (N=3)	93.0	87.2	74.0

Time Intervals

With two exceptions, there were no appreciable changes in either peripheral response times or central task scores for successive intervals within the experimental runs. Group II exhibited a statistically significant ($P < 0.02$) *decrease* in mean peripheral response time during the course of the surface exposure. This seemed to be a learning effect. Group III exhibited a consistent (but not statistically significant) decrease in the mean percentage of dial signals detected as the experimental runs progressed in each environment.

Sex Differences

In the surface exposures, the mean response time to the peripheral light for the male subjects was 0.89 seconds, and for the female subjects 1.27 seconds. The difference was statistically significant ($P < 0.02$) when analyzed by the Mann-Whitney U-Test. The female subjects also had longer response times in the tank, but their mean response time increase from surface to tank was no greater than that of the males. By the same analysis, the females worked significantly less addition problems than the males on the surface ($P < 0.03$) and in the tank ($P < 0.07$), and tended to do worse in dial signal detection under these conditions ($P < 0.20$ and $P < 0.05$, respectively). Too few female subjects participated in the ocean exposures to permit meaningful comparison of performance there. On the whole, the females appeared to perform on a lower level than the males, both in and out of the water. But the size of the two subject groups was too small to determine whether they were also more frequently unsteady.

DISCUSSION AND CONCLUSIONS

It is generally accepted that attention to a second task will hinder performance on a simultaneous visual monitoring task (Weiner, et. al., 1964; Schouten, et al., 1962) and that during a lengthy experimental run, monitoring performance will decline both in terms of percent signals detected (Frankmann and Adams, 1962) and mean response time to the signals themselves (Buck, 1966). The present study did not substantiate these previous findings for the peripheral light task. Simultaneous performance of the addition or dial monitoring tasks did not significantly affect response time to the peripheral light during the surface exposure, and response time remained uniform over the course of all experimental runs. Whether the present outcome resulted from the undemanding nature of our task combinations, too short run lengths, a highly motivated subject group, or some other factor, it demonstrated that the central tasks alone were not sufficient to interfere substantially with peripheral vigilance. Despite this, a distinct subgroup of the dual-task subjects exhibited markedly increased response times to the peripheral light during diving, and the times were typically longer in the ocean than in the tank. The increased response times appeared both for the active (addition) and passive (dial monitoring) central task. They were apparently not due to a general deterioration of capability underwater, because central task performance did not suffer correspondingly for this unsteady subgroup.

It seems reasonable to attribute the observed changes in peripheral vigilance to the element of risk in diving, which includes by implication those factors, such as breathing gear, wave action, etc. which determine the diver's safety. No alternative explanation fits as well. The present diving depths were not enough to induce noticeable nitrogen narcosis. Ambient light levels were nearly the same underwater as on the surface; and an effect due to lighting would have probably been more uniform over the entire subject group. It was cold and uncomfortable in the ocean; on the other hand, response times also lengthened appreciably in the tank, where it was warm and comfortable. Boredom during the course of the experiment, the greater novelty of the underwater exposures, or mechanical problems of underwater manipulation might have been precipitating causes; but it would seem that such factors would act on the central tasks as well. In addition, there were several indications that the unsteady subjects were more apprehensive than the others. For example, one Group III subject failed his initial ocean "check-out," evidencing clear signs of apprehension (overbreathing, wide open eyes, hesitancy to submerge, etc.) This subject showed large and consistent increase in peripheral response time in both tank and ocean. Questioned casually after his tank run, he volunteered that his thoughts wondered "to the chrome screw on the dial case" . . . *to what to do if the air gave out* . . . but not to sex." Another Group II subject was characterized as "unusually wary" during his training period. He appeared also in the Unsteady subgroup. In the ocean tests, a Group I subject appeared extremely reluctant to submerge near the pier through fairly large surface swells; there was some question whether he would begin his run. This subject had exhibited low and extremely uniform response times to the peripheral light in his surface and tank runs. During the first 8-minutes in the ocean, his mean response time increased 250% over the equivalent tank runs. But as the ocean exposure continued, his response times decreased and steadied, finally approaching his surface and tank scores. Thus although no definitive conclusions could be drawn, it appeared that our original hypotheses were at least partially validated. Perceptual narrowing was evidenced as anticipated, but for only part of the subject group.

Some dual-task subjects remained relatively unaffected by underwater exposure, although on the whole, peripheral response times lengthened in the ocean. If the psychological effect of risk was the major cause of perceptual narrowing in the present study, large individual differences should not be surprising, particularly since the actual danger involved was small. We know historically and personally that people differ in their judgment of and response to danger. Berkum (1964) reported significant individual variations in behavior during his simulated life-risk situations. Bowen, et. al (1966), in their recent study of the Sealab II project were able to assign the participant divers positions on a scale of self-admitted "fear" and "arousal," and to show that the greater his emotional response to diving, the less time a diver spent at work in the water. Sharply defined individual differences have also appeared in vigilance experimentation, which our study resembled, leading Frankmann and Adams (1962) to postulate a motivational relationship between stimulus conditions and subject responsiveness.

To account for individual variation one needs a better understanding than we now have of perceptual narrowing itself. For example, it is not obvious at present whether the observed phenomena can best be explained by reference to psychological concepts such as "preoccupation" and "instrument fascination" (Flinn, 1965), or "reduction in spare mental capacity" (Brown, 1962), or by reference to underlying physiological events. A Sealabs II diver stated that "so much of your mental capacity is devoted to listening to your exhaust, wondering whether its working right, keeping in mind how far you are from the laboratory . . ." (Bowen, et. al., 1966; p. 196.) Bursill (1958) found that peripheral vision constricted during execution of a difficult central task in the heat, but that the effect did not occur when the perceptual load of the central task was reduced. Such evidence favors an explanation based on central nervous system processes.

Nevertheless, profound circulatory changes, including peripheral vasodilitation, can accompany psychological stress (Burch and De Pasquale, 1965, Williams and Williams, 1965). Some of these changes may be implicated in perceptual narrowing through their effect on retinal blood supply. Increased pupil size has also been reported during emotional states (Hess, 1965). This affords a possible optical explanation for the observed deterioration in peripheral vision. Interestingly, a so-called "wide open eyes" syndrome has long been used by diving instructors as an indicator of apprehension in students. Further experimentation will be necessary to clarify these points. It also remains to be determined whether the perceptual narrowing phenomenon is consistently demonstrable; whether it is similar in diverse situations; whether its appearance in individuals is predictable; whether it is the same for noncompetitive as for competitive sensory inputs; and whether for the visual case, it always involves the physical periphery, or is only easier to measure there.

In summary, the present study has provided at least partial evidence for a narrowing of visual perception in beginning divers more closely related to the element of risk in underwater activity than to simultaneous environmental stresses. As such, narrowing could also appear in other dangerous situations, such as automobile driving, flying, extra-vehicular space activity, etc. If the effect on perception is appreciable, it could directly influence performance, and should accordingly be accounted for in human factors design. It is paradoxical that in dangerous situations, we require the most from the human operator, yet we know the least about his performance characteristics. Hopefully, the present study represents a step toward the acquisition of that knowledge.

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VISION

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19

VISION

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Much is now known about underwater vision, both how and why it differs from vision in air. The foundations for this knowledge lie in many different fields: studies of oxygen toxicity, hydro-optics, and limits of diving. Research on hyperbaric oxygen gained impetus from the fields of aviation, diving, and medicine. While adverse effects of hyperbaric oxygen on the pulmonary system were noted early, realization of the consequences for the visual system came more gradually.

The pioneering work of Behnke, Forbes, and Motley (1936) on the effects on man of breathing oxygen at 3 ATA for up to 4 h first documented the dramatic decrease in visual fields occurring prior to impending collapse. Impairment of visual acuity was also severe just prior to collapse. Behnke and his colleagues' research was all the more remarkable because it was performed on man; other diverse and toxic effects of hyperbaric oxygen on the visual system were naturally first documented on patients or animals. The first clinical demonstration correlated retrolental fibroplasia in infants with the amount of hyperbaric oxygen breathed (Patz, Hoeck, and De La Cruz, 1952).

The remarkable susceptibility of visual cells to hyperbaric oxygen was first demonstrated by Noell (1962); visual cell death occurred in all rabbits exposed to 100% oxygen for 40 h, even though they may not have shown other symptoms of oxygen toxicity. Another severe consequence of breathing hyperbaric oxygen is retinal detachment, which Beehler, et al. (1963) documented after dogs had breathed 90 to 100% oxygen for no longer than 48 h.

One of the first signs of hyperbaric oxygen, decrease in calibre and increase in redness of retinal vessels, first noted by Cusick, Benson, and Boothby (1940), is not necessarily pathologic, but may serve simply to protect the eye from excessive oxygen. Nonetheless, many have speculated that this adaptive effect may result in reduction of essential nutrients.

Many of these visual signs and symptoms are now used as a warning system to protect against CNS poisoning by oxygen in air diving; they become particularly important in air saturation diving because of the possibility of longterm cumulative effects.

Hydro-optics and the physics of light transmission by water was another important research field for underwater vision. Duntley's (1963) careful analysis of the attenuation of light by water, its impact on contrast, and consequently on divers' ability to see, remains the foundation of hydro-optics. While dependence of spectral transmittance of sea water upon quantities of silt, plankton or pollution was known since the early work of Hulbert (1945), the effects on divers' underwater color perception was first measured by Kinney, Luria, and Weitzman (1967). Similarly, the perceptual consequences of many other physical principles of light propagation underwater, such as refraction, were assessed by Luria and Kinney (1970), including visual acuity, stereoacuity, perception of size and distance, and hand-eye coordination.

Finally, there is knowledge obtained as a consequence of the practical determination of limits to which diving can be pushed without severe or incapacitating effects. Such limits are continually being extended so that today's list will undoubtedly be superseded tomorrow. Nonetheless, several determinations of the lack of effects of various breathing mixtures and pressures on vision should be noted.

Thus, subjects breathing 100% O_2 at sea level for 24 h showed no visual decrements on the extensive test battery of Gallagher, et al. (1965), which included all visual functions likely to be affected by O_2 toxicity. Similarly, Kelley, et al. (1968) showed no adverse effects on the vision of divers using an extensive battery of tests in a pressure chamber simulation, with helium-oxygen, to depths of 1025 ft. Most recently, Montabana and Lambertsen (1978) reported only small or insignificant decrements in simulated dives to 1600 fsw.

VISION

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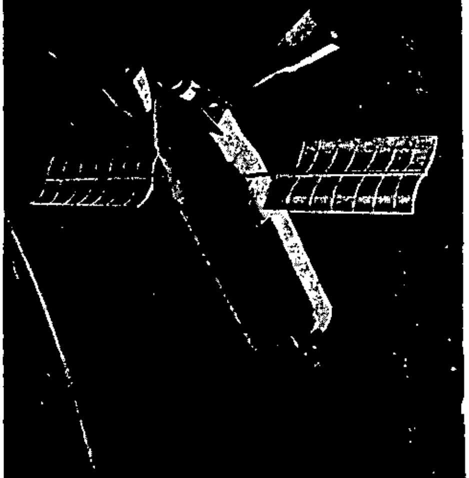
DEPARTMENTS



35th Annual Scientific Meeting
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May 11-14, 1964

OFFICIAL PUBLICATION OF THE
AEROSPACE MEDICAL ASSOCIATION

Ocular Hyperoxia

Capt. Cecil C. Beehler, USAF, MC, Capt. Norris L. Newton, USAF, MC,
Lt. Col. James F. Culver, USAF, MC, and Major Thomas Tredici, USAF, MC

THE WIDESPREAD use of high partial pressures of oxygen in aerospace and clinical research today demands that its toxicity be clearly defined. It is well known, for instance, that the misuse of oxygen in premature infants may lead to permanent damage in the form of retrolental fibroplasia. Recent studies indicate that such damage may not be limited to immature animals. This study was initiated to determine the effect of high oxygen environments on the visual system of mature animals.

METHOD

Healthy adult mongrel dogs were exposed to high partial pressures of oxygen in a specially constructed chamber. The oxygen partial pressure was maintained between 680 and 760 mm. Hg (90 to 100 per cent) or 610 and 680 mm. Hg oxygen (80 to 90 per cent), depending upon the desired concentration. The humidity ranged between 40 and 90 per cent and the temperature was held between 24 and 25° C. The concentration of CO_2 was not permitted to exceed 0.9 per cent and was usually well below this level. The animals were subjected to oxygen according to several different time schedules. Group I was exposed to 680 and 760 mm. Hg of oxygen continuously for an average of 72 hours. In Group II each animal was exposed to 680 and 760 mm. Hg of oxygen for an average of 85 hours, but was allowed to breathe room air for 1 or 2 hours each day. In a third experiment (III) a single animal was exposed to 610 and 680 mm. Hg of oxygen for 236 hours, but was also permitted to breathe room air for 1 or 2 hours per day. The animals from experimental groups II and III were examined for eye changes daily during the air breathing intervals. Intraocular pressures were estimated with a standard Schiotz tonometer. The animals were routinely tranquilized with Sparine® (30 to 45 mm. IM). The pupils were dilated with Mydriacyl® for ophthalmoscopic examinations. When ocular tensions were taken, the cornea was anesthetized with 0.5 per cent Tetracaine HCl ophthalmic solution.

RESULTS

Group I (10 animals)

Continuous exposure to 680 and 760 mm. Hg. of oxygen for 72 hours proved to be fatal for all animals. They were either dead at the time of removal from the chamber or died shortly thereafter due to pulmonary complications. Nevertheless, 50 per cent of the animals showed gross eye lesions at the end of this time. These findings included bilateral retinal detachments, conjunctival edema, corneal haze, and anterior chamber hemorrhage.

Histologic sections confirmed the above findings. Sections from the conjunctiva with edema showed a heavy lymphocytic infiltrate just under the squamous epithelium.

Group II (6 animals)

When significant eye lesions were found during the

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Fig. 2. Same animal as in Fig. 1 showing conjunctival edema.

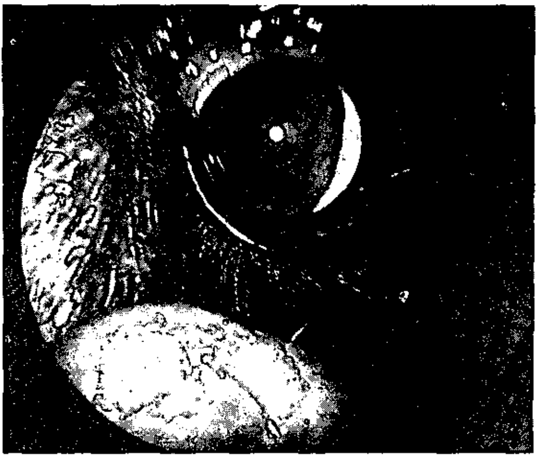

Fig. 1. Animal from group II showing large retinal detachments which occurred after 92 hour exposure to oxygen.

daily examination, oxygen exposure was discontinued. Fifty per cent (3) of these animals survived exposure and 83 per cent (5) showed significant eye changes, including all animals which survived. The lesions included bilateral retinal detachment, conjunctival edema, hypotony, and dilated, fixed pupils. The retinal detachments were always large, bilateral, and involved large areas of both tapetal and nontapetal retina (Figure 1-4). The drop in intraocular pressure averaged 12 mm. Hg, ranging from 8.5 to 21 mm. Hg. In all cases in which the animals survived, the retina appeared to be reattached, and normal intraocular tensions were re-established within one week. Sections taken from those animals surviving more than one week were normal in all but two cases. In one case sections showed the sensory retina separated from the underlying pigment epithelium by an eosinophilic staining exudate lying in the subretinal space. Under higher magnification, macrophages can be seen engulfing pigment material. The rod and cone layer shows degeneration. These findings would be expected in a retinal detachment of several weeks' duration.

In the animal exposed to 610 and 680 mm. Hg of oxygen for 236 hours (III), the intraocular pressure dropped from a control level of 20 mm. Hg to 12 mm. Hg at 212 hours. When the animal was removed at 236 hours, the pressure was 6 mm. Hg bilaterally. No detachments developed. Four days after the animal was removed from the chamber, a grade III iritis was present and a ¾ mm. fibrin clot was seen attached to the cornea in the anterior chamber of one eye (Figure 5).

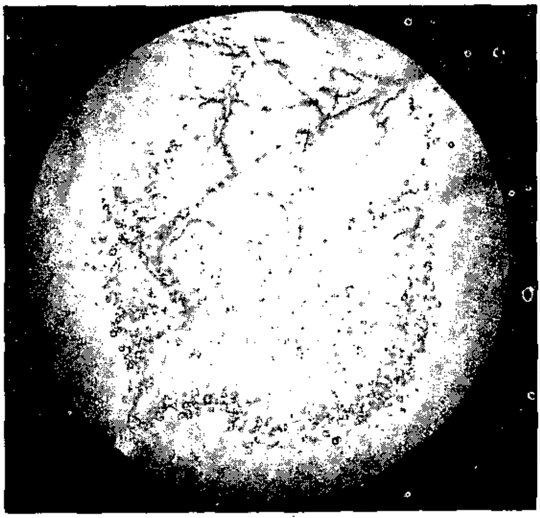

Fig. 3. Same animal as Fig. 1 showing extent of retinal detachment.

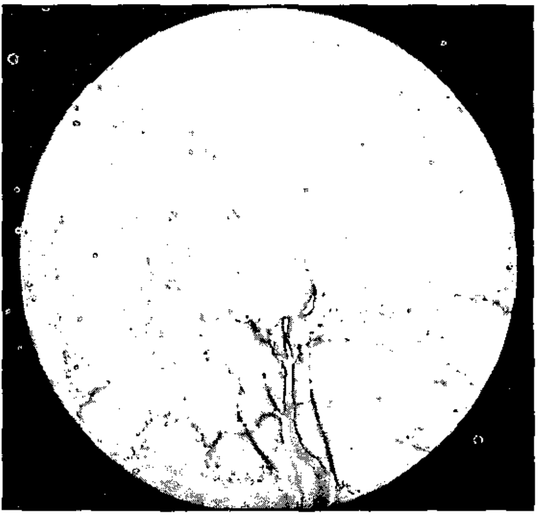

Fig. 4. Same animal as Fig. 1 showing extent of retinal detachment.

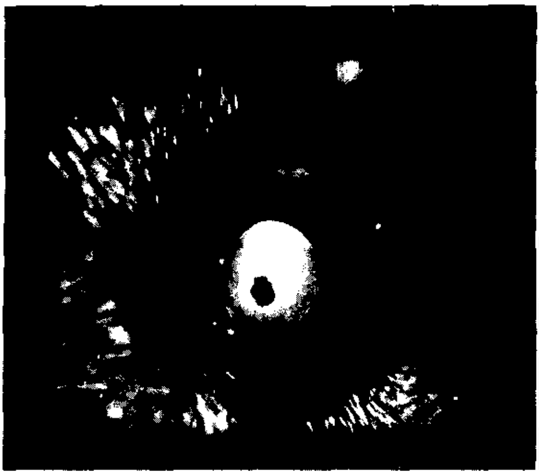

Fig. 5. Animal from experiment III showing fibrin clot seen in anterior chamber which developed four days after oxygen exposure was terminated.

Fig. 6. Normal dog fundus demonstrating appearance of the tapetum.

Dissection of the eyes from this animal revealed brownish 1 mm. nodules adjacent to the ciliary body. Under microscopic examination these structures were found to be ciliary cysts with large collections of fibrin under the ciliary epithelium.

DISCUSSION

The dog retina differs from the human retina in several respects; the most striking difference is the presence of a tapetum. This structure is a highly reflective layer of pigment, located between the retina and the choroid. It is responsible for the shining effect seen in animals' eyes at night. The tapetum is roughly triangular in shape and is limited to the superior half of the retina (Figure 6).

The mechanism of retinal detachment in our experiments is not known. It is interesting that retinal detachment is also a prominent feature of retrolental fibroplasia. In retrolental fibroplasia, however, the detached retina organizes to form an opaque mass behind the lens, while in our experiments the retina always reattached within one week.

Retinal detachments in adult animals due to oxygen toxicity have not been reported previously, although this has been noted by Lee.[3] Detachments occurring as a result of toxicity of any kind is certainly unusual, but have been reported in dogs as a result of the ingestion of certain zinc chelating agents, such as hydroxpyridinethione.[1] This is believed to be primarily a result of the action of the chelating agent on the very high content of zinc in the dog tapetum (8.5 per cent dry weight). It appears to be species specific, as the same drugs do not result in detachments in monkeys or rabbits, which do not have a tapetum. The detachments in our series did not seem to originate in any particular area, and in some cases were limited to the lower, nontapetal, portion of the retina. Therefore, we have no reason to believe that the mechanism of detachment is related to the tapetum in our experiments.

The degenerative changes which occurred in the rod and cone layers appear to have been primarily a result of retinal detachment. However, Gyllensten[2] found atrophy of the ganglion layer, inner nuclear layer, and outer plexiform layer in new born mice exposed to 100 per cent oxygen for five days. Noell,[4] has reported degeneration of the visual cells and atrophy of the outer nuclear layer in rabbits exposed to high partial pressures of oxygen, but did not observe retinal detachments. He attributed these changes to metabolic poisoning of the cells similar to that produced by iodacetate.

It should be emphasized that these tensions were obtained by a standard Schiotz tonometer, whose foot plate was designed for a human cornea. The instrument was not calibrated for the dog eye. Thus, while the absolute pressures may be erroneous, the comparative values are significant. It is conceivable that the hypotony occurred on the same basis as the ciliary cyst found in Experiment III, but this is pure conjecture on our part.

The conjunctivitis which was noted in three animals is difficult to explain. Originally, it was thought to be an allergic reaction to the drugs used in the examination, but the conjunctivitis cleared spontaneously even though we continued to use the medications on a daily basis. Further, eosinophiles did not predominate in the inflammatory reaction.

The minimum time and partial pressure necessary to produce retinal changes are not established. Noell,[4] however, found electroretinogram changes in rabbits after 36 hours' exposure to 100 per cent oxygen. In our experiments, we have noted small retinal detachments after 48 hours.

It is not known whether or not these findings have any relation to changes occurring in human eyes during exposure to high partial pressures of oxygen. In light of the fact that permanent eye damage occurs in both rabbits and dogs, however, the possibility should be considered until more conclusive studies can be completed.

SUMMARY

It has been shown that exposure to 680 and 760 mm. Hg of oxygen for no longer than 48 hours can result in profound eye damage in mature animals' eyes. Clinically, the animals developed retinal detachment, conjunctivitis, iritis, and hypotony. Histologic studies revealed subretinal fluid, degeneration of the rod and cone layer, as well as ciliary cysts. As with other types of oxygen poisoning, the mechanism by which these changes occur is not known.

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CIRCULATORY AND VISUAL EFFECTS OF OXYGEN AT 3 ATMOSPHERES PRESSURE

BY

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CIRCULATORY AND VISUAL EFFECTS OF OXYGEN AT 3 ATMOSPHERES PRESSURE[1]

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In dogs anesthetized with sodium barbital, oxygen at a pressure of 4 atmospheres produces a fall in blood pressure and convulsive seizures which terminate in paralysis of respiration (Shaw, Behnke, and Messer, 1934). Since these phenomena are rapidly reversed when air replaces oxygen, the inference may be drawn that oxygen acts directly on the central nervous system, and possibly reflexly through the carotid sinuses.

In man oxygen at a pressure of 4 atmospheres induces either sudden syncope or convulsive seizures followed by complete recovery when air is again breathed (Behnke, Johnson, Poppen and Motley, 1935). In view of these striking phenomena, the question arose concerning the symptoms of oxygen toxicity for man at pressures less likely to produce sudden collapse.

The results reported in this paper indicate that oxygen at a pressure of 3 atmospheres brings about definite but rapidly reversible changes in man, namely, concentric contraction of the visual field, diminution of visual acuity, dilatation of the pupils, a rise in blood pressure, constriction of the facial vessels, and increased pulse rate.

EXPERIMENTAL METHOD. Four healthy young men breathed oxygen from either a closed or open system equipped with mask (4 experiments) or helment (5 experiments) for periods up to 4 hours at a pressure of 3 atmospheres (30 lb. gauge). To accomplish this they were placed in the large pressure chamber described by Thomson, Yaglou and Van Woert (1932). The observations include records of the leucocyte count, blood pressure, heart rate, respiratory rate and minute volume, acuity of vision, area of the visual field, and the appearance time of a negative after-image. The visual field of each eye was measured on a perimeter immediately before and after oxygen breathing. Visual acuity was tested by the ability to distinguish two black lines drawn parallel on white piece of cardboard and separated by a distance of 0.35 mm. The negative after-

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[1] This research was aided by the Miriam Smith Rand Fund.

[2] Member of the United States Naval Medical Corps.

image was induced by allowing the subject to fix on a red and green cross held at a distance of 1 meter from the eye for a period of 20 seconds.

Results. The period of oxygen breathing can be divided into two intervals. The first covers 3 hours during which oxygen was well tolerated. The second comprises a period of impending collapse which comes on abruptly during the 4th hour. The detailed results of a representative experiment are given in table 1.

Oxygen breathing up to the 4th hour. The usual symptoms were moderate facial pallor and dilatation of the pupils, a rise in diastolic blood pressure of about 10 points, and impairment in visual acuity up to 25 per cent. In several experiments vision and blood pressure were not appreciably affected. There were usually no abnormal subjective symptoms during this period.

TABLE 1

Circulatory and visual effects of oxygen at 3 atmospheres pressure (subject 1)

TIME	BLOOD PRESSURE	PULSE RATE	VISUAL ACUITY DECREASE	TIME OF NEGATIVE AFTER-IMAGE	REMARKS
a.m.			*per cent*	*seconds*	
10:49—air	132/86	96	0		10:50 to 2:15, subject felt well. Facial pallor noted at 1:04 2:15, subject stated that his field of vision was decreased and that his fingers and toes felt numb 2:19, feeling of dizziness and impending collapse. Sense of precordial oppression, and inability to cough. Numbness of fingers and toes. Intense facial pallor. Dilated pupils 2:23, field of vision contracted to the 10° circle of perimeter chart 3:30, return of the visual field to normal
10:50—O_2					
11:10	126/84	90			
11:45	115/90	75	3	8	
p.m.					
12:15	110/86	75	10	16	
12:47	114/88	63	20	18	
1:15	124/84	57	28	18	
1:47	138/102	57	26	18	
2:00	120/94	63			
2:19	150/104	75	60	20	
2:22		81			
2:23	Off O_2				
2:35—air	140/92	81	40	7	

Oxygen breathing during the 4th hour. Progressive contraction of the visual field was a constant symptom during the 4th hour. Measurements on the perimeter immediately following removal of oxygen showed a concentric contraction for each eye ranging from one-half the initial area down to the 10° circle, as shown in figure 1. In a single experiment the contracted field suggested left temporal hemianopsia, and the right pupil was dilated to a greater degree than the left. Central vision for form and color was impaired but not seriously until the period of impending collapse, when visual acuity was reduced as much as 60 per cent or even temporarily lost during the transfer from oxygen to air. A delay of 50 to 100 per cent in the time of appearance of the negative after-image paralleled the reduction of visual acuity. At the end of 2 out of 4 experiments the colors red and green were not recognized. An intense pallor of the face was present during the 4th hour, accompanied by wide dilatation of the pupils which reacted to light and accommodation. Both systolic and diastolic blood pressure readings were increased. In one experiment, however, in which the blood pressure did not change the subject was in good condition at the end of 4 hours although contraction of the visual fields and facial pallor were present. Usually the abrupt onset of dizziness, nausea, and a feeling of impending collapse terminated the experiments in the fourth hour. Impending collapse was always signalized by an increase in pulse rate, rise of both systolic and diastolic pressure of 15 to 20 points, rapid contraction of the field of vision and failure in visual acuity for form and color. Although consciousness was retained at the end of all experiments the subjects looked dazed, and the delay in answering questions suggested partial stupefaction.

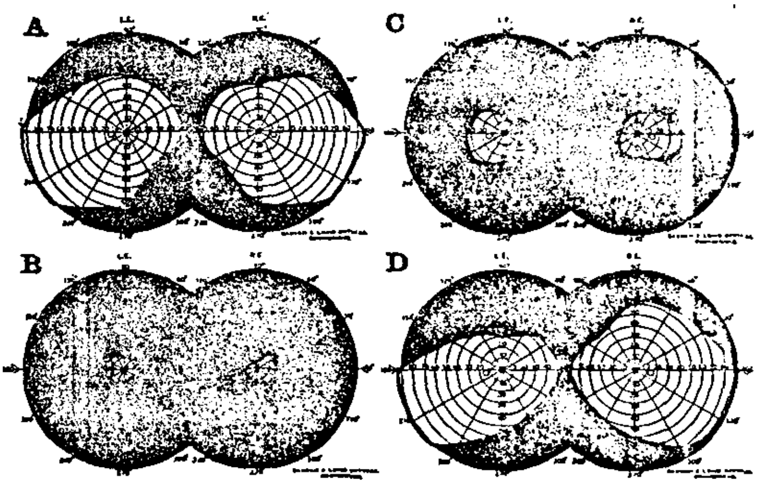

Fig. 1. Perimetric measurements made before and after 3½ hours' oxygen breathing at 3 atmospheres' pressure (30 lb. gauge). *A*, normal field limits; determinations made with the Ferree-Rand perimeter and exposure method with 7 foot-candles illumination. *B*, *C*, and *D*, field limits 5, 25, and 50 minutes, respectively, following 3½ hours' oxygen breathing; observations made at atmospheric pressure with a black perimeter of 25 cm. radius illuminated by a blue bulb placed behind and above the observer's head; moving stick stimuli were used and checked by the exposure method; test object was a white disc 6 mm. in diameter.

In two examinations retinal ischemia or constriction of vessels could not be detected.

The respiratory rate and minute volume were constant in all experiments. The leucocyte and differential counts did not show any unusual changes, and there were no subjective symptoms pointing to pulmonary injury.

In one experiment, after the subject breathed oxygen for 3 hours and 56 minutes without discomfort, the blower was stopped and the subject rebreathed the gas in the helmet. Within two minutes he approached a condition of collapse. It is believed that the increased carbon dioxide tension was responsible for the abrupt change.

The period of recovery. Gradual recovery took place within 20 to 60 minutes after air replaced oxygen. Nausea and dizziness disappeared within a few minutes but the return of blood pressure, pulse rate, size of the pupils, visual acuity, and facial color to normal took place concurrently over a considerably longer period of time. The contracted visual fields usually regained their initial limits within an hour (fig. 1). The period of recovery was roughly proportional to the time between the onset of visual field contraction and the termination of the experiment. The significant point about recovery was the feeling of alertness and stimulation.

Calibre of the pial vessels of the cat in relation to oxygen at a pressure of 4 atmospheres and to increased carbon dioxide tension. In order to determine the effect of oxygen and of oxygen and carbon dioxide on blood vessels the pial arteries of the cat were observed through a window placed in the skull according to the method of Forbes (1928). The observations indicated that oxygen breathing at a pressure of 4 atmospheres did not appreciably alter the calibre of the pial arteries. The action of carbon dioxide (approximately 60 mm. tension) in combination with oxygen resulted in a dilatation of the arteries followed by constriction when carbon dioxide was removed (fig. 2). While the experiments are too few for conclusions to be drawn with respect to the action of oxygen at high pressure on pial vessels, the dilating effect of carbon dioxide in combination with a high pressure of oxygen is definite and in accord with the results of other investigators working with normal oxygen tensions.

DISCUSSION. Severe functional disturbances similar to those associated with high oxygen pressure are without parallel in pharmocologic reactions in regard to the complete and rapid recovery which invariably follows. Temporary oxygen deprivation or withdrawal of cerebral blood supply for very short periods of time perhaps most closely simulate the oxygen effects.

Oxygen toxicity in relation to circulatory changes. Tolerance for oxygen at a pressure of 3 atmospheres is closely related to the stability of blood pressure and pulse rate. In the experiments of 4 hours' duration, which were symptomless except for contraction of the visual field, the blood pressure remained constant. The circulatory disturbance in man associated with the toxic action of oxygen is essentially a peripheral vasoconstriction. At a pressure of 3 atmospheres the period of impending collapse was always signalized by the abrupt rise of both diastolic and systolic blood pressure, increased pulse rate, facial pallor, and dilatation of the pupils—symptoms which suggest stimulation of the sympathetic nervous system. At a pressure of 4 atmospheres, a rise in blood pressure (not previously reported) from 116/86 to 130/104 immediately preceded a violent convulsive seizure (Behnke et al., 1935).

Whether the circulatory changes are direct effects of the high oxygen pressure or compensatory reactions remains to be determined. The experimental results, however, bring up the fundamental question whether oxygen acts directly on nervous tissue to produce at 4 atmospheres the convulsive seizure and at 3 atmospheres contraction of the visual field, or whether these phenomena are the result of cerebral and retinal angiospasm induced by oxygen. Aid in answering this question is afforded by a consideration of the effect of carbon dioxide on cerebral vessels in relation to oxygen toxicity. The constriction of blood vessels would not, of course, deprive the brain of oxygen in view of the high partial pressure of this gas in the arterial blood (23 times the normal tension), but would tend to limit the supply of other necessary substances and hinder the removal of metabolites.

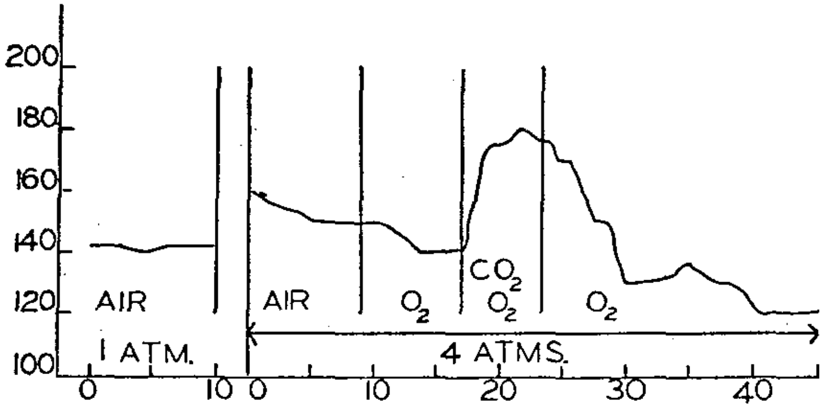

Fig. 2. Changes in the diameter of a pial arteriole of a cat breathing a 2 per cent carbon dioxide (equivalent to 8 per cent carbon dioxide at 1 atmosphere) and 98 per cent oxygen mixture at 4 atmospheres' pressure. *Ordinate*, diameter in microns; *abscissa*, time in minutes.

Action of carbon dioxide on cerebral vessels. The experiments of Gibbs, Gibbs, and Lennox (1935) indicate that human cerebral blood flow is increased by raising the alveolar carbon dioxide tension. In cats, increased carbon dioxide tension dilates the pial vessels (Forbes, 1928; Wolff and Lennox, 1930) and increases the blood flow in the medulla and hypothalamus (Schmidt and Pierson, 1934; Schmidt, 1934–1935). Conversely, decreased carbon dioxide tension constricts pial vessels and decreases blood flow.

Carbon dioxide in relation to high oxygen pressure. From the observations reported in this paper on the pial vessels of the cat, the dilating action of carbon dioxide on arterioles is not altered by high oxygen pressure. The effect of carbon dioxide on cerebral vessels and blood flow offers, therefore, a partial explanation of the finding of Shaw et al. (1934) that with an oxygen pressure of 4 atmospheres, convulsive seizures and a fall in blood pressure can be rapidly induced in anesthetized dogs by raising the alveolar carbon dioxide tension to 65 mm., or prevented by lowering the carbon dioxide tension to 22 mm. From this fact it is inferred that carbon dioxide renders a given oxygen tension more toxic by increasing cerebral blood flow, and that decreasing cerebral blood flow by lowering the alveolar carbon dioxide tension will render the given oxygen tension less toxic.

That carbon dioxide increases oxygen toxicity in man is inferred from the condition of impending collapse which was rapidly brought about by stopping the circulation of oxygen during the 4th hour and allowing rebreathing to take place for a period of 2 minutes. If carbon dioxide dilates retinal and cerebral vessels in man and increases blood flow when oxygen is breathed at a pressure of 3 and of 4 atmospheres, then it can be concluded that cerebral and retinal angiospasm are not responsible under these circumstances for the toxic action of oxygen. The inference follows that oxygen acts directly on nervous tissues, and that peripheral vasoconstriction is probably a compensatory reaction.

In a study of the physicochemical reactions brought about in the nerve cell by high oxygen pressure, certain essential facts should be kept in mind: *a*, the action of oxygen is characterized by severe functional disturbances without apparent structural injury to nervous tissue; *b*, a latent period of about 3 hours at a pressure of 3 atmospheres and of 45 minutes at a pressure of 4 atmospheres precedes severe toxic symptoms in man; *c*, the circulatory, visual, and convulsive symptoms which lead to the collapse of the individual appear rather abruptly during the course of oxygen breathing; *d*, complete recovery is promoted by the substitution of air for oxygen, and requires a period of time roughly proportional to the duration of the toxic symptoms, i.e., 10 to 60 minutes; *e*, in man the sympathetic division of the autonomic nervous system is apparently stimulated since a rise in blood pressure, increase in pulse rate, and dilatation of the pupils accompany visual loss and mental impairment at a pressure of 3 atmospheres, while at a pressure of 4 atmospheres a rise in blood pressure precede a convulsive seizure; recovery, moreover, is attended by a feeling of stimulation; *f*, in dogs anesthetized with sodium barbital, a fall in femoral or carotid blood pressure is the constant and early sign of oxygen toxicity and always precedes the convulsive seizure; *g*, increased carbon dioxide tension hastens the fall in blood pressure and the convulsive seizure, while decreased carbon dioxide tension delays or prevents these symptoms.

SUMMARY

Oxygen at a pressure of 3 atmospheres (30 lb. gauge) can be breathed by healthy men for 3 hours without distressing symptoms. During the 4th hour a progressive contraction of the visual field with dilatation of the pupils and some impairment in central vision is the most constant criterion of oxygen toxicity.

Circulatory changes indicative of peripheral vascular constriction are associated with the visual impairment, and culminate during the 4th hour in an abrupt rise of systolic and diastolic blood pressure, increase in pulse rate, and extreme pallor of the face. At this stage the subjects experience dizziness and a feeling of impending collapse. A condition of partial stupefaction is indicated by the facial expression and the slowed mental responses.

Rapid and complete recovery attended by a feeling of alertness and stimulation takes place within an hour after air is substituted for oxygen.

We wish to express our appreciation and thanks to Dr. Marion R. Stoll of the Massachusetts Eye and Ear Infirmary for the perimetric studies, figure 1.

We wish to acknowledge our indebtedness to The Linde Air Products Company who supplied the oxygen used in these experiments, and to D. E. Billington, W. T. Denyer, B. L. Fahey, and F. Murray of the United States Navy for their coöperation throughout the experimental work.

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CONTENTS

EFFECT OF ANOXIA AND OF HIGH CONCENTRATIONS OF OXYGEN ON THE RETINAL VESSELS: PRELIMINARY REPORT

P. L. Cusick, M. D., Section on Ophthalmology, O. O. Benson, Jr., M. D., Capt. M. C., U. S. Army, Assigned to The Mayo Foundation, and W. M. Boothby, M. D., Section on Metabolic Investigation: Recently we have been investigating the effect of anoxia and of high concentrations of oxygen on the eye. One of the more interesting observations has been the changes in caliber of the retinal vessels.

A number of investigators have made ophthalmoscopic observations in these conditions and have noted especially color changes. They have stated that in anoxia the veins appear cyanotic and the arterioles take on a venous appearance, whereas with oxygen there is an approximation of the venous to the arterial color. This is in accord with our findings. However, no one as yet has reported any changes in caliber (diameter of blood column) in the retinal vessels and no measurements have been made. In this study two different methods of measurement were used: the Morgan graticule and a prism displacement method developed by Dr. C. W. Rucker.

In this investigation a number of observations were made in the low pressure chamber at pressures simulating altitudes of 18,000 to 21,000 feet. In other cases anoxia was produced by a nitrogen-oxygen mixture. With anoxia there was a measurable increase in the size of the vessels, varying between 10 and 20 per cent, which was more marked in the veins (fig. 1*a* and *b*).

Following this, another group of subjects was given essentially 100 per cent oxygen by means of the B. L. B. inhalation apparatus with the rate of flow at 9 liters per minute continued for thirty minutes. In this group there was a measurable decrease in the size of the vessels (fig. 1*c*). As can be seen from table 1, there was a diminution in caliber varying between 10.5 and 37.7 per cent for the arterioles and between 16.2 and 37.5 per cent for the veins. The diminution averaged 24 per cent for the arterioles and 28.2 per cent for the veins.

Evans and McFarland[1] have reported a widening of the angioscotomata in the visual field in anoxia and Rosenthal[2] has reported a narrowing with high concentrations of oxygen. They attributed this to changes in the retina itself and not to changes in caliber of the retinal vessels. As a result of our investigation we believe these changes can be in part, at least, explained on the basis of change in caliber of vessels.

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[1] Evans, J. N. and McFarland, R. A.: The effects of oxygen deprivation on the central visual field. Am. J. Ophth. 21: 968-980 (Sept.) 1938.

[2] Rosenthal, C. M.: Changes in angioscotomas associated with inhalation of oxygen. Arch. Ophth. n. s. 22: 385-392 (Sept.) 1939.

Tinel,[3] Schmidt,[4] Lennox and Gibbs,[5] and others, working on animals, have described a contraction of the pial or superficial cerebral vessels when the inspired air was of high oxygen content, but simultaneous observations of the retinal and cerebral vessels have not been made by us or have such observations been carried out to our knowledge.

Several interesting observations on the effect of changes in the oxygen content of the inspired air on the retinal circulation have been described. The fact that the retinal veins dilate or contract in conjunction with the arterioles might have been anticipated but now remains a matter of direct observation. These changes are of about the same magnitude in both arterioles and veins. The dilatation of both the retinal arterioles and veins during anoxemia may be accepted as evidence of increased blood flow through the retina and can be assumed to be a compensatory vascular reaction to supply more oxygen to the tissues. The fact that both arterioles and veins appear dark and the entire retina appears dusky during anoxemia is due to an increase in reduced hemoglobin in the vessels and is directly related to the degree of anoxemia. When essentially 100 per cent oxygen is inhaled for thirty minutes, there is a definite increase in the redness of the retina and veins as well as a decrease in caliber of both arterioles and veins. The reduction in caliber of the vessels would indicate a decreased blood flow which might be interpreted

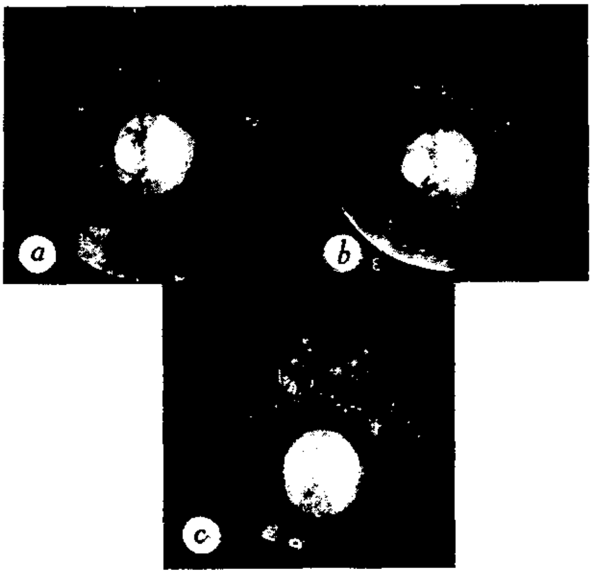

Fig. 1. Change in appearance of retina and retinal vessels in anoxemia and with high concentrations of oxygen: a, normal; b, in anoxemia; c, following inhalation of oxygen for thirty minutes.

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3. Tinel, J.: Régulation de la circulation cérébrale à l'inhalation d'oxygène. Compt. rend. Soc. de biol. 96: 665 (Mar. 12) 1927.
4. Schmidt, C. F.: The intrinsic regulation of the circulation in the hypothalamus of the cat. Am. J. Physiol. 110: 137-152 (Nov.) 1934.
5. Lennox, W. G. and Gibbs, Erna L.: The blood flow in the brain and the leg of man and the changes induced by alteration of blood gases. J. Clin. Investigation 11: 1155-1177 (Nov.) 1932.

as a regulatory mechanism to protect the tissues from too high a concentration of oxygen. However, despite the reduction in caliber of the vessels, the color of the blood in the veins approximates that of the arterioles. These observations would indicate that in spite of a slight arteriolar contraction, the tissues are receiving not only an adequate but even an increased oxygen supply as a result of the inhalation of 100 per cent oxygen.

SUMMARY

One of the more interesting and hitherto unreported effects of anoxia and of high concentrations of oxygen is the changes in the caliber of the retinal vessels. In this study two methods were used in measurement, a graticule and a prism displacement method. In anoxia at simulated altitudes of 18,000 to 21,000 feet (5.5 to 6.4 kilometers) a dilatation of the vessels varying between 10 and 20 per cent has been noted, this being more marked in the veins. With high concentrations of oxygen diminution in caliber takes place, varying between 10.5 and 37.7 per cent. As a rule this is also more marked in the veins. Knowing the intimate relationship between the cerebral and the retinal circulation, this and work done by others on the cerebral vessels of animals suggest that the same effects take place in the cerebral circulation. They also suggest that changes in the size of angioscotomata in the visual field in these two conditions may be, in part at least, due to changes in the caliber of the retinal vessels. Finally they suggest that the retina has an autoregulatory mechanism for the control of its circulation.

Table 1

Caliber changes in normal retinal vessels following inhalation of 100 per cent oxygen for 30 minutes

Subject	Arterioles			Veins		
	Average caliber, microns		Diminution in caliber, per cent	Average caliber, microns		Diminution in caliber, per cent
	Before oxygen	After oxygen		Before oxygen	After oxygen	
1	90	74	17.7	144	90	37.5
2	90	56	37.7	135	113	16.2
3	85	76	10.5	140	93	33.5
4	102	90	11.7	153	108	29.4
5	83	66	20.4	106	77	27.3
6	90	60	33.3	180	135	25.0
7	72	52	29.1	151	97	35.7
8	90	60	33.3	149	117	21.4
Average			24			28.2

Four to six arteries and veins measured in each case.

Contribution 1499

LIGHT IN THE SEA

Seibert Q. Duntley

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Light in the Sea*

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(Received 27 August 1962)

Light in the sea may be produced by the sun or stars, by chemical or biological processes, or by man-made sources. Serving as the primary source of energy for the oceans and supporting their ecology, light also enables the native inhabitants of the water world, as well as humans and their devices, to see. In this paper, new data drawn from investigations spanning nearly two decades are used to illustrate an integrated account of the optical nature of ocean water, the distribution of flux diverging from localized underwater light sources, the propagation of highly collimated beams of light, the penetration of daylight into the sea, and the utilization of solar energy for many purposes including heating, photosynthesis, vision, and photography.

INTRODUCTION

AN interest in the aerial photography of shallow ocean bottoms prompted the author to begin, nearly 20 years ago, a continuing experimental and theoretical study of light in the sea. Some of the principles discovered or extended and generalized by the author and his colleagues are summarized in this paper. Early discussions with E. O. Hulburt and D. B. Judd as well as publications by many investigators[1] provided a valuable starting point. By 1944 the author was using a grating spectrograph, specially designed by David L. MacAdam, in a glass-bottomed boat off the east coast of Florida to obtain the spectroradiometric data shown in Fig. 1; the presence of reefs and sandy shoals show clearly in the green region of the spectrum.[2] When the spectrograph was flown in an airplane 4300 ft above the same ocean locations, the radiance spectra shown in Fig. 2 were obtained.[3,4] The data in Figs. 1 and 2, displayed in colorimetric form by Fig. 3, exhibit many intricate and beautiful phenomena which are manifestations of some of the physical principles discussed in this paper.

The importance of light in the sea is apparent when it is recalled that solar radiation supplies most of the energy input to the ocean and supports its ecology

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[1] See E. F. DuPré and L. H. Dawson, "Transmission of Light in Water: An Annotated Bibliography," U. S. Naval Research Laboratory Bibliography No. 20, April, 1961 for abstracts of 650 publications by over 400 authors in more than 150 Swiss, German, French, Italian, English, and U. S. journals and other sources from 1818 to 1959.

[2] S. Q. Duntley, *Visibility Studies and Some Applications in the Field of Camouflage*, Summary Tech. Rept. of Division 16, NDRC (Columbia University Press, 1946), Vol. II, Chap. 5, p. 212.

[3] See J. G. Moore, Phil. Trans. Roy. Soc. (London) **A240**, 163 (1946–48) for a method of using such data to determine depth and attenuation coefficients of shallow water.

[4] See G. A. Stamm and R. A. Hengel, J. Opt. Soc. Am. **51**, 1090 (1961) for data on the spectral *irradiance* incident on the underside of an aircraft flying above the ocean.

through photosynthesis. The biological productivity of an acre of ocean has been estimated to be, on a worldwide average, comparable to that of an acre of land. Most of the surface of our "water planet" is covered by seas and its atmosphere contains great quantities of water in the form of vapor and clouds. Light in the sea enables the native inhabitants of the water world to find their food and to evade attack. Nowhere in nature is protective coloration more perfectly or dramatically displayed than in the feeding grounds of the sea. Man and his cameras may view underwater scenes by means of daylight or with the aid of artificial lighting devices. Many biological organisms, including some living at very great depth, produce their own light at or near the wavelength for which water is most transparent, presumably both for vision and for signaling. All of these aspects of light in the sea can be treated by describing the optical nature of ocean water, the distribution of flux diverging from localized underwater light sources, the propagation of highly collimated beams of light, and the penetration of daylight into the sea. An integrated account of these topics is the subject of this paper.

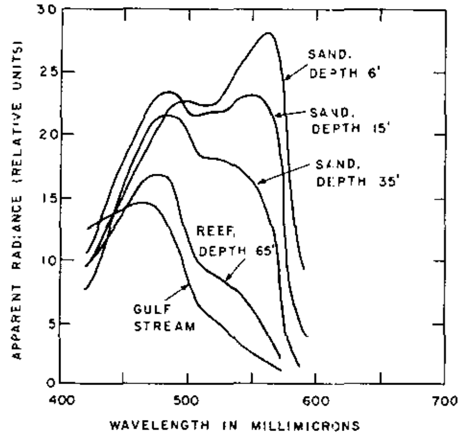

FIG. 1. Spectroradiometric curves of light from the nadir reaching a spectrograph mounted in a glass-bottomed boat over shoals off Dania, Florida (March 1944). Spectral resolution: 7.7 mμ; spatial resolution: 2.0×10^{-6} sr.

OPTICAL NATURE OF OCEAN WATER

Most of the optical properties of ocean water as well as many of the principles which govern the propagation of light in the sea can be studied by injecting a highly collimated beam of monochromatic light into otherwise unlighted water and measuring all aspects of the resulting distribution of flux. This investigative approach even provides a basis for understanding the distribution of daylight in the sea and the submarine lighting produced by artificial underwater light sources, for any optical input to the water may be represented by an appropriate superposition of highly collimated, monochromatic beams. The following paragraphs describe a variety of experiments which have been made by using a collimated, underwater light source, shown schematically in Fig. 4, at the Visibility Laboratory's Field Station at Diamond Island, Lake Winnipesaukee, New Hampshire.

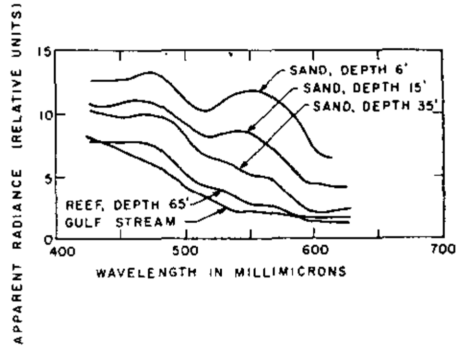

FIG. 2. Spectroradiometric curves of light from the nadir reaching a spectrograph in an airplane 4300 ft above the same ocean locations as in Fig. 1. Spectral resolution: 7.0 mμ; spatial resolution: 3.2×10^{-6} sr.

Attenuation of a Collimated Beam

If a collimated beam of monochromatic light is injected into macroscopically homogeneous water by

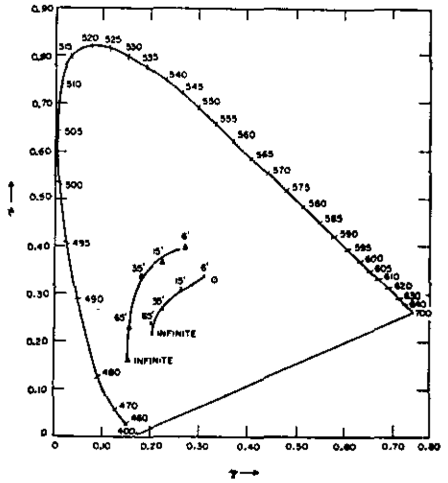

FIG. 3. CIE chromaticity diagram showing loci of the colors of ocean shoals as seen from an altitude of 4300 ft (shorter curve) and from a glass-bottomed boat (longer, upper curve). The points were calculated from the spectral radiance data in Figs. 1 and 2. The circled point represents CIE source C.

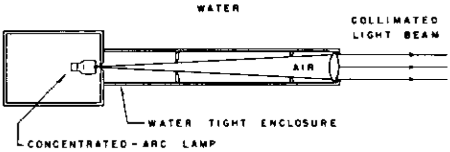

FIG. 4. Schematic diagram of the highly collimated underwater light source represented by a cross-hatched block in Figs. 5, 6, 7, 13, 20, and 21. This source was used in obtaining part or all of the data presented in Figs. 9, 10, 12, 17, 18, 20, and 22. Interchangeable 2, 10, 25, and 100 w zirconium concentrated-arc lamps in a water-tight air-filled enclosure produce nominal total beam spreads of 0.010°, 0.046°, 0.085°, and 0.174°, respectively, when used with a Wratten No. 61 green filter and a specially constructed air-to-water collimator lens having an effective first focal length of 495 mm. This lens, designed for the author by Justin J. Rennilson, is a cemented doublet 55 mm in diameter having radii $r_1=269.75$ mm, $r_2=r_3=102.60$ mm, $r_4=-325.0$ mm and axial thicknesses $t_1=3.0\pm0.2$ mm, $t_2=6.5\pm0.2$ mm. The first element is of Hayward LF-2 glass ($N_D=1.5800\pm0.0010$; $\nu=41.0$) and the second is of Hayward BSC-1 ($N_D=1.5110\pm0.0010$; $\nu=63.5$). The free aperture is 50.0 mm. The first back focal length of the doublet with its last surface in water is 493.88 mm. The air–glass surface was treated for increased light transmission. The achromatization is such that with the 2-W concentrated-arc lamp the extreme ray divergence is 0.0031°, 0.0039°, and 0.0109° at 480, 520, and 589 mμ, respectively, when the lamp is used in fresh water having a temperature of 20°C. A Wratten No. 61 green filter was used during all of the experiments with this lamp, but it does not appear in Fig. 4 because it was always incorporated in the photometer or the camera. An external circular stop (not shown) can be mounted in the water close to the lens whenever a smaller beam diameter is desired.

means of an underwater projector, as suggested by Fig. 5, it is found that the residual radiant power P_r^0 reaching a distance r *without having been deviated by any type of scattering process* is

$$P_r^0=P_0e^{-\alpha r}, \tag{1}$$

where P_0 represents the total flux content of the beam as it leaves the projector. The zero superscript on P_r^0 denotes the *zero scattering order*, i.e., nonscattered radiant power. The *spectral volume attenuation coefficient* α, defined by Eq. (1), has the dimension of reciprocal length and can be expressed in *natural log units per meter* (ln/m), natural log units per foot (ln/ft), etc; it is a scalar point function of position which may vary along any underwater path of sight if the water is macroscopically nonhomogeneous.

The attenuation of a beam of light by water results from two independent mechanisms: *scattering* and *absorption*. Scattering refers to any random process by which the *direction* of individual photons is changed without any other alteration. Absorption includes all of the many thermodynamically irreversible processes by which photons are changed in their nature or by which the energy they represent is transformed into thermal kinetic energy, chemical potential energy, and so on. Transformation of photon energy into thermal kinetic energy of the water is the major absorption mechanism in the ocean. Photosynthetic conversion of light into chemical potential energy is, of course, measurable and vital to the existence of life in the sea. Visible light fluorescence and transpectral effects are ordinarily too minute to be detected in ocean water. The volume attenuation coefficient α is the sum of the *volume absorption coefficient* a and the *total volume scattering coefficient* s: thus $\alpha=a+s$.

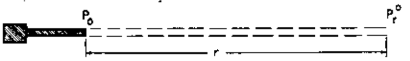

FIG. 5. Illustrating the geometry of Eq. (1). The cross-hatched block represents the collimated underwater light source (projector) shown schematically in Fig. 4.

Wavelength dependence. The attenuation coefficient of all water (pure, distilled, or natural) varies markedly with wavelength. Typical data are summarized in Table I, wherein the reciprocal of the volume attenuation coefficient, called *attenuation length*, has been tabulated rather than attenuation coefficient for three reasons: (1) a distance is easier to visualize and to remember than a reciprocal distance; (2) visibility calculations and many experiments by swimmers show that any large dark object (such as a dark-suited swimming companion) is just visible at a horizontal distance of about 4 attenuation lengths when there is sufficient underwater daylight; (3) many physicists like to characterize any absorbing-scattering medium (such as water) by the mean free path for a photon in the ordinary kinetic theory sense; this is the attenuation length $1/\alpha$. The term, "20-meter water," signifying water having an attenuation length of 20 m/ln, facilitates verbal discussions.

TABLE I. Attenuation length of distilled water at various wavelengths.[a–c]

Wavelength mμ	Attenuation length ($1/\alpha$) meters/ln
400	13.
440	22.
480	28.
520	25.
560	19.
600	5.1
650	3.3
700	1.7

[a] E. O. Hulburt, J. Opt. Soc. Am. 35, 698 (1945).

[b] For ultraviolet attenuation data see L. H. Dawson and E. O. Hulburt, J. Opt. Soc. Am. 24, 175 (1934).

[c] For near infrared attenuation data see J. A. Curcio and C. C. Petty, J. Opt. Soc. Am. 41, 302 (1951).

Water possesses only a single important window, the peak of which lies near 480 mμ unless it is shifted toward the green by dissolved yellow substances. Such yellow solutes, usually prominent in coastal waters, consist of humic acids, melanoidins, and other compounds which result from the decomposition of plant and animal materials. Clear ocean water is so selective in its absorption that only a comparatively narrow band of blue-green light penetrates deeply into the sea[5] (see Fig. 1) but this radiation has been detected at depths greater than 600 m with a multiplier phototube photometer.[6]

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[5] J. E. Tyler, Limnology and Oceanography 4, 102 (1959).

[6] S. Q. Duntley, Natl. Acad. Sci.—Natl. Research Council Publ. 473, 79 (1956).

Many have wondered whether there exists any fine structure in the volume attenuation function which was beyond the spectral resolution available to the investigators whose results are summarized by Table I. Is there, for example, a narrow-band window of high transmission? It is the concensus of most physicists that the atomic and molecular structures involved in water provide no reason to expect any significant fine structure in the spectral attenuation function. A careful spectroscopic examination of the region from 3750 to 6850 Å with a resolution of 0.2 Å and sensitivity sufficient to detect a variation of 0.02 ln/m in the attenuation coefficient has been reported by Drummeter and Knestrick.[7] They detected no fine structure, i.e., no narrow-band window.

Water Clarity

The clearest body of ocean water of large extent is reputed to be in the Sargasso Sea, a vast region of the Atlantic Ocean east of Bermuda. Jerlov has reported very clear water between Madeira and Gibraltar,[8] as summarized by Table II. Although clearer water was found at 10 m depth than at 90 m at this location, the reverse is often true elsewhere. Optical oceanographic data are not numerous. Jerlov's measurements during the Swedish Deep Sea Expedition of 1947–48 are classical examples. Table III shows some of these data selected to typify certain indicated locations.[9]

TABLE II. Attenuation length of the Atlantic Ocean for wavelength 465 mμ at various depths in the vicinity of Madeira and Gibraltar.[a]

Depth meters	Attenuation length $(1/\alpha)$ meters/ln
0–10	19
10–25	20
25–50	18
50–75	15
75–90	16

[a] N. G. Jerlov, Kgl. Vetenskap. Vitterh. Handl. F.6, Ser. B, BD8.N:o11 (1961).

DuPré and Dawson[1] give many references to water-clarity data; users of published data should note carefully whether the attenuation coefficients reported are expressed in ln/m or in log/m and whether the values refer to the attenuation coefficient α for nonscattered light, as in a collimated beam, or to some form of *diffuse attenuation coefficient* K, discussed later in this paper. No single number can adequately specify the clarity of any natural water because two independent mechanisms, absorption and scattering, govern water clarity. Even for monochromatic light, at least two coefficients, such as α and K, are required, and a more complete specification requires data on the volume scattering function $\sigma(\vartheta)$, defined in the paragraphs which follow.

TABLE III. Attenuation length of ocean water for wavelength 440 mμ at various locations.[a]

Location	Attenuation length $(1/\alpha)$ meters/ln
Caribbean	8
Pacific N. Equatorial Current	12
Pacific Countercurrent	12
Pacific Equatorial Divergence	10
Pacific S. Equatorial Current	9
Gulf of Panama	6
Galapagos Islands	4

[a] N. G. Jerlov, Reports of the Swedish Deep Sea Expedition of 1947–48 (1951), Vol. 3, p. 49, Table 27.

Daylight, abundant in the mixed layer near the surface, supports the growth of phytoplankton in the biologically productive regions of the oceans. These, in turn, feed a zooplankton population. The transparent planktonic organisms, ranging in size from microns to centimeters, scatter light and thereby produce optical attenuation. Settling of the plankton, particularly after death, tends to produce a high concentration of these scatters just above the thermocline which ordinarily exists at the lower boundary of the mixed layer in the sea.[10] Below the thermocline lies clearer water which may be optically uniform for tens or hundreds of meters before some different water mass is encountered. Interestingly, the optical structure of the ocean resembles, in a sense, that of the atmosphere if depth is considered as analogous to altitude and a proper allowance is made for the decrease of atmospheric density with height.

Scattering

Scattering of light in the sea is predominanfly due to transparent biological organisms and particles large compared with the wavelength of light. The magnitude of the scattering is, therefore, virtually independent of wavelength.[11] The variation of attenuation length with

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[7] L. F. Drummeter and G. L. Knestrick, U. S. Naval Research Laboratory Rept. No. 5642 (1961).

[8] N. G. Jerlov, Kgl. Vetenskap. Vitterh. Handl. F.6, Ser. B, BD8. N:o 11 (1961).

[9] N. G. Jerlov, Reports of the Swedish Deep Sea Expedition of 1947–48 (1951), Vol. III, p. 49, Table 27.

[10] Multiple thermoclines often form in the upper portion of the sea; the maximum optical attenuation is associated with the maximum vertical temperature gradient and frequently falls on a secondary thermocline. Internal waves shift the scattering layer vertically. See E. C. La Fond, E. G. Barnham, and W. H. Armstrong, U. S. Navy Electronics Laboratory Rept. 1052 (July 1961), p. 15. Also see J. Joseph, Deut. Hydrograph. Z., Nr. 5 (1961).

[11] Scattering is also contributed by fine particles, by molecules of water, and by various solutes, but these contributions are usually quite minor and often difficult to detect. Even in very clear, blue ocean water scattering by water molecules produces only 7% of the total scattering coefficient and is dominant only at scattering angles near 90°, where it provides more than 2/3 of the scattered intensity (see reference 8); although the magnitude of this small component of scattering varies inversely as the fourth power of wavelength (λ^{-4}), it is so heavily masked by nonselective scattering due to large particles that total scattering in the sea is virtually independent of wavelength. The prominent blue color of clear ocean water, apart from sky reflection, is due almost entirely to selective absorption by water molecules.

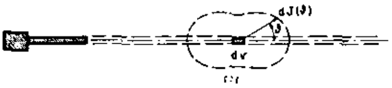

FIG. 6. Polar diagram illustrating Rayleigh scattering by pure water. The ratio of the light scattered into the rear hemisphere to that scattered into the forward hemisphere is 1 to 1. The cross-hatched block represents the collimated underwater light source shown schematically in Fig. 4.

wavelength (see Table I) is due almost wholly to selective absorption.

In the blue region of the spectrum, centering at 480 $m\mu$, approximately 60% of the attenuation coefficient of clear, blue ocean water is due to scattering and 40% is due to absorption; e.g., $s=0.030$ ln/m and $a=0.020$ ln/m.[8] In all other spectral regions absorption is overwhelmingly predominant in very clear water.

Since scattering is virtually independent of wavelength its detailed nature is best revealed by means of experiments conducted at or near the wavelength of minimum absorption. This means experiments with blue light in clear, blue ocean water and experiments with green light in greenish coastal and lake waters.

Scattering by pure water. Consider a scattering experiment performed in pure water, that is, in water molecules containing no dissolved or particulate matter whatsoever. As in Fig. 6, consider an element of volume dv receiving collimated, nonpolarized, monochromatic irradiance H to act as source of scattered light, producing radiant intensity $dJ(\vartheta)$ at scattering angle ϑ. Scattering by the water molecules will be Rayleighian, with $dJ(\vartheta)\sim\lambda^{-4}$ and with the shape of the intensity function $dJ(\vartheta)$ characterized by $(1+0.835\cos^2\vartheta)$ (see reference 12). Since even the most elaborately prepared distilled water samples show particulate matter when examined in a light beam, scattering by truly pure water has probably never been measured.

Scattering by distilled water. A colleague, John E. Tyler, has performed scattering experiments in many samples of commercial distilled water[13]; Fig. 7 shows a typical result. Obviously, the scattering produced by this sample of distilled water is very different from that predicted for pure water. The predominant forward scattering is caused by a comparatively few large particles. The dotted curve may be regarded either as a polar plot of the radiant intensity $dJ(\vartheta)$ or of the *volume scattering function* $\sigma(\vartheta)$, defined by the equation $dJ(\vartheta)=\sigma(\vartheta)\,H dv$, where H is the irradiance produced by the collimated lamp on the volume dv. The dimension of $\sigma(\vartheta)$ is reciprocal length; typical units are reciprocal steradian-meters or reciprocal steradian-feet. The polar curve in Fig. 7 is not complete; it begins at $\vartheta=22\ 1/2°$ and stops at $\vartheta=165°$. All conventional scattering meters designed to be used *in situ* possess the limitation that they cannot measure scattering at small angles. Fortunately, the total scattering coefficient s, defined by the relation

$$s=2\pi\int_0^\pi \sigma(\vartheta)\sin\vartheta d\vartheta,$$

is insensitive to the magnitude of small-angle forward scattering. Unfortunately, however, the propagation of highly collimated light does depend importantly on small-angle scattering.

Small-angle scattering. The author has devised a special (coaxial) *in situ* scattering meter to supply the missing forward part of the curve. Figure 8 is a schematic diagram of the instrument. It shows the optical system adjusted to measure the volume scattering function at a scattering angle of 1/2 deg. Such a datum was obtained with the coaxial scattering meter at the Diamond Island Field Station and determines the upper end of the upper curve in Fig. 9. This may be the first *in situ* measurement of small-angle scattering by natural water. The very large scattering found at small scattering angles is believed to have been caused primarily by re-

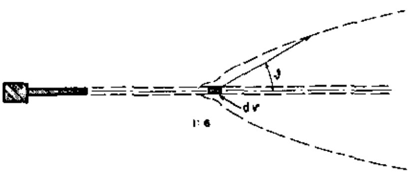

FIG. 7. Polar diagram illustrating measured scattering by a typical sample of commercial distilled water. The ratio of the light scattered into the rear hemisphere to that scattered into the forward hemisphere is 1 to 6 for this water sample. Data are by Tyler (see reference 13). The scale of this polar plot is smaller than that used in Fig. 6.

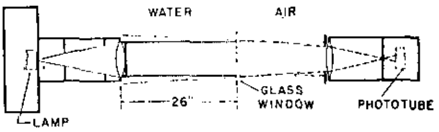

FIG. 8. Coaxial scattering meter for *in situ* measurement of the volume scattering function at small scattering angles. In this schematic drawing the vertical scale has been exaggerated five times over the horizontal scale in order to illustrate the principle of the device more clearly. The collimated underwater light source shown in Fig. 4 is used with the addition of an external opaque central stop which results in the formation of a thin-walled hollow cylinder of light. This traverses 26 in. of water to a high-quality glass window behind which, in air, is a photoelectric telephotometer with a 2° total field of view. The light source and the telephotometer are coaxial, but the latter is equipped with an external stop small enough to exclude the hollow cylinder of light so that only light scattered by the water is collected. The cylindrical scattering volume is indicated by cross-hatching. The upper limit of the scattering angle is determined by the field of the telephotometer and the lower limit is set by the size of its external stop, i.e., by the entrance pupil. A detailed geometrical analysis of the configuration depicted above shows that the scattering is measured at 0.47 deg±0.15°; this datum is used as the volume scattering function for 1/2° scattering angle in Figs. 9 and 10. Photometric calibration of the scattering meter is achieved by removing the external stop on the telephotometer.

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[12] L. H. Dawson and E. O. Hulburt, J. Opt. Soc. Am. 31, 554 (1941).

[13] J. E. Tyler, Limnology and Oceanography 6, 451 (1961).

fractive deviations produced by the passage of the collimated light beam through transparent plankton having an index of refraction close to that of water. The curve shape at small scattering angles is chosen to suggest that the magnitude of the volume scattering function may merge tangentially with that of the irradiating beam at vanishingly small angles.

Chemists have, for many years, made laboratory measurements of very small-angle scattering from tiny volumes of scattering materials.[14] Koslyaninov[15] has reported volume scattering measurements at angles down to 1 deg by means of a shipboard laboratory apparatus using water samples brought on board for measurement. Figure 10 shows the data of Koslyaninov for the East China Sea superimposed upon the lake data from Fig. 9 after normalization at a scattering angle of 90°, as denoted by the small circle in the figure. The forward-scattering portions of the curves are similar in shape.

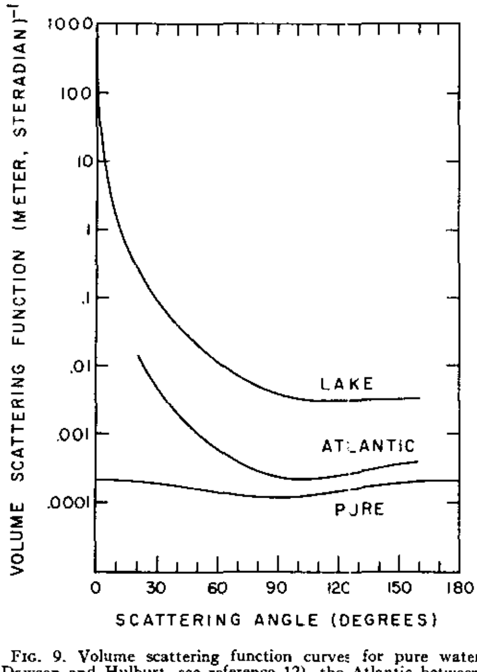

FIG. 9. Volume scattering function curves for pure water (Dawson and Hulburt, see reference 12), the Atlantic between Madeira and Gibraltar (Jerlov, see reference 8), and the Diamond Island Field Station, Lake Winnipesaukee, New Hampshire. The upper curve (lake) represents *in situ* measurements at 5° intervals between scattering angles 20°>ϑ>160° by means of a conventional type, pivoted-arm scattering meter and a single datum at ϑ=0.5° obtained *in situ* with the coaxial scattering meter shown schematically in Fig. 8; the data are of 20 August 1961; and are for green light isolated by means of a Wratten No. 61 filter.

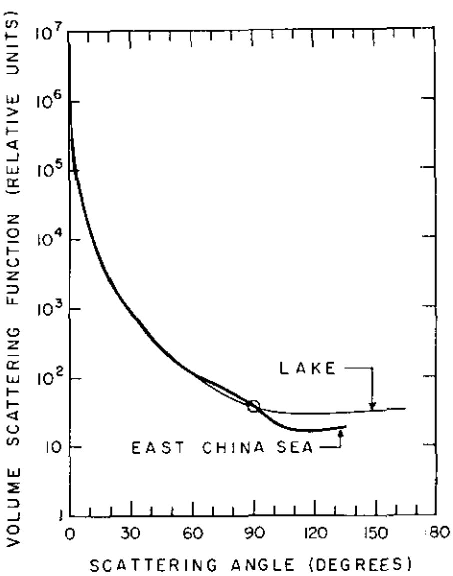

FIG. 10. Comparison of the shape of the *in situ* volume scattering function data for Lake Winnipesaukee, New Hampshire, from Fig. 9 with the shape of a curve representing the *in vivo* scattering data obtained by Koslyaninov (see reference 15) using a shipboard laboratory apparatus and a sample of water taken from the East China Sea. The curves have been normalized at a scattering angle of 90° (circled point) for purposes of shape comparison. Koslyaninov used blue light isolated by means of an absorption filter having an effective wavelength of 494 mμ; he reported data at scattering angles of 1, 2.5, 4, 6, 10, 15, 30, 50, 70, 110, and 144 deg. The curves are similar in shape for scattering angles less than 60°.

Comparison with distilled water. Figure 11 shows a comparison of *in situ* scattering measurements by Tyler[13] of commercial distilled water and clear Pacific water. Ocean water scatters more light than does distilled water but the similarity of the shape of the curves is striking and interesting in its implication of the predominant role of large particle scattering.

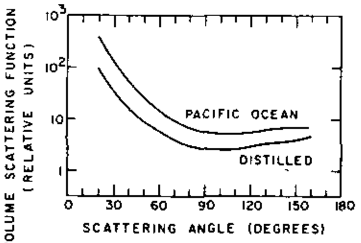

FIG. 11. Comparison of *in situ* scattering data by Tyler (see reference 13) in clear Pacific ocean water near Catalina with comparable data for a typical sample of commercial distilled water. Both curves were obtained with the same pivoted-arm scattering meter and are in the same relative units. The data are for green light isolated by means of a Wratten No. 61 filter.

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[14] H. F. Aughey and F. J. Baum, J. Opt. Soc. Am. **44**, 833 (1954).

[15] M. V. Koslyaninov, Trudy Inst. Okeanol. Acad. Nauk S.S.S.R. **25**, 134 (1957).

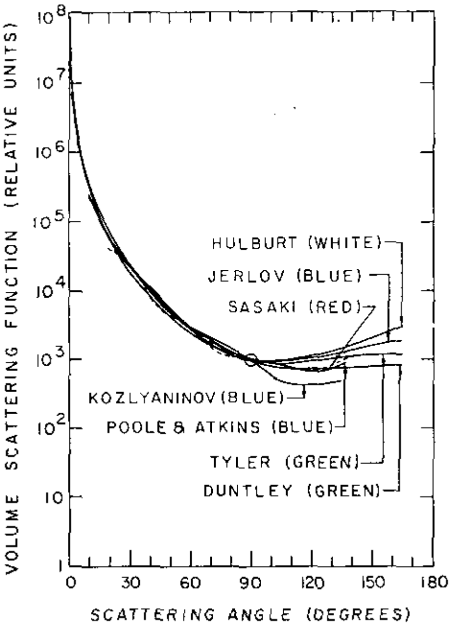

FIG. 12. Comparison of scattering data by seven investigators using dissimilar instruments in seven different parts of the world. All curves are superimposed at a scattering angle of 90°, as indicated by the circled point. Gross similarity in curve shape is apparent in the forward ($0<\vartheta<90°$) scattering directions despite major differences in water clarity (2 m/ln$<1/\alpha<$20 m/ln), spectral region, geographical location, instrumental design, and experimental technique. Most of the scattering in natural waters is caused by transparent organisms and particles large compared with the wavelength of light. The scattering is believed to result chiefly from refraction and reflection at the surfaces of these scatterers. As a consequence, scattering at small forward angles predominates and polarized light tends to preserve its polarization. To the extent that all scattering curves have identical shapes the scattering by natural waters can be specified in terms of some single number, such as the total volume scattering coefficient s or the volume scattering function at some selected angle.

Comparison between natural waters. A comparison of the scattering properties of natural waters is afforded by Fig. 12, which shows a superposition of measurements by seven different investigators using seven dissimilar instruments in seven different parts of the world. Three of the measurements were made with blue light, two were made with green light, the dashed curve was obtained with red light, and one investigator employed white light. The attenuation lengths of the waters ranged 2 m/ln for the author's lake data to 20 m/ln in the case of Jerlov's data for the Atlantic. It appears that the shape of the forward portion of the volume scattering function is remarkably similar in all of these natural waters, but that significant differences occur in the character of the backscattering they produce.

Although it is a useful first-order concept that natural waters are somewhat similar in the shape of their volume scattering functions, it is important to note therefore that measurable differences apparently exist and that ocean water masses might therefore be identified by their scattering function curves.

Multiple scattering. The propagation of light in the sea is complicated by multiple scattering. Consider, as in Fig. 13, a plane surface irradiated at normal incidence by the collimated lamp shown in Fig. 4. Every point on the plane receives scattered light from every volume element within the light beam. It receives, moreover, multiply scattered light from every elementary volume of water near the beam. In fact, every volume element within the sea is irradiated by every other volume element both inside and outside the beam. The figure illustrates how irradiation is produced throughout the plane by second-, third-, and fourth-order scattering.

Although theoretical treatments of the effects of multiple scattering on the distribution of light in the sea both from underwater sources and from daylight have been undertaken with partial success by several workers, no fully practical solution has yet been evolved. Some derivations include only secondary scattering and neglect higher-order effects. Others, following the practice of neutron physics, assume the scattering to be virtually isotropic, that is to say, the shape of the volume scattering function is assumed to be spherical or nearly so; this is, of course, highly unrealistic. Four patterns of approach characterize the theories: (1) *Multiple integration* using the volume scattering function, the attenuation coefficient α, and the inverse square law; these treatments suffer from complexity, are never complete, and may neglect sizeable components of flux but some useful approximate solutions have been achieved in special cases. (2) *Diffusion theory.* This applies rigorously only to isotropic or very mildly nonisotropic scattering systems which are not found in the sea; nevertheless, considerable success has been achieved in the prediction of *irradiance* at long ranges; diffusion theory is, however, unable to yield much information concerning the directional characteristics of the underwater light field. (3) *Radiative transfer.* This method is based upon equations of transfer, sometimes in vector form; these integro-differential equations are solved in practice by iterative procedures on the largest electronic computers. (4) *Monte Carlo procedures.* These also require the use of large electronic computers. Al-

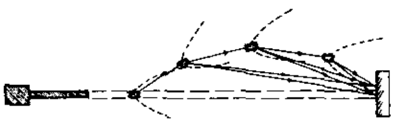

FIG. 13. Illustrating the irradiation of an object by multiply scattered light at arbitrary points inside and outside the light beam. The dotted curve associated with each cross-hatched volume element has the shape shown in Fig. 7 and represents a polar plot of the volume scattering function. The need for additional scattering data at small forward angles is obvious.

though, *in principle*, either of the two latter approaches appears to be capable of handling all underwater light propagation problems, neither has thus far achieved appreciable practical success in the treatment of point source or collimated beam geometrics, for the calculations are too massive for even the largest of electronic computers. Success has, however, been achieved for the case of daylight in the sea,[16] wherein the development of theory and the evolution of practical computation procedures followed quickly after experimental explorations of underwater daylight radiance distributions had produced a body of data, described later in this paper, from which valid assumptions could be made and against which predictions could be checked. This experience prompted the author to begin a program of experimental explorations of the distribution of light produced by submerged divergent light sources and by collimated lamps underwater. These explorations are still in progress, but some of the conclusions reached thus far are summarized in the following section.

DIVERGENT LIGHT IN THE SEA

Marine organisms which emit nearly hemispherical flashes of light are found at virtually all depths in the sea. Underwater lighting for vision, television, or photography is often accomplished by means of incandescent lamps or flash tubes which approximate point sources and emit divergent flux. Quantitative prediction of the irradiation produced by such lamps at the object, on its background, and throughout the observer's path of sight can enable optimum lighting arrangements and camera positions to be planned in advance and exposure to be predicted with sufficient accuracy to permit high-contrast photographic techniques to be employed effectively.

Apparent Radiance at the Object

Every underwater object and every elementary volume of water irradiated by a submerged divergent light source is lighted by an apparent radiance distribution which depends upon the radiant intensity distribution of the lamp, the optical properties of the water, and the lamp distance. This radiance distribution can be seen, photographed, and measured by an observer stationed at the position of the object. To such an observer a receding, uniform, spherical lamp appears to be surrounded by a glow of scattered light which becomes proportionately more prominent as lamp distance is increased, until at some range, often 18 to 20 attenuation lengths, the lamp image can no longer be discerned and only the glow is visible. The glow, however, may be seen for a considerably greater distance, depending upon the radiant intensity of the source and the ambient level of light in the sea.

Apparent radiance of the lamp. Densitometric measurements of the lamp images in a series of photographs of a receding spherical underwater light source produced the results shown in Fig. 14, wherein the close fit of the data to the solid straight line shows that the apparent radiance of the lamp is attenuated exponentially, as the equation

$$N_r = N_0 e^{-\alpha r}, \tag{2}$$

where N_r is the apparent radiance at distance r, N_0 is the inherent radiance of the lamp surface, and α is the attenuation coefficient for apparent radiance. The dashed lines, constructed from data secured with a light-beam transmissometer designed to conform with the requirements of Eq. (1), provide evidence that numerically identical attenuation coefficients α apply in

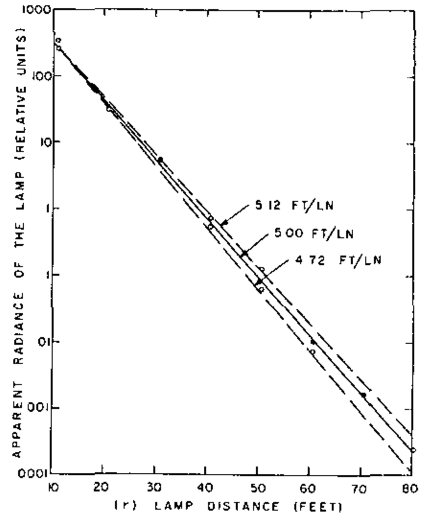

FIG. 14. Apparent radiance of a uniform, spherical underwater lamp at various distances, illustrating the exponential nature of the attenuation of apparent lamp radiance with distance. Photographic photometry was employed using a Wratten No. 61 filter and Eastman Plus X 35-mm film (Emulsion No. 5061-64-16A) developed to unity gamma in D-76. Exposure time at $f/1.5$ varied from 1.75 msec at a lamp distance of 10.5 ft to 180 000 msec when the lamp was 80 ft from the camera. The source of light was a 1000-W incandescent "diving lamp" (No. MG25/1) manufactured by the General Electric Company. The 3-in. spherical lamp envelope was sprayed with a white gloss lacquer in order to produce a uniform translucent white covering which gave the lamp the same radiant intensity in all directions (to within ±7%) except toward the base, which was turned away from the camera. Two or more exposure times differing by 5- or 10-fold were used at each lamp distance. Open circles represent data from a single time of exposure; solid points indicate that identical values of apparent radiance were obtained from negatives made with two different exposure times. A solid straight line, representing an attenuation length $1/\alpha = 5.00$ ft/ln, has been drawn near the points. Dashed lines corresponding to attenuation lengths of 4.72 ft/ln and 5.12 ft/ln, respectively, represent values measured by means of a light-beam transmissometer before and after the all-night experimental session. Cooling of the water during the night correlated with the observed increase of attenuation length, presumably due to plankton shrinkage. Data are of 26 August 1959 at Diamond Island Field Station.

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[16] W. H. Richardson and R. W. Preisendorfer, Scripps Inst. Oceanog., Ref. 60-43 (1960).

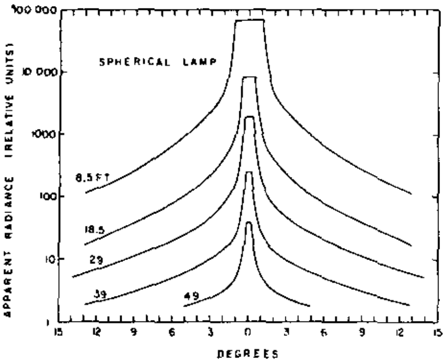

FIG. 15. Angular distribution of apparent radiance produced by a uniform, spherical, underwater lamp at distances of 8.5, 18.5, 29, and 39 feet. The lamp was identical to the one described in connection with Fig. 14. The photometry was by means of an automatic scanning, photoelectric, telephotometer having a circular acceptance cone 0.25° in diameter and with its spectral response limited by a Wratten No. 61 filter. Attenuation length was 5.1 ft/ln. Data are of 3 August 1961 at the Diamond Island Field Station.

Eqs. (1) and (2), indicating thereby that images are formed by photons transmitted without being scattered and that the contribution of scattered light to the exposure of the image portion of the negative was negligible.

Apparent radiance of the glow. Distributions of the apparent radiance of the glow surrounding the distant lamp were obtained by densitometry of the same series of photographs, but more accurate results have been achieved by means of an automatic scanning photoelectric telephotometer which was more free from stray light than was the camera. Distributions of apparent radiance as measured photoelectrically from the target position are shown in Fig. 15. The irradiance on any surface of the target facing the lamp can be computed from these curves and, if the reflectance and gloss characteristics of the target surfaces are known, the inherent radiance of the target in any specified direction can be calculated. If, moreover, the volume scattering function of the water and its attenuation length are known, calculations of inherent background radiance, path radiance, and apparent target contrast can be made from Fig. 15.

Irradiance at the Object

The surface of any underwater object is irradiated by (1) direct (nonscattered) light from the lamp and (2) scattered light. The *nonscattered* or *monopath irradiance* H_r^0 produced at normal incidence by a lamp radiant intensity J at distance r is given by the relation

$$H_r^0 = Je^{-\alpha r}/r^2. \tag{3}$$

In addition to H_r^0, the object is irradiated by the scattered or *multipath irradiance* H_r^*. Thus the *total irradiance* $H_r = H_r^0 + H_r^*$. Since H_r can be measured (see Fig. 16) and H_r^0 can be calculated by means of Eq. (3), H_r^* can be found by subtraction; thus, $H_r^* = H_r - H_r^0$.

Diffusion theory[17,18] based upon the assumption of isotropic scattering suggests that

$$H_r^* = JKe^{-Kr}/4\pi r, \tag{4}$$

where K is an attenuation coefficient for scattered light. If this K is given a value numerically equal to the attenuation function for daylight scalar irradiance k, as discussed later in the portion of this paper devoted to daylight in the sea, Eqs. (3) and (4), when summed, fit the data of Fig. 16 within experimental uncertainty both at short and at long lamp distances; between 10 ft (2 attenuation lengths) and 70 feet (14 attenuation lengths), however, the measured total irradiance is as much as twice the predicted values. A semiempirical modification of Eq. (4) which, added to Eq. (3), fits the data of Fig. 16 within experimental error is

$$H_r^* = 2.5(1 + 7e^{-Kr})JKe^{-Kr}/4\pi r. \tag{5}$$

Effect of beam spread. Underwater sources of divergent light are seldom completely spherical in their radiant intensity distribution. Many underwater lamps

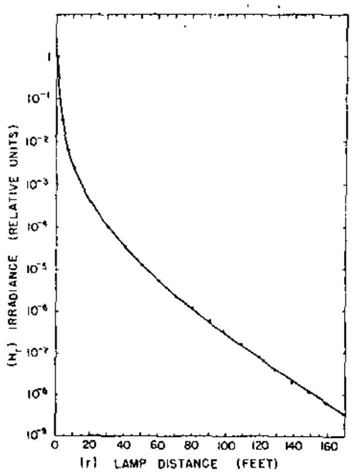

FIG. 16. Total irradiance produced at various distances by a uniform, spherical underwater lamp at the Diamond Island Field Station. The solid curve was passed through the data points by means of a least-squares procedure. The lamp was identical with the one described in connection with Fig. 14. The photometry was by means of an underwater photoelectric irradiance meter facing directly toward the lamp. The spectral response of the irradiometer was limited by means of a Wratten No. 61 green filter. The attenuation length of the water was 5.0 ft/ln. Data are of 26 August 1959.

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[17] S. Glasstone and M. C. Edlund, *Elements of Nuclear Reactor Theory* (D. Van Nostrand and Company, Inc., Princeton, New Jersey, 1952), p. 107.

[18] R. W. Preisendorfer (private communication).

emit roughly conical patterns of flux 20° or more in total angular extent. Monopath irradiance is, of course, unaffected by the beam spread, and the effect on multipath irradiance is not large unless the lamp produces a highly collimated beam. Experiments with an underwater light source having a continuously variable beam spread down to 20° resulted in an empirical modification of Eq. (5) to the form

$$H_r^* = (2.5 - 1.5\log_{10} 2\pi/\beta) \times[1+7(2\pi/\beta)^{1/2}e^{-Kr}]JKe^{-Kr}/4\pi r, \quad (6)$$

where β is the total beam spread. Equation (6) should not be used for beam spreads less than 20°.

Equations (4), (5), and (6) have been tested by the author only at the Diamond Island Field Station, but because of the similarity in the shape of the volume scattering functions of natural waters, as illustrated by Fig. 12, they may have nearly universal applicability as approximations for engineering purposes.

COLLIMATED LIGHT IN THE SEA

Underwater projectors producing beam spreads small compared with 1° exhibit distinctive properties. When seen from the position of the irradiated target, the head-on appearance of a distant, highly collimated lamp is remarkably similar to that of a broad-beam lamp at some lesser range. Thus, the bright disk-shaped image of the lamp is surrounded by a glow of scattered light, having an apparent radiance distribution like that shown in Fig. 17. Although it is difficult to distinguish a distant collimated lamp from a distant divergent source when each is observed from within its beam, radiance distribution measurements reveal subtle differences, the nature of which can be seen by comparing Figs. 15 and 17.

The appearance presented by a moderately distant, slightly averted collimated lamp is, however, very different from that of its divergent counterpart because the intense small-angle scattering, common to all natural waters, produces a readily visible, sharply defined, nearly cylindrical luminous column extending toward the observer from the collimated lamp. Near the lamp and on the axis of this column the monochromatic monopath irradiance normal to the beam at distance r is $H_r^0 = H_0 e^{-\alpha r}$, where the irradiance H_0 in the water at the lens of the projector is given by $H_0 = J\psi^2 D^{-2}$ in terms of radiant intensity J, total beam spread ψ, and diameter D of the light beam. Beyond the distance $r' = D/\psi$, at which the lens replaces the source as the aperture stop of the irradiating system, H_r^0 is given by

$$H_r^0 = Je^{-\alpha r}/r^2 = H_0 e^{-\alpha r}(D/\psi r)^2 = H_0 e^{-\alpha r}/(r/r')^2 \quad (7)$$

if diffraction is negligible.

The dashed lines in Fig. 18 illustrate the foregoing relations applied to the case of three collimated lamps having a divergence of 1/6° and exit pupil diameters of 1/300, 2/300, and 8/300 of an attenuation length, respectively. For these three lamps the distances r' are 1.15, 2.30, and 9.20 attenuation lengths. The points at $r = r'$, beyond which Eq. (7) applies, lie within the diagram for both of the two smaller lamps and are indicated by triangles. In all cases, diffraction will lower the dashed curves.

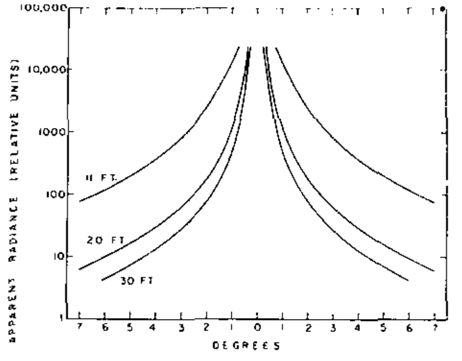

FIG. 17. Apparent radiance produced by scattering from the beam of the highly collimated underwater lamp shown in Fig. 4. The photometry was by means of an automatic scanning, photoelectric telephotometer having a circular acceptance cone 0.25° in diameter and with its spectral response limited by a Wratten No. 61 filter. The beam from the lamp had a divergence of 0.01°; it was directed toward the telephotometer and filled the entrance pupil of that instrument at all times. Lamp distances of 11, 20, and 30 ft were used. Tests of the telephotometer showed that the data in Fig. 17 are free from stray-light effects. Attenuation length of the water was 6.7 ft/ln. The data are of 11 August 1961 at the Diamond Island Field Station.

The total irradiance H_r on the axis of a collimated beam exceeds the monopath irradiance H_r^0 by the multipath contribution H_r^*; i.e., $H_r = H_r^0 + H_r^*$. This is illustrated by the experimental data points shown in Fig. 18 and the solid curves which have been fitted to them. In the case of the two smaller lamps the multipath contribution was not detected at ranges shorter than r', indicated by the triangle points, but this is not true in the beam from the large-diameter lamp where H_r^* and H_r^0 are approximately equal throughout much of the range of distances covered by the data. The steadily increasing separation of the solid and dashed curves in each of the lower pairs implies that multipath irradiance becomes dominant at large lamp distances.

Data such as those in Fig. 18 can be used to calculate the ratio of monopath to multipath irradiance; i.e., H_r^0/H_r^*. This ratio, independent of the intensity of the lamp or its radiant power output, is a measure of the beam content of the light; it is the ratio of image-forming light transmitted by the water path to the non-image-forming (scattered) light arriving at the irradiated object. Applications dependent on the retention of narrow-beam geometrical characteristics, of coherence, or of single-valued transmission time may require that some usable fraction of the irradiance consist of nonscattered (monopath) light. Figure 19 is a

[231]

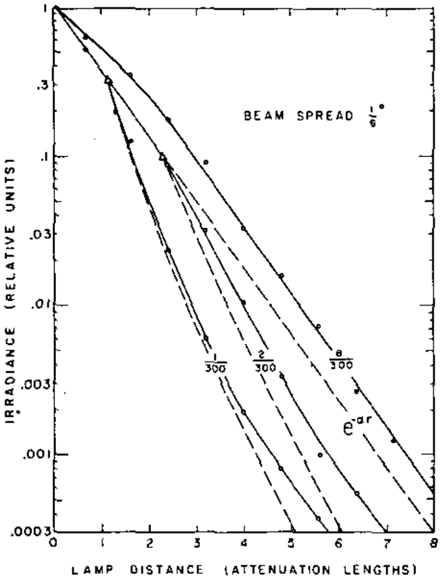

FIG. 18. Irradiance normal to the axis of the beam of light having a divergence of 1/6° produced by a *collimated underwater lamp* (Fig. 4) at distances up to 8 attenuation lengths is shown by the data points and the solid lines for beam diameters of 1/300, 2/300, and 8/300 of an attenuation length. The data are of 14 August 1961 at the Diamond Island Field Station; attenuation length $1/\alpha=6.3$ ft/ln. Dashed lines represent the monopath irradiance in each case computed from Eq. (7). Geometrical divergence reduces the axial monopath irradiance at all lamp distances beyond the points marked by triangles, which occur at 1.15 and 2.30 attenuation lengths for the two smaller lamps and at 9.20 attenuation lengths (not shown) for the largest lamp. Spreading of the beam by diffraction also reduces the monopath irradiance at all lamp distances, often dramatically. In a plot involving dimensionless lamp distance (such as Fig. 18), the dashed lines cannot be drawn to include the potentially major effect of diffraction because the wavelength of light is independent of the attenuation length, but they should be appropriately lowered when the figure is interpreted in terms of actual dimensions. The vertical separation between the dashed and the solid curves in each pair is a measure of the multipath irradiance. *Caution*: The data in this figure relate only to the axis of an aplanatic underwater projection system having a beam spread $\psi=1/6°$; they should *not* be scaled by the ratio D/ψ; they do *not*, for example, apply to the case of $\psi=1/60°$ and lamp diameters $D=1/3000$, 2/3000, or 8/3000 attenuation length.

plot of H_r^0/H_r^* for divergent sources. It shows that for a beam spread of 20°, $H_r^*=H_r^0$ at 1.4 attenuation lengths and that multipath irradiance predominates at large lamp distances. Experiments now in progress with light beams of small diameter and high collimation may produce corresponding curves for collimated lamps.

Irradiance near a highly collimated beam. All of the foregoing discussion has concerned irradiance produced on the axis of a collimated beam. Measurements of irradiance outside the light beam at various distances from the collimated lamp are shown in Fig. 20.

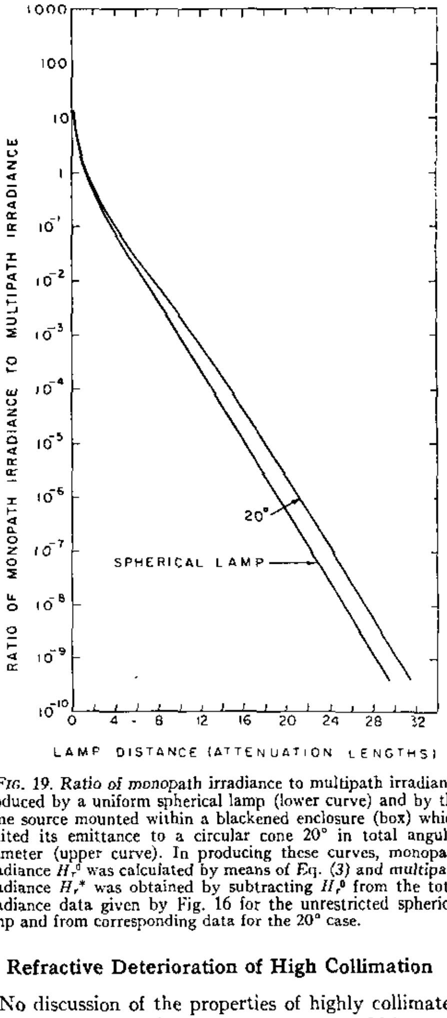

FIG. 19. Ratio of monopath irradiance to multipath irradiance produced by a uniform spherical lamp (lower curve) and by the same source mounted within a blackened enclosure (box) which limited its emittance to a circular cone 20° in total angular diameter (upper curve). In producing these curves, monopath irradiance H_r^0 was calculated by means of Eq. (3) and multipath irradiance H_r^* was obtained by subtracting H_r^0 from the total irradiance data given by Fig. 16 for the unrestricted spherical lamp and from corresponding data for the 20° case.

Refractive Deterioration of High Collimation

No discussion of the properties of highly collimated underwater light or image-forming rays would be complete without mention of certain commonly encountered refractive effects which limit the resolution of fine detail and tend to destroy high collimation. Natural waters often contain refractive nonhomogeneities of two kinds: (1) small scale point-to-point variations in refractive index due, for example, to temperature differences; and (2) transparent biological organisms (plankton) which may range in size from microns to centimeters. The effects of these optical nonhomogeneities has been observed by allowing the beam from the 2-in.-diameter 0.01° divergent lamp shown in Fig. 4 to fall on an underwater viewing screen after traversing any convenient water path or by photographing the effect with an underwater camera having no lens, in the manner

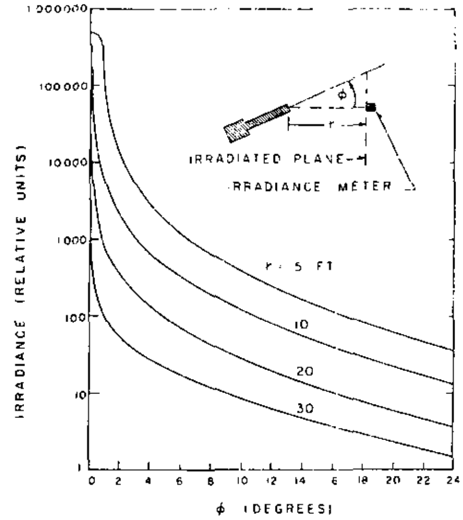

FIG. 20. Irradiance outside a collimated beam of light. Beam divergence: 0.046°; beam diameter: 2-in. Filter: Wratten No. 61. Attenuation length 4.8 ft/ln; Diamond Island.

suggested by Fig. 21. If such a photograph is made in well-mixed distilled water, only a uniform white field is recorded, but if the distilled water is allowed to stand, a pattern of shadows appears as thermal structures develop. If transparent plankton are added, their refractive shadows are superimposed.

Figure 22 is a photograph of the pattern obtained when such a picture was taken in the clear, natural water at the Diamond Island Field Station in Lake Winnipesaukee, New Hampshire. In this case the light beam passed through 10 ft of lake water. The circular shadows were caused by transparent plankton somewhat less than 1 mm in size whose refractive index differed only slightly from that of water. No effects due to thermal tubulons have been identified in this picture. The light beam was horizontal and 30 in. beneath the surface of the water. A shutter speed of 1/50 second was used because the pattern was in constant restless motion, primarily due to slight wave action, but also due to plankton movements and possibly to thermal drifts.

Loss of resolution. Wavefronts passing through natural waters are distorted by these refractive effects. The edges of objects appear blurred and the apparent contrast of small objects is reduced. Thus, resolving power is impaired and fine details are obliterated. It is said that in some clear, south-sea waters the concentration of transparent plankton is so great that a swimmer cannot distinguish his toes even though his foot is clearly visible at high contrast. Conditions are much less severe at the Diamond Island Field Station, where

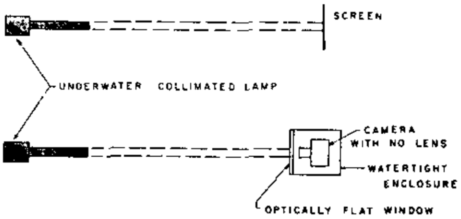

FIG. 21. Techniques for observing (upper figure) and recording (lower figure) the effects of refractive inhomogeneities on the transmission of a highly collimated beam of light through natural water.

magnification is necessary to make the loss of resolution obvious.

An experimental study of this loss of resolution was performed several years ago at the Diamond Island Field Station and a theoretical treatment of the effect was evolved.[19,20] At Diamond Island the loss of resolution was comparable to that caused by the on-axis aberrations of a flat water-to-air window of 1/4-in.-thick commercial plate glass when 10 ft of water separated the object from the camera. The angular magnitude of the blur increases as the square root of the object-to-camera distance, and the apparent contrast of fine details is decreased inversely as the third power of the distance in macroscopically uniform water.[20]

DAYLIGHT IN THE SEA

Most of the light in the sea is from the sun and the sky. In sunny weather each square meter of the water surface may be irradiated by as much as one kilowatt of solar power. Approximately 95% of this power en-

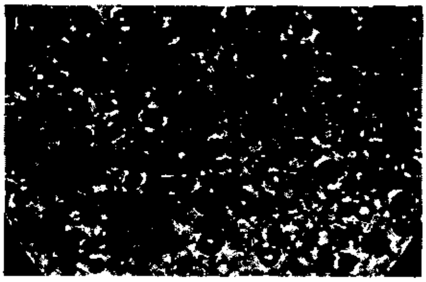

FIG. 22. Photograph of the light distribution from the collimated underwater lamp (Fig. 4) after traversing 10 ft of water in the manner shown schematically in Fig. 21. Camera: Contax without lens. Exposure time: 1/50 sec. Film: Eastman Plus-X. Development: normal, D-76. Beam spread: 0.01°. Beam diameter: 2 in. Attenuation length: 5.6 ft/ln; Diamond Island; 22 August 1961. The diameter of the outer black circular border (caused by the opening in the camera body) measured 1.3 in. on the negative.

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[19] S. Q. Duntley, W. H. Culver, F. Richey, and R. W. Preisendorfer, J. Opt. Soc. Am. 42, 877(A) (1952).

[20] S. Q. Duntley, W. H. Culver, F. Richey, and R. W. Preisendorfer, J. Opt. Soc. Am. (to be published).

ters the water and is absorbed somewhere beneath the surface. Daylight is the principal source of energy for the sea, supplying it with heat and supporting its ecology through photosynthesis. Nearly half of the irradiation is infrared, most of which is absorbed within a meter of the surface. As much as one-fifth of the daylight may be ultraviolet and this can penetrate somewhat more deeply if the concentration of dissolved organic decomposition products ("yellow substance") is low. Fortunately, the peak of the solar spectrum is not far from the wavelength (480 mμ) of greatest transparency in clear ocean water. Blue-green light, representing less than one-tenth of the total incident solar power, penetrates so deeply into the sea that it has been detected photoelectrically below 600 m. Visibility, important to inhabitants of the underwater world, is possible chiefly because of this blue-green light.

Directional Distribution of Daylight Underwater

Sunlight entering at the surface becomes progressively more diffuse with depth until a state of diffusion is reached which (1) is characteristic of the water mass, (2) is independent of the solar altitude and the prevailing sky condition, and (3) is invariant with further increases in depth unless optically different water is encountered. This behavior of daylight in water, a subject of conjecture for more than 30 years, was probably first definitively postulated by Whitney[21,22] in brilliant speculations based neither upon adequate radiance distribution data nor upon a valid theoretical analysis but chiefly upon insightful interpretations of irradiance measurements. Whitney's hypothesis could not be confirmed until 1957, when an eight-year experimental program, initiated by the author and conducted in its later stages chiefly by several of his colleagues, culminated in the definitive radiance distribution data of Tyler.[23] These data were obtained with superlative equipment representing nearly a decade of apparatus development. The experiments were conducted in a mountain lake containing optically uniform water of very great depth. This lake (Pend Oreille, Idaho) was used only after many futile attempts had been made to find sufficiently uniform, deep water at sea and in other lakes. Even at Pend Oreille optical uniformity occurs only for a few days during the spring of each year. The Pend Oreille data show an unmistakable, systematic trend toward the formation of a characteristic (or *asymptotic*) distribution of underwater daylight radiance. A series of figures developed from Tyler's tabulated Pend Oreille data[23] and described in the section which follows summarize this experimental evidence for the *asymptotic radiance distribution* hypothesis and illustrate the progressive transformation of the light field from the sunny condition near the surface to the characteristic diffuse distribution which prevails at great depth. A theoretical proof of the existence of characteristic diffuse light (asymptotic radiance distribution) in natural waters has been given by Preisendorfer[24] and confirmatory experimental data in other natural waters have been obtained by Jerlov and Fukuda[25] and Sasaki.[26]

Depth Profiles of Underwater Radiance

The most usable graphical representation of the distribution of daylight radiance in the sea is a family of radiance distribution profiles like those in Fig. 23. Con-

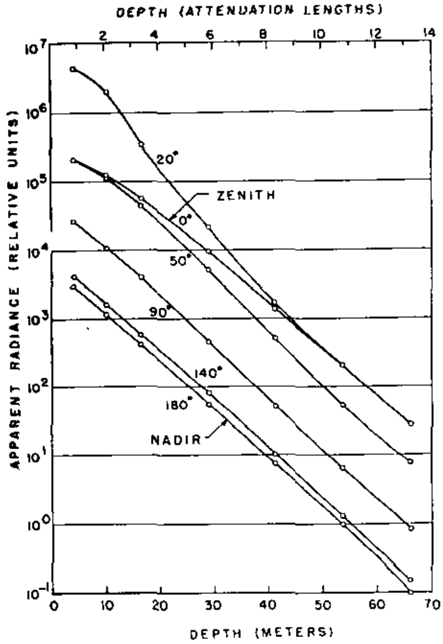

FIG. 23. Depth profiles of underwater apparent radiance for several paths of sight (i.e., zenith angles) in the plane of the sun on a clear, calm, cloudless, sunny day (28 April 1957) at Pend Oreille, Idaho. The circles denote data by Tyler (see reference 23). The solar zenith angle was 33.4°. The submerged photoelectric radiance photometer measured blue light by means of an RCA 931A multiplier phototube equipped with a Wratten No. 45 filter; its field of view was circular and 6.6° in angular diameter. The water was nearly uniform in its optical properties; i.e., the attenuation length (as measured by means of a light beam transmissometer having a tungsten source, an RCA 931A phototube, and a Wratten No. 45 filter) was 2.52 m/ln just beneath the surface and increased very slightly at a steady rate to 2.62 m/ln at a depth of 61 m; that is to say, the change in attenuation length with depth was barely detectable. Additional families of radiance profiles in vertical planes at other azimuths can be constructed from Tyler's tables, which also provide corresponding data for overcast conditions. All such sets of profiles are remarkably similar at great depth. Parallel profiles signify that the radiance distribution has its asymptotic form.

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[21] L. V. Whitney, J. Marine Research 4, 122 (1941).

[22] L. V. Whitney, J. Opt. Soc. Am. 31, 714 (1941).

[23] J. E. Tyler, Bull. Scripps Inst. Oceanog. 7, 363 (1960).

[24] R. W. Preisendorfer, J. Marine Research 18, 1 (1959).

[25] N. G. Jerlov and M. Fukuda, Tellus 12, 348 (1960).

[26] T. Sasaki, Bull. Japan. Soc. Sci. Fisheries 28, 489 (1962).

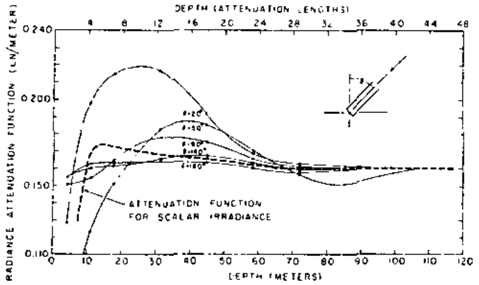

FIG. 24. The solid curves are radiance attenuation functions (i.e., slopes) of the depth profiles of apparent radiance in Fig. 23. The circled points are from Tyler's attenuation function tables (see reference 23). The dashed curve is the attenuation function for scalar irradiance; i.e., the slope of the depth profile of scalar irradiance, a radiometric quantity proportional to the response of a spherical diffuse collector such as that at the top of the instrument pictured in Fig. 25. The transformation of the light field to its asymptotic form is illustrated by the convergence of the radiance attenuation functions to a common, steady value at sufficient depth.

ceptually, each curve represents the results of lowering vertically into the sea a radiance photometer having a fixed zenith angle and azimuth. The unique utility of such profiles arises from the fact that the contrast transmittance of any path of sight in the day-lighted sea is given by the ratio of the apparent background radiances at the *terminals of the path* multiplied by the beam transmittance of the path [see Eq. (8)]. This important general theorem is rigorously true despite any degree of stratification or nonhomogeneity possessed by the water and despite any amount of nonuniformity in the lighting throughout the path of sight. Radiance distribution profiles like those in Fig. 23 enable the apparent background-radiance ratio to be read for any pair of terminal points regardless of the shape of the profile.

In Fig. 23 each curve is nearly, but not quite, straight and nearly, but not quite, parallel with its fellows. When, at sufficient depth, all of the profiles are parallel, the asymptotic radiance distribution prevails.

Radiance Attenuation Functions

The inverse slope of the semilogarithmic underwater radiance distribution profiles in Fig. 23 is called the *radiance attenuation function*. It is symbolized by $K(z,\theta,\phi)$, where z refers to depth, θ specifies the zenith angle of the radiance photometer, and ϕ denotes its azimuth. Figure 24, developed from similar ones by Preisendorfer,[27,28] is a plot of the radiance attenuation functions (slopes) of the radiance profiles shown in Fig. 23. The curves in Fig. 24 have been extrapolated beyond the greatest depth explored by Tyler's measurements in order to illustrate the asymptotic radiance distribution concept more completely. Differential equations for the radiance attenuation functions have been evolved by Preisendorfer.[27]

Attenuation Function for Scalar Irradiance

The slope of a vertical profile of scalar irradiance $h(z)$, a radiometric quantity measurable by means of a spherical diffuse collector, is called the *attenuation function for scalar irradiance* at depth z and is denoted by $k(z)$. This function is shown by the dashed curve in Fig. 24. The limiting value $k(\infty)$ of $k(z)$ is a convenient experimental parameter for describing the optical properties of the sea because (1) $k(z)$ approaches its asymptotic value at less depth than do the radiance attenuation functions, and (2) it is easier to measure. Figure 25 shows a water-clarity meter proposed by the author and constructed

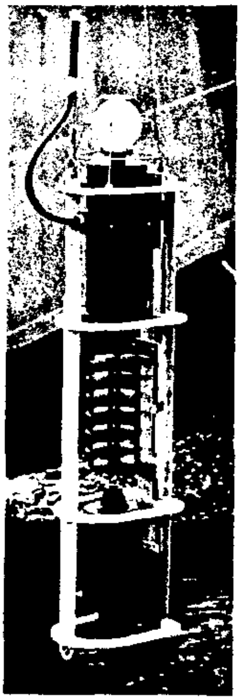

FIG. 25. Water-clarity meter for measuring depth profiles of scalar irradiance $h(z)$ and attenuation coefficient $\alpha(z)$ at sea. The hollow, translucent, white sphere at the top of the instrument is the collector for the measurement of scalar irradiance. Attenuation is measured by means of a highly collimated beam of light, produced by a projector in the lower compartment, which travels upward to a photoelectric telephotometer in the upper chamber. Baffles are used to minimize the effect of daylight in near surface measurements. The use of multiplier phototubes enables this equipment to produce profiles of scalar irradiance at depths greater than 10 attenuation lengths. A pressure transducer is incorporated in the instrument to indicate its depth. Due to the spherical nature of the irradiance sensor, the orientation of the instrument is not important; it can, if desired, be oriented horizontally (see reference 29).

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[27] R. W. Preisendorfer, Scripps Inst. Oceanog. Ref. **58-59**, (1958).

[28] R. W. Preisendorfer, Scripps Inst. Oceanog. Ref. **58-60**, (1958).

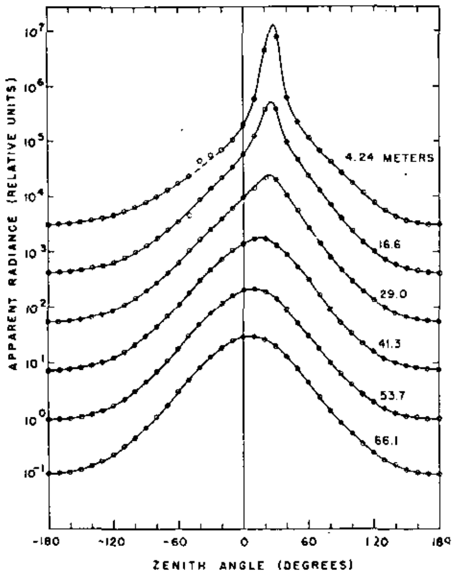

FIG. 26. Underwater radiance distributions in the plane of the sun on a clear, sunny day at depths of 4.24, 16.6, 29.0, 41.3, 53.7, and 66.1 m, respectively. The circles denote data by Tyler (see reference 23) at Pend Oreille, Idaho, 28 April 1957. The solar zenith angle was 33.4° For additional experimental details see Fig. 23. At the shallowest depth measured (4.24 m), the peak of the radiance distribution is at a slightly greater zenith angle than refracted rays from the sun (24.4°); see Fig. 29. At progressively greater depths the distribution becomes less sharply peaked and the maximum moves toward zero zenith angle. The radiance distribution is nearly in its asymptotic form at 66.1 m, the greatest depth at which data were taken. Corresponding trends appear in similar plots of data obtained by Sasaki in ocean water near Japan (see reference 26) and in Gullmar fjord by Jerlov and Fukuda (see reference 25).

by his colleagues,[29] which measures simultaneous vertical profiles of scalar irradiance $h(z)$ and attenuation coefficient $\alpha(z)$ in routine oceanographic surveys.

Shapes of the Underwater Radiance Distribution

The shapes of a typical family of underwater radiance distributions in the plane of the sun at progressively greater depths are shown by Fig. 26, which includes the same data plotted in Fig. 23. At shallow depths the distribution is sharply peaked, approximately in the direction of the refracted rays from the sun. At increasingly greater depths the distribution becomes less sharply peaked and the maximum moves progressively toward the zenith. The change in curve shape is better illustrated by Fig. 27, wherein the upper four curves of Fig. 26 have been superimposed at their respective maxima.

The lower two curves in Fig. 26 do not appear in Fig. 27 because their shape does not differ from that of the 41.3-m curve within the precision of the data. It may be noted, therefore, that the form of the radiance distribution changes throughout only the first 41 m of depth (about 16 attenuation lengths or *optical depths*). At that depth, however, the shift of the maximum toward the zenith is incomplete and continues to change rapidly as depth is progressively increased. Figure 28 shows how the maximum of the underwater daylight distribution shifts toward the zenith with increasing depth; it suggests, by extrapolation, that a depth of 20 attenuation lengths (100 m) or more is required in order for the true asymptotic radiance distribution to be reached.

Irradiance Profiles

When the underwater radiance distribution has its asymptotic form, the irradiance incident on a plane oriented in any direction will decrease exponentially with depth at the same rate as will the irradiance on planes oriented in any other directions. A family of semilogarithmic profiles of the irradiance on planes oriented in various directions is merely a group of parallel straight lines having a slope corresponding to $k(\infty)$, the limiting value of the attenuation function for scalar irradiance. In most ocean water the irradiance $H(z,-)$ on the upper surface of a horizontal plane at any depth z is approximately 50 times as great as the irradiance $H(z,+)$ on the lower surface of the same plane; the irradiance on planes oriented in all other directions at this depth lies between $H(z,-)$ and $H(z,+)$.

At lesser depths, where the underwater radiance distribution departs from its asymptotic form, the semilogarithmic irradiance profiles differ somewhat from parallelism and straightness. Such perturbations are, however, comparatively minor and for many purposes they are negligible. For example, some of the attenuation functions at a depth of 2.5 ft on an overcast day

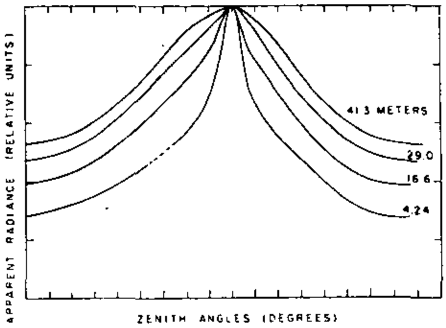

FIG. 27. In this figure the underwater radiance distribution curves for depths 4.24, 16.6, 29.0, and 41.3 m from Fig. 26 have been superimposed at their respective maxima in order to compare their shapes. The radiance curves for depths 53.7 and 66.1 m are not shown since, within the limits of experimental error, their shapes are identical with the curve for 41.3 m depth. Thus, the *shape* of the underwater radiance distribution has nearly completed its transformation to the asymptotic form at 41.3 m depth. The maximum of the curve has not, however, reached zero zenith angle at this depth and is, in fact, changing at maximum rate; see Fig. 28.

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[29] R. W. Austin, Scripps Inst. Oceanog. Ref. 59-9, (1959).

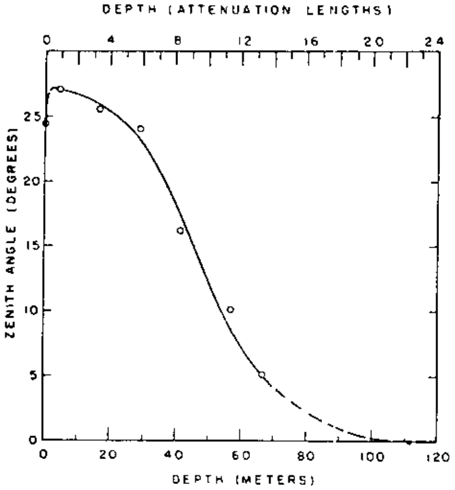

FIG. 28. Illustrating how the peaks of the underwater daylight radiance distributions shown in Fig. 26 shift toward zero zenith angle with increasing depth. At shallow depths in these data the peak occurs at a greater zenith angle than the direction (underwater) of rays from the sun. The extrapolated (dashed) portion of the curve suggests that a depth of more than 100 m is required to bring the peak to zero zenith angle; i.e., to complete the transformation of the light field to its asymptotic form.

(28 August 1959) at Diamond Island were $K(2.5,-)=0.067$ ln/ft, $k(2.5)=0.063$ ln/ft, $K(2.5,+)=0.051$ ln/ft, and $\alpha(2.5)=0.18$ ln/ft.

Contrast Transmittance

Introduction. Underwater sighting ranges are always short compared with sighting ranges in clear air. Nearly all objects, therefore, subtend so large a visual angle when seen underwater that the exact size of the object is of almost no consequence. Except for very tiny objects or the fine details of larger ones, underwater sighting ranges depend almost entirely upon the contrast transmittance of the path of sight when ample daylight prevails. Along horizontal paths of sight dark objects (such as black-suited swimmers) approach detection threshold near the distance $4/\alpha(z)$ when viewed against a water background, although bright objects (including light sources) can be seen further.[30] For objects of sufficient angular size, horizontal daylight sighting ranges underwater are remarkably similar to horizontal daylight sighting ranges in the atmosphere if both are expressed in attenuation lengths. This quantitative similarity does not hold, however, when the path of sight is inclined either upward or downward because water, unlike air, absorbs light so strongly that all aspects of daylight in the sea diminish rapidly with depth. Contrast reduction along inclined paths of sight through optically uniform water are treated after certain general principles have been discussed.

General case. A completely general phenomenological treatment of the reduction of apparent contrast by any scattering and absorbing medium has been given by the author and two of his colleagues in an earlier paper[31] concerned with the atmosphere; Eq. (1) through (10) of that paper and the discussions which accompany them apply also to the reduction of contrast along all underwater paths of sight, and the notation employed in reference 31 has been used throughout the present paper, except that z is used to denote depth (rather than altitude) and is positive from the sea surface downward. Although, in the interest of brevity, only one [Eq. (7)] of those equations is discussed here, they constitute the foundation for all of the relations which follow in this paper.

Equation (7) in reference 31 states that the ratio of the apparent contrast $C_r(z,\theta,\phi)$ of an object at distance r from an observer at depth z along a path of sight having zenith angle θ and azimuth ϕ to the inherent contrast $C_0(z_t,\theta,\phi)$ of a target at depth z_t is

$$C_r(z,\theta,\phi)/C_0(z_t,\theta,\phi)=T_r(z,\theta,\phi)\,{}_bN_0(z_t,\theta,\phi)/{}_bN_r(z,\theta,\phi), \quad (8)$$

where $T_r(z,\theta,\phi)$ is the beam transmittance of the path of sight for image-forming light and ${}_bN_0(z_t,\theta,\phi)/{}_bN_r(z,\theta,\phi)$ is the ratio of the apparent radiances of the background at the *terminals* of the path of sight. This equation is rigorously true despite any amount of nonuniformity in the water or in its lighting. Profiles of underwater radiance, such as those in Fig. 23, provide the two background radiance values required by Eq. (8) and the beam transmittance can be found from a profile of attenuation length by means of Eq. (16) in reference 31. It should be noted that the beam transmittance $T_r(z,\theta,\phi)$ must include the factor $[n(z)/n(z_t)]^2$ required by geometrical optics when the refractive index $n(z)$ of the medium at the observer differs from that at the target $n(z_t)$, as in the case of underwater observation through a flat face plate or a plane window.

Uniform water. If the underwater path of sight lies entirely within a single optically uniform stratum and if the profile of monochromatic apparent radiance (see Fig. 23) can be approximated by a straight line and represented by the differential equation

$$dN(z,\theta,\phi)/dr=-K(z,\theta,\phi)\cos\theta N(z,\theta,\phi), \quad (9)$$

where $r\cos\theta=z_t-z$, Eq. (10) of reference 31 can be replaced by differential equations of transfer for spectral field radiance

$$dN(z,\theta,\phi)/dr=N_*(z,\theta,\phi)-\alpha(z)N(z,\theta,\phi), \quad (10)$$

---

[30] Along any underwater path of sight a remarkable proportion of the objects ordinarily encountered can be seen at limiting ranges between 4 and 5 times the distance $1/[\alpha(z)-K(z,\theta,\phi)\cos\theta]$, regardless of their size or the background against which they appear, provided ample daylight prevails [see Eqs. (14) and (15)].

[31] S. Q. Duntley, A. R. Boileau, and R. W. Preisendorfer, J. Opt. Soc. Am. 47, 499 (1957).

and for apparent spectral target radiance

$$d\,{}_tN(z,\theta,\phi)/dr=N_*(z,\theta,\phi)-\alpha(z)\,{}_tN(z,\theta,\phi). \quad (11)$$

Equations (9), (10), and (11) can be combined and integrated throughout the path of sight to produce the important relation

$$\begin{aligned}{}_tN_r(z,\theta,\phi)={}&{}_tN_0(z_t,\theta,\phi)\exp[-\alpha(z)r]\\&+N(z_t,\theta,\phi)\exp[+K(z,\theta,\phi)r\cos\theta]\\&\times\{1-\exp[-\alpha(z)r+K(z,\theta,\phi)r\cos\theta]\},\end{aligned} \quad (12)$$

where ${}_tN_r(z,\theta,\phi)$ is the apparent spectral radiance of the target and ${}_tN_0(z_t,\theta,\phi)$ is its inherent spectral radiance. In Eq. (12) *the first term on the right represents* residual image-forming light from the target and the *second term represents radiance due to scattering of* light in the sea throughout the path of sight, i.e., the *path radiance* $N_r^*(z,\theta,\phi)$. A graphical illustration of Eq. (12) is provided by Fig. 29, which shows how black objects and white objects submerged in deep water appear to emerge gradually from the background as they are approached from above by a descending, downward-looking underwater observer or camera.

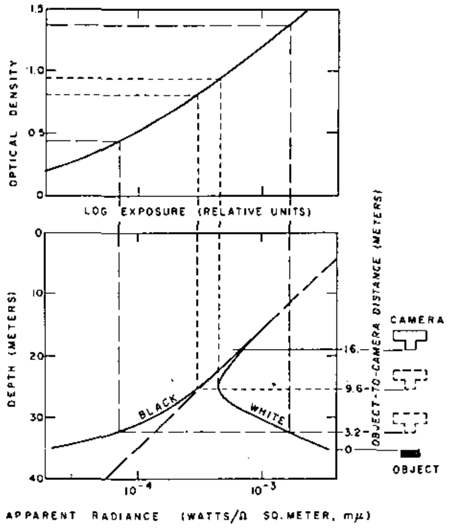

Fig. 29. Illustrating the effect of (vertical) object-to-camera distance on the apparent radiance (lower figure) and the photographic contrast (upper figure) of an object having both white and black areas submerged 35 m beneath the surface of deep, optically uniform water characterized by an attenuation length ($1/\alpha$) of 3.2 m/ln, $(\alpha/K)=2.7$, $H(z,+)/H(z,-)=0.02$, and asymptotic radiance distribution. The prevailing spectral irradiance on the surface of the water is assumed to be 1 W/m², mμ.

As a downward-looking camera is lowered from the sea surface, the apparent radiance presented by the water decreases at the rate of $K=0.116$ ln/m, as shown by the diagonal dashed line in the lower figure. At 19 m depth (i.e., an object-to-camera distance of 16 m or 5 attenuation lengths) the apparent radiances of the object differ but little from that of the surround. When the camera is 9.6 m (i.e., 3 attenuation lengths) above the target, the white area presents an apparent radiance significantly greater than the surround (diagonal dashed line) but the black area appears only slightly darker than the water background. Near this camera position the two terms in the right-hand member of Eq. (12) are equal, so that $dN(z,\pi,0)/dr=0$; at greater camera depths the second term predominates. When the camera is 3.2 m or 1 attenuation length above the object, both the black and the white areas of the target differ markedly in apparent radiance from the surround (diagonal dashed line). The upper figure illustrates, by means of the characteristic curve of a negative material, the range of photographic densities corresponding with object-to-camera distances of 3.2 m (dashed lines) and 9.6 m (dotted lines).

In Eq. (12), $\alpha(z)$ and $K(z,\theta,\phi)$ are considered to be constants throughout the path of sight. In uniform water this is true of $\alpha(z)$ but not of $K(z,\theta,\phi)$ unless the radiance distribution is asymptotic. Figure 24 illustrates how $K(z,\theta,\phi)$ changes with z and θ in the plane of the sun; corresponding figures can be constructed from Tyler's tables[23] to illustrate changes with ϕ. Such data should be used to ascertain the variation of $K(z,\theta,\phi)$ on the particular segment of the path of sight to be used; the degree of approximation represented by Eq. (12) [and by Eqs. (14), (15), and (16)] can then be estimated. Because underwater sighting ranges rarely exceed $2/K$, the effect of K variation is seldom appreciable, except near the surface of the sea. General equations, remarkably similar in form to Eqs. (12), (14), (15), and (16), have been written by Preisendorfer (private communication); these involve, for example,

$$\exp\left\{-\int_0^r[\alpha(z)-\cos\theta K(z,\theta,\phi)]dr'\right\}$$

instead of

$$\exp[-\alpha(z)r+\cos\theta K(z,\theta,\phi)r];$$

they are also applicable to nonuniform water and even to multi-media paths of sight.

Equation (12) also specifies the apparent radiance of any background against which a target may be seen; when used for this purpose the presubscript-t (for target) should be changed to b (for background). Subtraction of the background form of Eq. (12) from Eq. (12) itself yields the relation

$$\begin{aligned}&{}_tN_r(z,\theta,\phi)-{}_bN_r(z,\theta,\phi)\\&\quad=[{}_tN_0(z_t,\theta,\phi)-{}_bN_0(z_t,\theta,\phi)]\exp[-\alpha(z)r].\end{aligned} \quad (13)$$

Equation (13) implies that along *any* underwater path of sight, radiance differences are transmitted with exponential attenuation at the same space rate as image-forming rays.

The two forms of Eq. (12) *can be combined with the* defining relations for inherent spectral contrast, $C_0(z_t,\theta,\phi)$, and apparent spectral contrast $C_r(z,\theta,\phi)$, which are, respectively,

$$C_0(z_t,\theta,\phi)=[{}_tN_0(z_t,\theta,\phi)-{}_bN_0(z_t,\theta,\phi)]/{}_bN_0(z_t,\theta,\phi),$$

and

$$C_r(z,\theta,\phi)=[{}_tN_r(z,\theta,\phi)-{}_bN_r(z,\theta,\phi)]/{}_bN_r(z,\theta,\phi).$$

When this is done, the ratio of inherent spectral contrast to the apparent spectral contrast is found to be

$$C_0(z_t,\theta,\phi)/C_r(z,\theta,\phi) = 1-[N(z_t,\theta,\phi)/{}_bN_0(z_t,\theta,\phi)] \times\{1-\exp[\alpha(z)r-K(z,\theta,\phi)r\cos\theta]\}. \quad (14)$$

If ${}_bN_0(z_t,\theta,\phi)=N(z_t,\theta,\phi)$, as in the special case of an object suspended in deep water, Eq. (14) reduces to

$$C_r(z,\theta,\phi)=C_0(z_t,\theta,\phi) \times\exp[-\alpha(z)r+K(z,\theta,\phi)r\cos\theta]. \quad (15)$$

Whenever the underwater daylight radiance distribution has, effectively, its asymptotic form, the radiance attenuation function $K(z,\theta,\phi)$ is a constant, independent of z, θ, and ϕ. Equation (15) may then be written

$$C_r(z,\theta,\phi)/C_0(z_t,\theta,\phi)=\exp[-\alpha+K\cos\theta)]r. \quad (16)$$

The right-hand member of Eq. (16), sometimes called the *contrast reduction factor*, is independent of ϕ, the azimuth of the path of sight. This and other implications of Eq. (16) were discovered by the author in the course of early experiments as illustrated, in part, by Figs. 30 and 31.

Horizontal paths of sight. Along horizontal paths of sight $\cos\theta=0$ in Eqs. (9), (12), (14), (15), and (16), which show that both the apparent radiance and the apparent contrast of objects seen horizontally underwater change with distance in a manner dependent on α but not on K. When $\cos\theta=0$, Eq. (10) indicates that some unique ***equilibrium radiance*** $N_q(z,\pi/2,\phi)$ must exist at each point such that the loss of radiance within the horizontal path segment is balanced by the gain, i.e.,

$$dN_q(z,\tfrac{1}{2}\pi,\phi)/dr=0=N_*(z,\tfrac{1}{2}\pi,\phi)-\alpha(z)N_q(z,\tfrac{1}{2}\pi,\phi). \quad (17)$$

Even in nonuniform water there is an equilibrium radiance for each element of horizontal path although this may differ from point to point. Inclined paths of sight do not have a true equilibrium radiance, as will be clear from Eq. (9), but they possess an exponential counterpart which is illustrated by the diagonal dashed line in Fig. 29.

A method[32] for measuring the attenuation coefficient

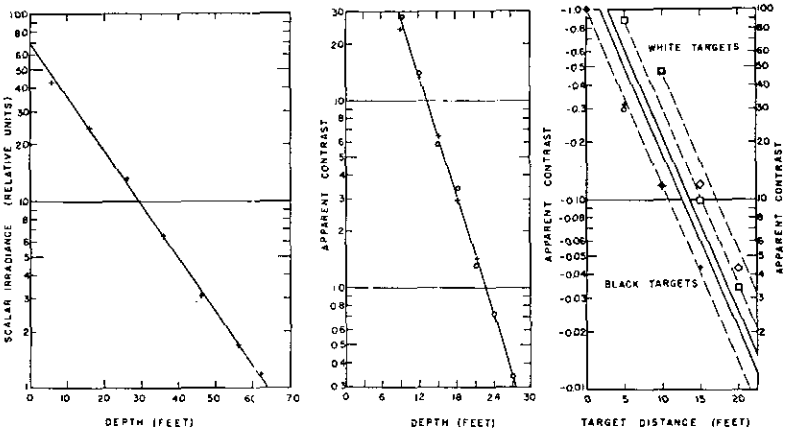

FIG. 30. Interrelated experiments from the September 1948 series at the Diamond Island Field Station: (*Left*) Semilogarithmic depth profile of scalar irradiance obtained by lowering a 6-in.-diameter, air-filled, hollow, translucent, opal glass sphere having a photovoltaic cell sealed in an opening at its bottom. The straightness of the curve indicates optical homogeneity of the water and a depth invariant attenuation coefficient $k(z)=0.066$ ln/ft. (*Center*) Semilogarithmic plot of the absolute apparent contrast of a horizontal, flat, white target lowered vertically beneath a telephotometer mounted in a small, hooded, glass-bottomed boat; calm water, clear sky, low sun. The long, straight portion of the curve illustrates Eq. (15) and its slope indicates that $\alpha(z)+K(z,\pi,0)=0.247$ ln/ft. Because the sun was low the radiance distribution was approximately asymptotic, so that $K(z,\pi,0)\approx k(z)=0.066$ ln/ft and, by subtraction $\alpha(z)=0.181$ ln/ft or the attenuation length $1/\alpha=5.5$ ft/ln. (*Right*) Two semilogarithmic plots of apparent contrast vs target distance along 60°-downward-sloping paths of sight for black targets (lower portion) and white targets (upper portion) have been combined to demonstrate (1) that the apparent contrast is exponentially attenuated with target distance at the same space rate for both light targets and dark targets, (2) that this space rate is independent of azimuth, and (3) that Eq. (16) is valid. All four paths of sight have the same zenith angle, $\theta=150°$, but the azimuth angles relative to the plane of the sun are $\phi=0$ (circled points) and $\phi=45°$ (crosses), $\phi=95°$ (diamonds) and $\phi=135°$ (squares). The dashed straight lines are constructed parallel and, in accordance with Eq. (16), they have a slope $0.181+0.066\cos 150°=0.214$ ln/ft. These lines were passed through the uppermost datum point of each series without regard to the lower points; the lines are provided solely to facilitate judgment of the slope and linearity of the data. Photographic underwater telephotometry; green light, calm water, clear sky, low sun.

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[32] S. Q. Duntley, J. Opt. Soc. Am. 37, 994(A) (1947) and U. S. Patent No. 2,661,650.

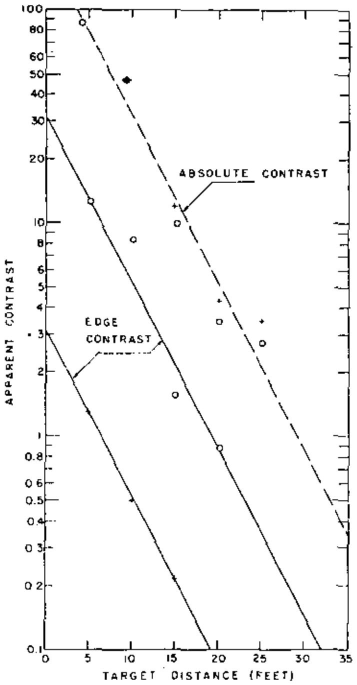

FIG. 31. Comparison of apparent absolute contrast with apparent edge contrast of white targets for two horizontal underwater paths of sight having azimuths relative to the direction of the sun of 95° (crosses) and 135° (circles), respectively. The three lines are parallel and correspond to an attenuation length $1/\alpha=5.65$ ft/ln. The data are of 24 September 1948 at Diamond Island. Photographic telephotometry; green filter.

$\alpha(z)$ is suggested by Eq. (17) and the fact that in optically uniform water ${}_qN(z,\frac{1}{2}\pi,\phi)=N(z,\frac{1}{2}\pi,\phi)$; thus

$$\alpha(z)=N_*(z,\tfrac{1}{2}\pi,\phi)/N(z,\tfrac{1}{2}\pi,\phi). \tag{18}$$

In Eq. (18), $N_*(z,\frac{1}{2}\pi,\phi)$ can be approximated by the apparent radiance of a very black object, such as an opening in a small black box, located at a unit distance which is small compared with the attenuation length, and $N(z,\frac{1}{2}\pi,\phi)$ is the apparent radiance of the unrestricted water background. This technique is especially convenient for documenting conditions in underwater photography by daylight. The value of $\alpha(z)$ so obtained agrees precisely with data obtained by (1) properly designed light beam transmissometers, (2) measurements of the apparent contrast of underwater objects observed along horizontal paths of sight, and (3) underwater telephotometry of the apparent radiance of the surface of a distant submerged frosted incandescent lamp or other diffusely emitting source.

Field experiments. Experimental explorations of the distribution of daylight in the sea and underwater image transmission phenomena were begun by the author in 1948 and are still in progress. Most of the physical principles discussed in this paper were discovered or generalized early in the course of these experiments. The data guided a collaborative development of the foregoing equations by Dr. Rudolph W. Preisendorfer and the author.[33-35]

Experiments were conducted concurrently in lakes and at sea almost from the beginning because optical principles can be explored better and more inexpensively in lakes whereas the magnitude of the optical constants of ocean waters can be measured only at sea. Most of the data used in this paper to illustrate principles were obtained at a field station established by the author in 1948 at Diamond Island in Lake Winnipesaukee, New Hampshire. Examples of data from the field station are provided in Fig. 30. These data, taken from the 1948 series, illustrate several important principles which are implied and summarized by Eq. (16). Figure 30 shows that the attenuation coefficients $k(z)$ and $\alpha(z)$ obtained by means of a depth profile of scalar irradiance and measurements of the apparent radiance of a white object lowered vertically (in the manner of a Secchi disk) can be used with Eq. (16) to predict the apparent contrast of any object, black or white, along various underwater paths of sight. Measurements of apparent contrast with highly refined photoelectric equipment have been made along many paths of sight and under many kinds of lighting conditions in the course of the field station experiments; all of these experiments support the validity of Eqs. (15) and (16).

The water-clarity meter pictured in Fig. 25 produces a profile of scalar irradiance similar to that shown in Fig. 30 and, therefore, a measure of $k(z)$; it also measures the attenuation coefficient $\alpha(z)$, providing, thereby, the necessary input information for using Eq. (16) to calculate contrast reduction, since $K=k(z)$.

Telephotometry of either black or white targets along any two paths of sight having different inclinations (i.e., zenith angle θ) yields two values of the contrast attenuation coefficient $(\alpha-K\cos\theta)$ from which α and K can be found. The use of a horizontal path for determining α, and a downward vertical path for determining $\alpha+K$, is often a convenient choice.

Absolute contrast. The water immediately surrounding a submerged white object sometimes appears to glow. This effect is caused by the intense small-angle forward scattering of light which is reflected by the target in directions adjacent to that of the observer. The effect is most noticeable when a strongly lighted white object is observed against a dark background. The apparent radiance of the scattered glow has been found to be attenuated at the same space rate as the target itself; this is shown by Fig. 31 wherein the semi-logarithmic attenuation curves for apparent *absolute contrast* and apparent *edge contrast* are parallel. Apparent absolute contrast is relative to the apparent background

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[33] S. Q. Duntley, Proc. Armed Forces-Natl. Research Council Vision Committee 23, 123 (1949); 27, 57 (1950); 28, 60 (1951).

[34] S. Q. Duntley and R. W. Preisendorfer, MIT Rept. N5ori 07864 (1952).

[35] R. W. Preisendorfer, Scripps Inst. Oceanog. Ref. 58-42 (1957).

radiance that would be observed if the target were absent; apparent edge contrast is relative to the apparent background radiance which appears immediately adjacent to the target. Ordinarily, few underwater objects are white enough to cause the two types of contrast to differ significantly. When the glow is prominent, absolute contrast is usually the more meaningful measure of object detectability, but a full treatment of this topic can be made only in context with details concerning the characteristics of the detector (eye, camera, etc.), a matter beyond the scope of this paper.

Absorption

If radiant power in the sea is to be useful for heating or for photosynthesis it must be absorbed. The monochromatic radiant power absorbed per unit of volume at any depth depends upon the amount of power received by the volume element and the magnitude of the absorption coefficient; i.e., upon the product of the scalar irradiance and the volume absorption coefficient.[36] A more frequently useful relation[37] has been evolved as follows: The net inward flow of radiant power to any element of volume *dv* in any horizontal lamina of thickness *dz* at depth *z* in the sea is

$$\frac{dP(z)}{dv}=\frac{d}{dz}\{H(z,-)-H(z,+)\}$$
$$=\frac{d}{dz}\left\{H(z,-)\left[1-\frac{H(z,+)}{H(z,-)}\right]\right\}. \quad (19)$$

The ratio $H(z,+)/H(z,-)$, sometimes called the *reflection function* of water, has been found by experiment to be virtually independent of depth and to have a value of 0.02±0.01 for most natural waters unless large quantities of suspended matter are present; the reflection function is rigorously independent of depth when the underwater daylight radiance distribution has its asymptotic form in optically uniform water. To the extent to which 2% effects are negligible, Eq. (19) becomes

$$dP(z)/dv \approx H(z,-)K(z,-), \quad (20)$$

since, by definition, $K(z,-)=-[dH(z,-)/dz]/H(z,-)$. Thus, the radiant power absorbed per unit of volume at any depth in the sea can be measured simply by lowering an upward-facing, diffusely collecting, flat photocell and determining the product of the magnitude and slope of the resulting profile of downwelling irradiance, as illustrated by Fig. 32.

Alternatively, the quantity $\{H(z,-)-H(z,+)\}$ can be measured directly by lowering an assembly of two diffusely collecting, flat photocells mounted back to back so that one faces upward and the other downward. Such an assembly, sometimes called a *janus cell*, can be used to measure $dP(z)/dv$ by means of Eq. (19) in turbid waters for which $\{1-[H(z,+)/H(z,-)]\}$ is not negligible.

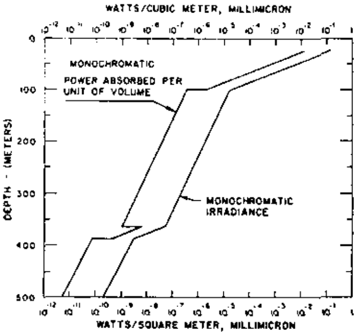

FIG. 32. Superimposed semilogarithmic plots of monochromatic downwelling irradiance vs depth and monochromatic radiant power absorbed per unit of volume vs depth illustrate the (approximate) relation between these quantities expressed by Eq. (20). Monochromatic downwelling irradiance is the total monochromatic radiant power per unit of area received by the upper surface of a horizontal plane at arbitrary depth *z*. The product of this irradiance and its depth attentuation function (slope of its depth profile) is, within about 2%, equal to the monochromatic power absorbed per unit of volume. Thus, at a depth of 50 m in Fig. 32, $H(50,-)=6.3\times10^{-3}$ W/(m², mμ), $K(50,-)=0.114$ ln/m, and $dP(50)/dv\approx(6.3\times10^{-3})(0.114)=7.2\times10^{-4}$ W/(m³, mμ). Neither of the curves in this figure represent specific experimental data, but the irradiance profile is typical of the Pacific Ocean off California. The presence of a deep scattering layer is shown below 350 m.

CONCLUSION

Although no research program is ever fully completed and the author hopes to participate in studies of light in the sea for many years to come, the investigations which, with many colleagues, have been made thus far, coupled with the findings of other workers all over the world, have produced a sufficient quantitative understanding of the optical properties of ocean water and the behavior of underwater light to provide scientific guidance and optical engineering methods for those persons whose interests or occupations involve light in the sea.

ACKNOWLEDGMENTS

The long research program, spanning two decades, from which this paper is drawn has involved too many persons to permit complete acknowledgment here. Special mention should be made, however, of the important technical contributions of Dr. David L. MacAdam, Willard P. Greenwood, Capt. Dayton R. E. Brown, Professor George E. Russell, John Frankovitch, Frederick C. Spooner, Robert W. Sandberg, Walter Rutkowski, Robert J. Uhl, Frances Richey, Dr. Rudolph W. Preisendorfer, Roswell W. Austin, Almerian R. Boileau, John E. Tyler, Justin J. Rennilson, William Hadley Richardson, Dr. William H. Culver, Theodore J. Petzold, Charles W. Saunders, Jr., Sidney Lindroth, Alden D. J. Hooton, Roger A. Howerton, and Clarence Fred Pinkham who, since 1949, has superintended nearly all of the field operations.

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[36] R. W. Preisendorfer, Scripps Inst. Oceanog. Ref. 58-41, (1957).

[37] S. Q. Duntley, Natl. Acad. Sci./Natl. Research Council Publ. 473, 85 (1956).

U. S. NAVAL AIR ENGINEERING CENTER

PHILADELPHIA, PENNSYLVANIA

AEROSPACE CREW EQUIPMENT LABORATORY

The Effects of Various Oxygen Partial Pressures on Scotopic and Photopic Vision

By LCDR T. J. Gallagher, MSC, USN, LCDR R. E. Mammen, MC, USN,
LT F. T. Nobrega, MC, USNR, and LT T. Turaids, MC, USN

NAEC-ACEL-530 26 JULY 1965

NAVAL AIR ENGINEERING CENTER, PHILA., PA. 19112
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37 p., 2 Figs., 19 Tables, 1 App., 26 July 1965.

1. Report NAEC-ACEL-530
2. BUWEPS Problem Assignment No. 005AE13-24
3. BUMED Work Unit MF022.03.02-6001
4. NASA Defense Purchase Request No. T-23829-G
5. Available to U.S. Government Agencies at DDC

To determine the effects of increased oxygen partial pressures on the function of the visual system, human subjects were exposed to 100% oxygen atmospheres at the following pressures and durations: 258 mmHg (27,000 ft) for 72 hr; 380 mmHg (18,000 ft) for 72 hr, and 760 mmHg (sea level) for 24 hr.

The visual functions investigated included: visual acuity, color discrimination, stereopsis, vertical and lateral phoria, critical flicker fusion, retinal perimetry, dark adaptation, electroretinography, and intraocular tension. Examinations were given after 6, 24, 48, and 72 hours exposure to 100% oxygen during the runs conducted at altitude, and at 6 and 24 hours during the sea level run. Control data were also obtained for all of the variables measured while the subjects were breathing air at sea level. No consistent differences from the control values were noted in the visual functions measured as a result of the experimental conditions.

In addition, hematological and biochemical studies were carried out at the same time, including analyses for bilirubin, serum glucose, lipase, hemoglobin, hematocrit, and the following enzymes: NAD, NADP, LDH, ICD, and G-6-P dehydrogenase. No significant changes attributable to the experimental conditions were found.

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ABSTRACT CARD OFFSET MARGINAL GUIDE
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PLATE NO. 583

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ADMINISTRATIVE INFORMATION

The work reported here was done in connection with National Aeronautics and Space Administration Defense Purchase Request T-23829-G of 2 January 1964, concerning the evaluation of the physiological effects of various oxygen partial pressures and durations of exposure on human vision. Authorization for this work was provided by Bureau of Naval Weapons WEPTASK RAE 13C 005/2001/R005 01 01, Problem Assignment No. 005AE13-24 entitled "Effect of Various Oxygen Partial Pressures on Peripheral Vision" and Bureau of Medicine and Surgery Work Unit MF022.02.02-6001 entitled "Physiological Evaluation of Full Pressure Suits." BUPERS letter Pers-A212-mh of 13 September 1963 approved the use of volunteer personnel for this purpose.

The initial proposal and experimental procedure were prepared by CDR George T. Critz, who entered private practice before the beginning of this study. Dr. Arnold Popkin of the University of Pennsylvania assisted in developing the procedures used in obtaining the electroretinograms and performed ophthalmic examinations before and during the study. CDR M. J. Damato and ENS W. L. Gibbs assisted in the collection of data, acted as observers during the runs, and participated in other phases of this study. Dr. C. J. Lambertsen of the University of Pennsylvania was ready at all times to provide his services in case of the development of serious decompression sickness, and successfully treated one of our subjects in a hyperbaric chamber. Mr. Samuel Greco developed the procedure for recording and storing the electroretinograms and personally supervised all recording sessions.

LT L. J. Jenkins and Dr. R. Van Reen, who prepared Appendix A and performed the work described therein, are attached to the Naval Medical Research Institute, National Naval Medical Center, Bethesda, Maryland.

Finally, we wish to express our appreciation to the nine subjects for their willing participation.

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This technical documentary report has been reviewed and is approved.

Henry G Wagner

HENRY G. WAGNER
CAPT, MC, USN
Director

ABSTRACT

To determine the effects of increased oxygen partial pressures on the function of the visual system, human subjects were exposed to 100% oxygen atmospheres at the following pressures and durations: 258 mmHg (27,000 ft) for 72 hr; 380 mmHg (18,000 ft) for 72 hr, and 760 mmHg (sea level) for 24 hr.

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INTRODUCTION

The observation that oxygen at increased pressure may entail toxic effects was made by Priestley and Lavoisier a few years after its discovery. It has been generally recognized since the classical experiments of Paul Bert[1] that oxygen may be a highly toxic gas when administered too abundantly. Thus, it has been shown that at a breathing pressure of one atmosphere or less, the principal toxic effects of oxygen arise in the pulmonary system[2] while a marked disturbance of function of the central nervous system results when oxygen is breathed at pressures greater than one atmosphere[3]. These and other aspects of oxygen toxicity have been comprehensively reviewed by Bean[4] and Stadie et al.[5], among others.

A special aspect of oxygen toxicity is its effect on the visual mechanism. The role of high oxygen environments in the pathogenesis of retrolental fibroplasia is well established[6]. Young animals exposed to 450 to 600 mmHg of oxygen for four days or more show vitreous degeneration, retinal edema, and localized retinal detachment[7,8,9]. Adult rabbits exposed to 100% oxygen for 40 hrs at one atmosphere show disappearance of most of the visual cells on histologic section[10,11]. Men breathing 100% oxygen at three atmospheres develop progressive contraction of the visual fields, dilation of the pupils, and impairment of the central vision after four hours[12]. Inhalation of 100% oxygen for 30 min at sea level results in a reduction in caliber of retinal arteries and veins, which might be interpreted as an autoregulatory mechanism of the retina to protect the tissues from too high a concentration of oxygen[13].

The possible toxic effects of 100% oxygen at a partial pressure less than that at sea level is of concern with future manned spacecraft missions. Consequently, this present study was conducted to further examine the effects of several oxygen partial pressures on various visual functions.

MATERIALS AND METHODS

Nine U.S. naval enlisted men on active duty at the Philadelphia Naval Base volunteered to serve as subjects for this study. All were thoroughly interviewed as to past medical history and underwent a complete physical examination. Eye examinations were conducted by the Opthalmology Department of the University of Pennsylvania Hospital, and included tests for visual acuity, depth perception, heterophoria, accommodation, color vision, perimetry, intraocular tension, and a slit lamp examination. Laboratory studies included an electrocardiogram, chest x-rays, urinalysis, and a complete blood count. All of the above tests were within normal limits except as noted in Table 1. In addition, the subjects were also given the Minnesota Multiphasic Personality Index and Edwards Personal Preference Test. One prospective subject who showed strong paranoid tendencies was dropped from the study; all other subjects had normal test profiles. Those who did not have any previous experience with the altitude chamber, were given two indoctrination runs to 30,000 feet prior to the study. Physical characteristics and significant remarks pertinent to the past history of the subjects chosen are summarized in Table 1.

The experiments were conducted in the Bio-astronautical Test Facility (BATF). The living area of this altitude chamber was formed by an inner rectangular compartment measuring 6' by 6' by 22' which, in turn, was enclosed within an outer pressure shell 10 ft in diameter and 41 ft in length. The pressure between the inner compartment walls and the outer shell was kept slightly less than that within the inner compartment. The double-chamber concept thus assured that the direction of gas leakage was outward from the inner chamber, thus permitting close control of the environmental gas composition within the living compartment. The remainder of the outer shell formed an end compartment, which was used as a work space, and also as an elevator and transfer lock, to permit movement of personnel to and from the "inner chamber." A short tunnel connected the living compartment to the end compartment. Gaseous oxygen derived from a liquid oxygen source was fed into the inner chamber. Mercury manometers and altimeters were used to measure total pressure, which was maintained at a level to ±8 mmHg of the desired pressure. Mean cabin temperature was kept at a level equal to 72°F, and mean relative humidity varied between 25-30%. Carbon dioxide was maintained below 0.2% by flushing oxygen through the chamber periodically. Oxygen and nitrogen concentrations were monitored continuously with a Beckman Model F3 Oxygen Analyzer and a Model 300AR Nitralyzer, respectively. The maximum possible error in these measurements was ±1%, including errors due to changes in water vapor, inaccuracies in determining calibrating gas concentrations, altitude changes, and inherent sensitivity limitations of the equipment. A gas chromatographic system was also employed periodically to evaluate samples of the chamber environment, as well as to determine the purity of the liquid oxygen source. In addition, periodic analyses for oxygen and carbon dioxide were made using the Scholander micrometer gas analyzer. Carbon dioxide was monitored continuously with a Beckman Model L/B Infrared Analyzer.

The original experimental design for this study was modified after the initial test phase because of unexpected subject reactions and other problems, which are described later in this report. Subjects were exposed to 100% oxygen atmospheres at the following pressures and durations: 258 mmHg (27,000 ft) for 72 hr; 380 mmHg (18,000 ft) for 72 hr; 760 mmHg (sea level) for a maximum of 24 hr, or until onset of symptoms of oxygen toxicity; and 258 mmHg (27,000 ft) for 72 hr.

Subjects entered the chamber lock in pairs at 3 hr intervals, following preoxygenation for 30 min at sea level. They continued to breathe oxygen from masks while ascending to an altitude approximately 500 ft in excess of that in the living compartment. After disconnecting from the oxygen supply in the lock, they entered a pass-through tunnel containing a high concentration of oxygen. The altitude in the tunnel was maintained about 200 ft higher than that in the living compartment. After securing the hatch between the tunnel and the lock, the subjects entered the living compartment, which was maintained at one of the 100% oxygen atmospheres indicated above. This procedure, utilizing a gradient of three pressures, was followed for all entrances and exits from the living compartment when at altitude, in order to minimize contamination of the oxygen atmosphere within the latter. For the sea level condition, pressure in the living compartment was adjusted to be about 3 inches of water above ambient.

Tests of visual function were conducted in the chamber lock, and the following procedure was used in all four of the above conditions. Examinations were given after 6, 24, 48, and 72 hours exposure to 100% oxygen at altitude, and after 6 and 24 hours at sea level. The subjects were tested in pairs. After having a blood sample drawn, the subjects donned their oxygen masks and passed through the tunnel into the chamber lock. The examiners immediately connected each subject to an oxygen regulator set on safety pressure. The subjects were first light-adapted for one minute using the Goldmann-Weekers Adaptometer. They then followed each other sequentially through the first three tests: evaluation by the Titmus Vision Tester, critical flicker fusion, and perimetry. Upon completion of these tests, an electroretinogram was taken from the first subject, while the other subject measured his own dark adaptation with the Goldmann-Weekers Adaptometer. The subjects then changed places to complete the test series. The left eye was always used for measuring dark adaptation and the right eye for electroretinogram. Intraocular tension was measured with the Schiotz tonometer using a 5.5 gm plunger head following the last examination period in each condition. X-rays of the chest were taken at the nearby dispensary about 10-15 min after exit from the chamber, with the subjects continuing to breathe 100% oxygen by mask. Films were obtained whenever chest symptoms or a decrease of vital capacity led to a suspicion of atelectasis.

Titmus Vision Tester

This apparatus developed by the Titmus Optical Company was used to test several photopic visual functions described below. Principal internal components of the instrument are a rotatable drum on which 12 stereoscopic test slides are mounted and a pivoted eyepiece which is manually shifted from FAR to NEAR testing. The first eight slides, used to test "far vision," present targets at an optical distance of 20 ft from the subject and an average of 15° below the horizontal. These slides measure the following:

Visual Acuity (Slide 1 - binocular, Slides 2 and 3 - right eye, left eye). The figures used in this test are Landolt "C" Rings arranged in 14 groups of four rings each. The subject's visual acuity is determined by the limit of his ability to locate the solid (unbroken) ring in each group and the test is terminated when the subject makes two successive incorrect identifications. Corrected to Snellen equivalents, a measure of binocular or monocular acuity ranging from 20/200 to 20/13 is obtained.

Stereopsis (Slide 4) measures the subject's ability to judge relative distances when all cues except binocular triangulation are eliminated. In viewing this slide, the right and left images are fused to form an array of 9 groups of 4 circles each, in which one circle in each group appears to "float out" in front of the other circles. The groups are arranged from easy to difficult, and the relative difficulty of each of the nine groups in the series is determined by the disparity of the "key" circle in each group.

Color Discrimination (Slide 5). This test consists of six photographic reproductions of the Ishahari color test plates. It detects the presence of color deficiency, but does not classify as to type. The subject's task is to identify the numerals appearing in the targets.

Vertical Phoria (Slide 6) measures, in terms of prism diopters, the relative posture of the eyes in the vertical plane when all stimuli to binocular fixation are eliminated. In this slide, seven numbered musical notes are seen by the right eye and a series of horizontal red dashes by the left eye. The numbered note through which the red line passes indicates the subject's score on the test. The orthophoria position is note #4, with one-half prism diopters between each of the other notes.

Lateral Phoria (Slide 7) measures, in terms of prism diopters, the relative posture of the eyes in the lateral plane. A series of musical notes numbered from 1 to 15 are exposed to the right eye with five horizontal lines with a prominent arrow at the mid-point to the left eye. The two components when seen binocularly appear to the subject as a bar of music in which the arrow is pointing to one of the fifteen notes. The orthophoria position is note #8 with one prism diopter intervals between notes. Exophoria scores are measured to the right, and esophoria scores to the left, of note #8.

The last four slides to test "near vision" are presented at an optical distance of 14 inches from the subject and approximately 45° below the horizontal. The slides measure visual acuity (binocular, right eye and left eye - slides 9-11) and lateral phoria (slide 12). The method of measurement is the same as for the "far vision" tests.

Critical Flicker Fusion

Critical flicker fusion was determined by a method described by J. L. Brown[14]. The apparatus (Fig. 1) included two Dialco A131002-1735 subminiature transistorized neon lamps, L_p and L_s, with a bias voltage supply and a sine wave voltage generator. One of the lamps, L_s, was illuminated steadily and the other, L_p, was modulated by the sinusoidal voltage at 10 cps. Light from the two lamps combined in a mixing cube, P, after passing through polarizing filters, F_p. The latter were so oriented that the planes of the polarization for the two lamps were orthogonal when the light reached the analyzing filter, F_a. A neutral density filter, F_d, was located in the beam from lamp L_s, in order to balance the light levels from the two lamps at F_a. Rotation of the analyzing filter, F_a, resulted in an increase in transmittance of light from one of the lamps, and a corresponding decrease in transmittance of light from the other lamp. It was thus possible to vary the relative amounts of the modulated light and the steady light over a range in which the combined light appeared steady at one extreme and appeared to flicker at the other.

During each testing period, the subject's task was to adjust the analyzing filter, F_a, from a position where flicker was clearly evident, to a position where it just disappeared, or from a position where the light appeared steady to a position where flicker was just detectable. Each of these settings was made three times. Data were recorded in terms of the angular position of the analyzing filter F_a, as read from a protractor scale.

Perimeter

A one meter Ferree-Rand perimeter, manufactured by Bausch and Lomb, was used to plot the horizontal meridian of the retinal field of the right eye. A "scuba" mouthpiece attached to the chin rest provided a 100% oxygen source. A small mirror was added to the center of the arc, permitting the subject to use the image of his own eye as a fixation point. The test object, a 1° white target, was moved from the center to the periphery of the arc and the subject was instructed to tell the examiner as soon as he noted the disappearance of the object. The target was then moved from the extreme periphery to the center of the arc until the subject reported its appearance. This procedure was followed until twelve determinations were made: six for the nasal retinal field and six for temporal retinal field.

Dark Adaptation

Dark adaptation was measured with the Goldmann-Weekers adaptometer. A "scuba" mouthpiece was attehced in front of the viewing sphere to provide 100% oxygen for the subject. The test area inside the sphere used to measure dark adaptation was 11° in diameter with its center 11° below a small red fixation light. The luminosity of the test field could be varied within 7 logarithmic units with a movable, neutral-density, glass wedge. Initial luminosity was adjustable by means of a diaphragm, and was set to be always 1 lux at the beginning of dark adaptation. An initial three minutes of light adaptation was provided by two, 220-vold, 60-watt bulbs mounted inside the viewing sphere.

Modifications suggested by Gunkel and Bornschein[16] were incorporated into the apparatus to provide for operation of the intensity control by the subject, and recording of results. The original intensity control knob was replaced by a gear driven by a 2-rpm, synchronous, reversible motor. A braking mechanism constituted an integral part of the motor, and prevented movement of the wedge after the motor was de-energized. A spring clutch mounted on the shaft of the motor prevented damage to the mechanism in case of overdriving.

The direction of rotation of the motor, and hence the movement of the glass wedge, was controlled with two switches. One switch raised the wedge, increasing the luminance of the test field. It was locked in the ON position at the beginning of the test. The other, which the subject held in his hand, lowered the wedge, thus reducing the luminance of the test field. When activated, this switch was capable of overriding the former. When the subject could first see the test field after the initial light adaptation, he pressed the switch in his hand, thus gradually reducing the luminance of the test field until he could no longer see it. At this point he released the switch, allowing the other switch to raise the wedge and increase the luminance. When the subject again perceived the test field, he pressed the hand-held switch, reversing the movement of the wedge. This procedure was followed continuously for 35 minutes and threshold was determined as being midway between reversals.

Threshold values were recorded by means of a recording arm coupled to the wedge, indicating on a 7-unit logarithmic chart the luminance of the test field. The chart was secured to a drum which made one revolution every 50 minutes. The original stylus, which marked the chart by perforation, was replaced by a pen giving a continuous record.

To monitor the subject's level of dark adaptation outside the chamber, a 10-turn 10K Helipot was attached to the intensity control shaft. The mechanical movement of the wedge was transferred to electrical output by a voltage divider network of the Helipot, and was recorded on a 10 mv Honeywell "Electronik" strip-chart recorder. The records of the recorder and the recording drum inside the chamber were calibrated by using a luxmeter before each run.

Electroretinogram (ERG)

The apparatus used in obtaining the ERG may be divided into two parts - the visual stimulator and the recording system.

Visual Stimulator - An Anscomatic 11 slide projector was used as the light source. To prevent stray light signals from being picked up by the recording system, the projector was located outside the chamber. The Sylvania CZA 500-watt 25-hour lamps used in the projector were burned approximately one hour before each test period and changed after each experimental condition. A six foot length of Bausch and Lomb flexible, noncoherent fiberoptic light wire embedded in a pressure plug was used to transmit the light into the chamber. The distal end of the light wire was secured in a pantograph and positioned approximately ¼" above the subject's pupil. A sectored disc connected to a 60 rpm, synchronous motor was placed in front of the projector to interrupt the light and deliver a 12 msec stimulus per sec.

A filter holder was located beyond the sectored disc into which were placed Kodak Wratten light filters cemented in "B" glass. A Wratten 25A filter was used to provide the red stimulus, and a Wratten 47 C_5 filter provided the blue stimulus. To reduce the intensity of the light, a 0.60 neutral density filter was also placed in the holder.

A piece of window glass, placed beyond the filter holder at a 45° angle, reflected some of the light into a photo cell connected to the recording system, thus providing a record of the onset and duration of the stimulus.

Two types of ERG runs were recorded: one with a red light flashing in the subject's eye and one with a blue light flashing. A series of runs consisted of three red-light runs, followed by four blue, and then a fourth red. The light flashed every second for one minute with the exception of the third red, which ran for two minutes. A two minute interval of darkness intervened between the red-light runs and a seven minute interval intervened between the blue-light runs. The interval between the third red and first blue run was two minutes, and between the fourth blue and fourth red - thirty seconds. Initially, the subject was exposed for three minutes to steady white light through the fiberoptic light wire. Control recordings were obtained prior to each condition.

Recording System - A Jacobsen scleral electrode with a silver-silver chloride ring manufactured by the O'Brig Laboratories was used as the contact electrode. An opening in the center of the contact electrode permitted the space between the cornea and electrode to be filled with 1% methylcellulose solution, which served as a conducting medium. Adhesive electrodes applied to the subject's forehead and clavicle served as reference and ground electrodes, respectively.

Microdot-Twinax shielded cable was used to conduct signals from the subject to an 8-Channel Offner, Type T, Recorder. One channel, set for DC, was used to record the onset and duration of the stimulus. A second channel, using a one second time constant, recorded the subject's responses. A zero base line was recorded by a third channel. The speed of the recording paper was 50 mm/sec. Simultaneously with the recording on paper, the signals were also recorded on tape by a Sanborn 2000 Tape Recorder. A Textronix Type RM 565 Dual-Beam Oscilloscope was employed to monitor the input to, and the output from, the tape recorder.

Average ERG wave forms were obtained by a computer technique which summated individual responses, with the exception of the first ten, over an entire record in any given series[18]. The first ten responses were omitted in order to permit the eye to adapt and become stabilized. Summation was accomplished by using the photocell record of the stimulus flash as a constant reference for each ERG response. Summation of electroretinogram responses in this fashion tends to average random transients and other noise effects and permits visualization of those aspects of the response which occur regularly. In addition to the average waveforms, a record was also obtained of the relative variability expressed in standard deviation as a function of the time history of the ERG. This provided an immediate index of the relative reliability of a subject's response pattern as a function of time during the response to the stimulus.

Two additional analyses of the ERG responses were carried out in order to be certain that no information content had been overlooked in the visual inspection of average response records. In the first of these[17], the voltage amplitude of the ERG responses in each series was integrated during two timed intervals representing the early and the late part of the ERG. The rationale for this is the fact that the early part of the ERG is a pure representation of the retinal response prior to any secondary effect, such as the eyeblink. It was therefore believed that integration during the early time interval might represent a pure index of the effects of varying oxygen pressures on the retina.

The other analysis computed the power spectral density of the ERG[18]. This analysis broke down the ERG response into its Fourier components and calculated the relative powers as a function of component frequency.

Complete records were examined on each of four subjects following 24 hours of exposure to 100% oxygen at a partial pressure equivalent to 27,000 ft., 18,000 ft., and sea level with both red and blue light stimulation. Records of the ERG response were also obtained under the same experimental conditions with the subjects at sea level breathing air.

Retinal Photography

A *Nikon Fundus camera, using Ektachrome-X* color film, was utilized to obtain retinal photographs of three subjects prior to the second 27,000 ft. run, immediately after descent to sea level while still on 100% oxygen, and one hour after removing the oxygen mask. Negative enlargements, 12 inches in diameter, were made from the color film and the retinal vessels were measured with a caliper and steel rule with 1/64-inch divisions.

RESULTS AND DISCUSSION

The details of the various exposures, and the reactions of individual subjects to these exposures are described in the following paragraphs.

First condition - 100% oxygen at a simulated altitude of 27,000 ft (258 mmHg). Eight subjects were used in this session. The subjects preoxygenated for 30 min before entering the lock and ascending at a rate of 5,000 ft per min to 27,500 ft.

Subject	Hours in Chamber	Observations
JNH	72	No symptoms during run. 1500 ml decrease in vital capacity noted immediately after descent to sea level. Chest x-rays revealed plate-like atelectasis in right middle lobe and left lower lobe.
GEP	72	Pain in right knee shortly after reaching altitude, gradually clearing within first 24 hr.
CNC	7	Removed from chamber because of progressively increasing pain in both knees. Pain disappeared upon descent to sea level.
HTL	½	10 min. after ascent to altitude, this 242 lb man complained of pain in right shoulder. 5 min. later noted increasing pain and numbness over the whole right side of body and shortly thereafter collapsed, apparently losing consciousness. Removed from chamber in a semiconscious state with slurred speech and flaccid paralysis of right arm and leg. Treated in pressure chamber at University of Pennsylvania within the hour and made complete recovery.
HNR	11	In 4 hr complained of chest tightness and dyspnea, relieved somewhat by deep breathing. Blood sample taken after 7 hr showed marked lipemia. 4 hr later, there was even more marked lipemia and subject was removed from chamber.

Subject	Hours in Chamber	Observations
JJC	72	Mild chest tightness early in run, bilateral earaches, occipital headache.
RWM	72	Earaches; slight conjunctival irritation, mild substernal discomfort.
KJC	72	Mild right knee pain and mild G-I upset during first 48 hr.

Second Condition - 100% oxygen at a simulated altitude of 18,000 ft (380 mmHg). Six subjects were used in this condition. Because of the incidence of decompression sickness in the first condition, the rate of ascent to altitude was modified. Subjects preoxygenated at sea level for thirty minutes and then ascended on 100% oxygen at 3000 ft per min to 10,000 ft where they remained for 15 min before continuing to 18,500 ft at 500 ft per min.

Subject	Hours in Chamber	Observations
GEP	72	Wheezing left posterior chest upon descent to sea level.
CNC	72	No complaints
JJC	72	No complaints
RWM	72	Pain left lower chest relieved partly by antacids.
KJC	72	Nasal congestion
DTH	72	Bilateral earaches on descent to sea level. 1700 ml decrease in vital capacity. Chest x-ray revealed bilateral basilar plate-like atelectasis.

Third Condition - 100% oxygen at sea level. Six subjects were used and were to remain in this environment for a period of 24 hr. Chest x-rays of all subjects taken after their exit from the chamber were negative.

Subject	Hours in Chamber	Observations
GEP	24	After 14 hr complained of moderate parasternal chest pain. After 24 hr, chest exam revealed rales at right base. 200 ml decrease in vital capacity.
CNC	24	Conjunctival irritation, dryness of mucous membranes, excessive thirst. 200 ml decrease in vital capacity and slightly decreased breath sound right base after 24 hr.

Subject	Hours in Chamber	Observations
JJC	24	Substernal pain, occipital headache, back pains after the 16th hr. 1300 ml decrease in vital capacity.
RWM	24	Substernal chest pains after 16th hr. Expiratory rhonchi both bases after 24 hr.
KJC	24	Bilat. anterior chest pain - "like smoke inhalation" - after 12 hr. Pain in both shoulders.
DTH	19	Conjunctival irritation and sharp stabbing chest pains increasing in severity after 12 hr. 500 ml decrease in vital capacity.

Fourth Condition - 100% oxygen at a simulated altitude of 27,000 ft (258 mmHg). Because of the difficulties encountered in the first 27,000 ft condition, which resulted in the removal of three subjects and the inability to perform part of the visual examinations, the first experimental condition was repeated.

Subject	Hours in Chamber	Observations
JNH	25	Removed from chamber because of 1600 ml decrease in vital capacity. No respiratory symptoms. X-ray: bilateral basilar atelectasis.
GEP	8	Some shortness of breath and dyspnea. However, removed because of increasing pain in left knee, ankle, and shin.
CNC	5	Increasing pain in right knee progressing to right ankle and hip. Pains disappeared upon return to sea level.
JJC	72	No complaints
RWM	72	Minor earaches, mild conjunctival irritation.
KJC	72	Mild pain in right knee which disappeared after 36th hour.

Tables 2 through 7 give the results of the binocular and monocular visual acuity tests for both "near" and "far" vision. The values, which were obtained as Snellen equivalents, are presented in minutes of visual angle for ease of comparison. The control values are the means of all tests given before and after the four experimental conditions.

Tables 8, 9, and 10 present the results for all of the phoria tests, both lateral and vertical. The values given are deviations, in prism diopters, from the orthophoric position. A minus value is indicative of eso- or hypophoria and a plus value a measure of exo- or hyperphoria.

Tables 11 and 12 are the results of the perimetry test for the horizontal meridian. Each value presented is the mean of six determinations. Targets presented on the subject's nasal side describe the size of the temporal retinal field and those presented temporally describe the nasal retinal field.

Table 13 presents the results for the measurement of CFF. The figures given are the means of six determinations. Three of these were obtained by adjusting the filter from a point where flicker was obviously present to a position where it just disappeared, and three others by going from a position of steady light to a position where flicker was just detectable.

Inspection of the means presented in Tables 2 through 13 for each subject and each group of subjects in all experimental conditions reveals no consistent change as a result of variations in the experimental conditions. The differences obtained between the two 27,000 foot conditions, which were identical except for the preoxygenation time, are as variable as the differences between any of the other experimental conditions.

Data from tests used to measure depth perception and color vision were not quantifiable and could only be inspected to determine if any changes occurred in the number of targets correctly identified. No changes were noted; however, the plates used to measure color vision could be easily memorized, and only gross changes in color discrimination could be detected.

In the analysis of the dark adaptation curves, one minute samples were marked off on each curve for the fifth, tenth, fifteenth, and twentieth minutes. Within each of these one minute samples were several measures of the subject's level of light sensitivity. Approximately half of the scores defined the level where the test target just became apparent (appearance threshold) and half the level at which it ceased to be perceptible (disappearance threshold). The differences between each appearance and disappearance thresholds within the one minute sample were calculated. The mean of these differences was used to represent the level of dark adaptation for the one minute sample. The results presented in Tables 14 through 17 are the differences between the control values and experimental values. The control values used in calculating the difference scores were the means of all tests given before and after the experimental conditions. A minus value indicates an improvement and a plus value a decrement in dark adaptation level. Only the records obtained with the electronic recorder were analyzed and these were not converted to log units.

The results obtained for the tests of dark adaptation indicate a slight improvement in the thresholds as a result of breathing 100% O_2. Although this change is within the normal variation obtained in measurements of dark adaptation and represents a maximum improvement of only 0.5 log units, the consistent lowering of the threshold during the various experimental conditions is probably due to the more exact control exerted over the behavior of the subjects and some improvement as a result of learning. While in the chamber, the subjects had no access to cigarettes or alcohol and their sleep schedule required them to rest frequently. Again, the variability between the two 27,000 foot conditions was as great as for any of the other experimental conditions.

Changes occurring in intraocular tension as a result of the four conditions are presented in Table 18. These values are difference scores between the pre-run value and the value obtained after the last examination period in each condition. A minus value indicates a tension lower than, and a plus value a tension higher than the control value. Although the overall means for all subjects in all conditions show a minimal decrease in intraocular tension, the mean difference scores for the four conditions vary from -6.05 mmHg to +3.03 mmHg. Also, if we examine the difference values for the individual subjects, we find wide variations in the various conditions. This variation is most apparent in the two 27,000 ft conditions where the difference scores for both eyes changed signs. One of the main causes of this variance in the scores for intraocular tension was probably due to the fact that it was necessary to use four different examiners, none of whom had any extensive experience in using the Schiotz tonometer, to obtain these measurements.

The retinal photographs were analyzed by measuring the same three arteries and veins on each photograph. Each artery or vein was measured at the same point using the optic disc or a prominent A-V crossing as a reference. The diameter of the optic disc was the same in all photographs, thus insuring that any changes noted were not due to differences in the focus or the distance at which the pictures were taken. Mean values were obtained for the three arteries and veins measured, and the per cent change from the pre-run photograph calculated for the three subjects who had retinal photographs taken (Table 19). The "post" photographs, taken approximately 15-20 min after the subjects had returned to sea level following the 72 hr exposure, and while still breathing 100% oxygen by mask, show a decrease of 25% in the caliber of the retinal veins and 19% in the arteries. Photographs taken after the subjects had been breathing air for 1 hour show that both the arteries and veins had returned to their normal size. Figure 2 shows retinal photographs of two subjects before and while breathing 100% oxygen.

However, investigations conducted subsequently at this laboratory, indicate that this amount of decrease in the caliber of retinal vessels occurs within 5 min while breathing 100% oxygen at sea level, and that the degree of constriction appears to be directly related to the partial pressure of oxygen. Hence, the changes as noted in this experiment cannot be interpreted to be due to an effect of being in a 100% oxygen environment at 27,000 ft for 72 hr, but rather due to breathing 100% oxygen at sea level for more than 5 min.

The results of electroretinogram measurements showed little effect of breathing 100% oxygen at various partial pressures on this index of visual function. If increased partial pressure of oxygen influences the electroretinogram, its effect should be increasingly apparent in examining records from base-line conditions to 100% oxygen at 27,000 ft, to 18,000 ft, to sea level, respectively. Close scrutiny of the records, however, shows no consistent effect as partial pressure of oxygen, the experimental variable, was increased. This was true for all subjects for both red and blue light stimulation.

A late positive response appeared in one subject which was maximal following 24 hr of exposure to 100% oxygen at sea level. This late positive activity, probably representing eye blink activity, was somewhat reduced in records obtained at 18,000 ft, more reduced in records representing 27,000 ft, and absent in the original base-line data. Additional base-line data obtained at a later time, however, again showed this late positive activity very strikingly and, therefore, any possible significance of this is questionable. In the second 27,000 ft. run, the late positive activity, which appeared only in response to blue light stimulation, was absent.

A striking result in this experiment was the remarkable consistency and the individual distinctiveness in the ERG response for each subject. Results differed in a characteristic way when the stimulus was changed from red to blue light, but when the same stimulus color was used, the wave form of the ERG was constant for a given subject and was quite independent of the experimental condition.

It must be concluded that, as measured in this experiment, the electroretinogram did not reflect any consistent change in the visual function resulting from exposure to various partial pressures of 100% oxygen. Evaluation of data obtained after 6 and 72 hours of exposure did not in any sense alter this conclusion.

This independent electrophysiological index of visual function was thus in accord with the results of the other psychophysiological measurements, including critical flicker fusion, dark adaptation, visual acuity, and retinal perimetry.

Detailed results concerning changes in various blood constituents are described in more detail in Appendix A. However, the findings are summarized below. A complete blood count, fasting blood sugar, lipase, bilirubin, and the following enzymes: NAD, NADH, NADP, NADPH, LDH, ICD, and G-6-P dehydrogenase were determined before, during, and after each experimental condition. There was no evidence of hyperbilirubinemia, and the levels of hemoglobin, hematocrit, and erythrocyte glucose-6-phosphate dehydrogenase remained constant. This indicates that no hemolytic episodes occurred during these exposures. A hyperlipemia, probably secondary to stress, was observed in several subjects during the runs at altitude. In two subjects, an elevation of serum isocitric dehydrogenase (ICD) was observed, the significance of which is questionable. There were no alterations in the levels of serum glucose, lactate dehydrogenase (LDH), or either the oxidized or reduced forms of nicotinamide adenenine dinucleotide (NAD, NADH) or nicotinamide adenine dinucleotide phosphate (NADP, NADPH).

The occurrence of atelectasis in four of the seven subjects was investigated further and reported in reference[19]. Pulmonary function tests revealed that those subjects who developed atelectasis had predisposing factors not detected prior to exposure. A retrospective analysis of pulmonary mechanics allowed description of the mechanism whereby certain individuals seem to have developed atelectasis. In subject JNH, who twice developed atelectasis, the role of inert gas was investigated[20]. In brief, atelectasis was consistently produced in this subject when nitrogen concentration in the oxygen breathed at 27,000 ft was 2.5% or below, and atelectasis was not observed when nitrogen concentration was 5% or above.

It is concluded that breathing 100% oxygen at sea level for 24 hours or at pressures as low as 258 mmHg for 72 hours had no adverse effect on visual function as measured in this experiment.

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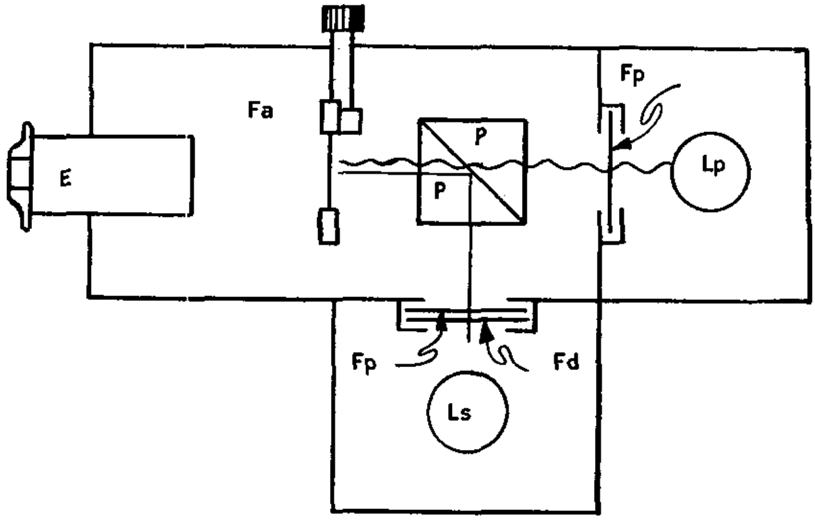

LEGEND:

E = Eyepiece with ground glass window
Fa = Scaled Polaroid Filter
Fd = Kodak 0.6 NDF
Fp = Polarizing Filters
Lp = Pulsating lamp
Ls = Steady lamp
P = 50/50 Beam Splitter Prism

APPARATUS USED IN MEASUREMENT OF CRITICAL FLICKER FUSION

FIGURE 1

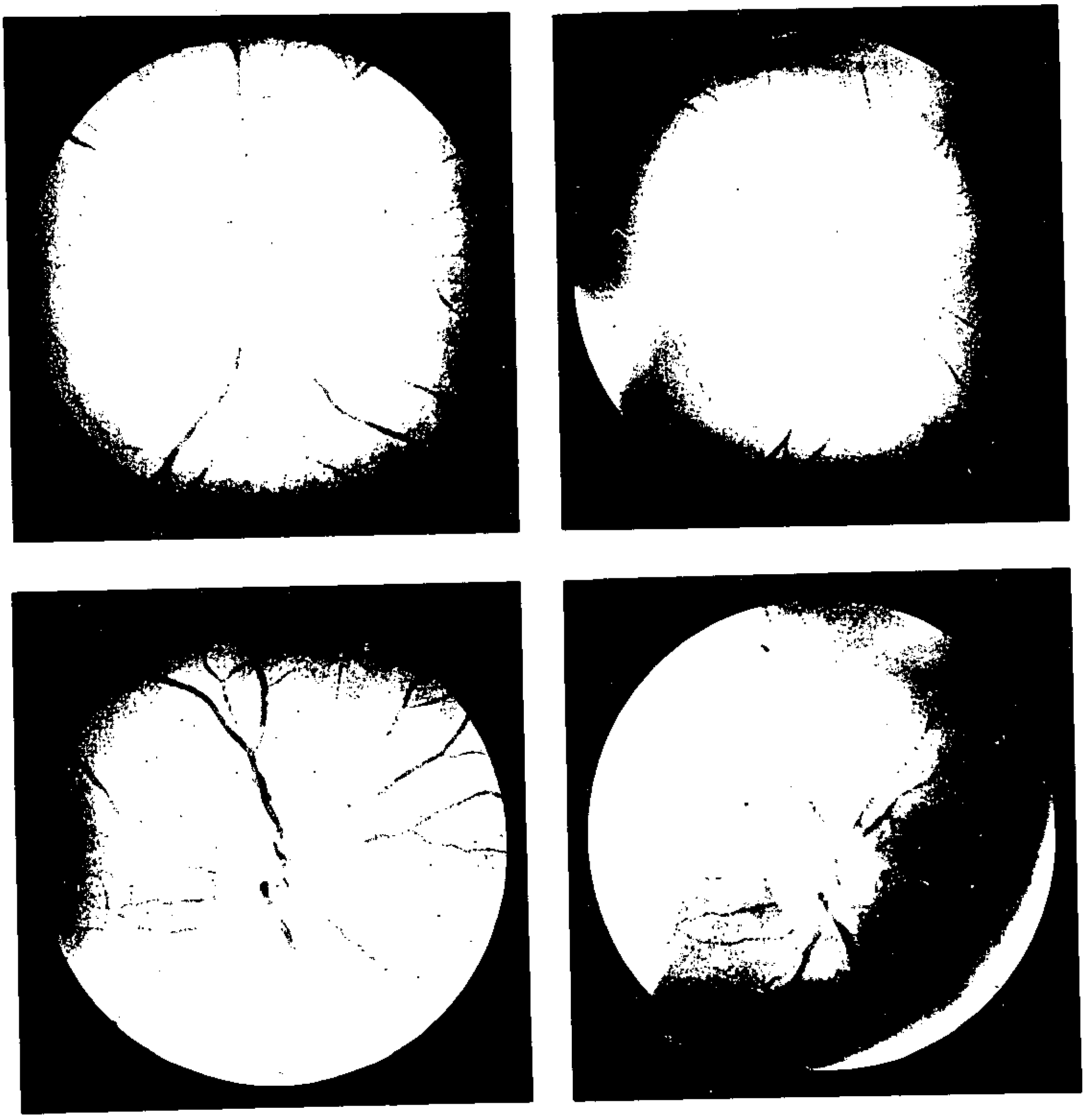

Figure 2 - Retinal photographs of two subjects before (left) and while breathing 100% oxygen (right) showing a decrease in caliber of vessels.

PHOTO NO: CAN-369908(L)-7-65

TABLE 1

CHARACTERISTICS OF TEST SUBJECTS

Subj.	Naval Rate	Age (yr)	Height (in)	Weight (lb)	Physical Examination	Chest X-ray	Comments: Past History
JNH	BMC	38	65	167	Mildly obese	Neg.	Nonsmoker
GEP	SFI	38	65	173	Liver down 1cm Mildly obese	Neg.	Heavy smoker. Moderate to heavy use of EtOH
CNC	ATI	38	68	132	WNL*	Small old scar, left base	20/200 O.D., 20/100 O.S. correct to 20/20 O.U. with lens
HTL	HM2	35	71	242	Obese	Neg.	
DTH	PRC	39	73	217	Mildly obese	Neg.	Operation of rt. shoulder for dislocation
HNR	HM3	23	68	198	WNL	Poss. old histoplasmosis	
JJC	TDAN	19	68	150	WNL	Neg.	History of multiple allergie
RWM	AB3	24	67	160	WNL	Neg.	
KJC	TDAN	24	69	136	WNL	Neg.	

*WNL = Within normal limits

TABLE 2

BINOCULAR VISUAL ACUITY MEASURED IN MINUTES OF VISUAL ANGLE (FAR VISION)

Condition	Subj.	Test Time					
		6 hr.	24 hr.	48 hr.	72 hr.	Mean	Control
27,000 (1)	JJC		.85	.90	1.10	.95	.85
	RWM		.65	.75	.90	.77	.72
	KJC		.75	.90	.65	.77	.65
	GEP	1.10	1.00	1.10	.85	1.01	.88
	JNH	1.50	1.00	1.25	.90	1.16	1.25
	Mean	130	85	9.8	88	.95	.87
27,000 (2)	JJC	.85	1.25	.85	.65	.90	.85
	RWM	.75	.75	.85	.75	.77	.72
	KJC	.65	.65	.65	.65	.65	.65
	GEP	1.00				1.00	.88
	JNH	1.10	1.25			1.17	1.25
	Mean	.87	.97	.78	.68	.84	.87
18,000	JJC	1.00	.90	.90	.85	.91	.85
	RWM	.75	.85	.85	.85	.83	.72
	KJC	.65	.75	.75	.75	.73	.65
	GEP	.85	.85	.65	.85	.80	.88
	CNC	.85	.85	.85	.90	.86	.88
	DTH	.75	.90	.65	.85	.79	.65
	Mean	.85	.85	.77	.84	.82	.77
Sea Level	JJC	.85	.85			.85	.85
	RWM	.75	.85			.80	.72
	KJC	.65	.65			.65	.65
	GEP	.75	1.00			.87	.88
	CNC	.85	.90			.87	.88
	DTH	.65				.65	.65
	Mean	.75	.85			.80	.77

TABLE 3

MONOCULAR VISUAL ACUITY MEASURED IN MINUTES OF VISUAL ANGLE - RIGHT EYE (FAR VISION)

Condition	Subj.	Test Time					
		6 hr.	24 hr.	48 hr.	72 hr.	Mean	Control
27,000 (1)	JJC		.75	.90	1.10	.92	.88
	RWM		1.00	.90	.75	.88	.87
	KJC		.75	.90	.85	.85	.75
	GEP	.90	.90	1.25	.90	.99	.97
	JNH	1.00	1.10	1.00	1.25	1.09	1.25
	Mean	.95	.90	.99	.97	.95	.94
27,000 (2)	JJC	.90	.90	.85	.90	.89	.88
	RWM	.90		.90	.85	.88	.87
	KJC	1.00	.75	.75	.85	.84	.75
	GEP	.90				.90	.97
	JNH	1.00	1.25			1.13	1.25
	Mean	94	.97	.83	.87	.90	.94
18,000	JJC	1.10	.90	.75	1.10	.96	.88
	RWM	.85	.85	.90	1.10	.93	.87
	KJC	.75	.85	.75	.90	.81	.75
	GEP	1.00	1.75	.75	1.00	1.13	.97
	CNC	1.25	1.50	1.50	1.75	1.50	1.08
	DTH	.75	1.00	.90	.65	.83	.65
	Mean	.95	1.14	.93	1.08	1.03	.87
Sea Level	JJC	.85	1.00			.93	.88
	RWM	.90	1.25			1.07	.87
	KJC	.65	.85			.75	.75
	GEP	.75	1.50			1.13	.97
	CNC	1.25	2.50			1.87	1.08
	DTH	.90				.90	.65
	Mean	.88	1.42			1.13	.87

TABLE 4

MONOCULAR VISUAL ACUITY MEASURED IN MINUTES OF VISUAL ANGLE - LEFT EYE (FAR VISION)

Condition	Subj.	Test Time					
		6 hr.	24 hr.	48 hr.	72 hr.	Mean	Control
27,000 (1)	JJC		1.00	1.25	1.25	1.17	.88
	RWM		1.00	1.00	.75	.92	.79
	KJC		.75	.90	.75	.80	.80
	GEP	.85	.90	.85	.90	.87	.97
	JNH	1.25	1.00	1.25	1.25	1.19	1.10
	Mean	1.05	.93	1.05	.98	.99	.91
27,000 (2)	JJC	1.00	1.10	1.10	.65	.96	.88
	RWM	.75	.75	.85	.85	.80	.79
	KJC	.85	.90	.85	.85	.86	.80
	GEP	.85				.85	.97
	JNH	1.75	1.00			1.37	1.10
	Mean	1.04	.94	.93	.78	.94	.91
18,000	JJC	1.10	.90	1.10	1.10	1.05	.88
	RWM	.90	1.00	.90	1.00	.95	.79
	KJC	.75	.85	.85	.90	.84	.80
	GEP	.90	.90	.75	.65	.80	.97
	CNC	.90	1.00	.75	1.00	.91	.88
	DTH	.65	1.00	.75	.65	.76	.75
	Mean	.87	.94	.85	.88	89	.85
Sea Level	JJC	1.50	1.25			1.37	.88
	RWM	.85	1.25			1.05	.79
	KJC	.65	.75			.70	.80
	GEP	.75	1.25			1.00	.97
	CNC	.90	.85			.87	.88
	DTH	.75				.75	.75
	Mean	.90	1.07			.98	.85

TABLE 5

BINOCULAR VISUAL ACUITY MEASURED IN MINUTES OF VISUAL ANGLE (NEAR VISION)

Condition	Subj.	Test Time					
		6 hr.	24 hr.	48 hr.	72 hr.	Mean	Control
27,000 (1)	JJC		.85	.85	.85	.85	.80
	RWM		.75	.85	.75	.78	.65
	KJC		.65	.85	.75	.75	.72
	GEP	.90	.75	.75	.85	.81	.72
	JNH	1.50	.85	1.25	.90	1.13	1.38
	Mean	1.20	.77	.91	.82	.88	.85
27,000 (2)	JJC	1.00	.90	.85	.65	.85	.80
	RWM	.65	.65	.75	.75	.70	.65
	KJC	.75	.75	.75	.75	.75	.72
	GEP	.75				.75	.72
	JNH	1.00	1.00			1.00	1.38
	Mean	.83	.83	.78	.72	.80	.85
18,000	JJC	.85	.75	.90	1.00	.87	.80
	RWM	.75			.85	.80	.65
	KJC	.75	.90	.75	.75	.79	.72
	GEP	.75	1.00	.90	.75	.85	.72
	CNC	.75	.75	.85	.75	.77	.75
	DTH	.75	.65	1.00	.65	.76	.75
	Mean	.87	.81	.88	.79	.81	.73
Sea Level	JJC	.90	.85			.87	.80
	RWM	.75	.75			.75	.65
	KJC	.75	.75			.75	.72
	GEP	.75	.85			.80	.72
	CNC	.85	1.00			.93	.75
	DTH	.90				.90	.75
	Mean	.82	.84			.83	.73

TABLE 6

MONOCULAR VISUAL ACUITY MEASURED IN MINUTES OF VISUAL ANGLE - RIGHT EYE (NEAR VISION)

Condition	Subj.	Test Time					
		6 hr.	24 hr.	48 hr.	72 hr.	Mean	Control
27,000 (1)	JJC		.90	.90	1.25	1.02	.82
	RWM		.85	1.00	.75	.87	.65
	KJC		.65	.90	.85	.80	.83
	GEP	1.00	.90	1.00	1.00	.97	1.05
	JNH	1.75	1.25	2.00	2.00	1.75	1.55
	Mean	1.37	.91	1.16	1.17	1.11	.98
27,000 (2)	JJC	.90	1.00	1.50	1.00	1.10	.82
	RWM	.90	1.00	1.50	1.00	1.10	.65
	KJC	.90	.90	.90	1.25	.99	.83
	JNH	1.00	2.00			1.50	1.55
	Mean	1.04	1.23	1.30	1.08	1.15	.98
18,000	JJC	.90	.90	.90	1.00	.93	.82
	RWM	.75	.75	.90	.90	.83	.65
	KJC	.90	1.00	1.00	1.00	.97	.83
	GEP	1.25	1.10	.90	.90	1.04	1.05
	CNC	.90	.90	.90	1.00	.93	.80
	DTH	.65	1.00	1.50	1.00	1.04	.65
	Mean	.89	.94	1.02	.97	.95	.80
Sea Level	JJC	.90	1.50			1.20	.82
	RWM	.90	1.50			1.20	.65
	KJC	.85	.90			.87	.83
	GEP	.65	1.10			.87	1.05
	CNC	1.00	1.25			1.13	.80
	DTH	.90				.90	.65
	Mean	.87	1.25			1.04	.80

TABLE 7

MONOCULAR VISUAL ACUITY MEASURED IN MINUTES OF VISUAL ANGLE - LEFT EYE (NEAR VISION)

Condition	Subj.	Test Time					
		6 hr.	24 hr.	48 hr.	72 hr.	Mean	Control
27,000 (1)	JJC		.65	1.25	.90	.93	1.13
	RWM		.90	1.10	.75	.92	.80
	KJC		.90	.90	.90	.90	.82
	GEP	.90	.90	.75	.75	.83	.97
	JNH	1.10	.90	1.10	1.75	1.21	1.07
	Mean	1.00	.85	1.02	1.01	96	.96
27,000 (2)	JJC	.85	1.50	1.10	.85	1.07	1.13
	RWM	.85	.75	.90	.75	.81	.80
	KJC	.90	.85	.90	.90	.89	.82
	GEP	.85				.85	.97
	JNH	1.10	1.25			1.17	1.07
	Mean	.91	1.09	.97	.83	.95	.96
18,000	JJC	1.25	1.10	1.00	.90	1.06	1.13
	RWM	.90	.85	.90	1.00	.91	.80
	KJC	.90	.90	.90	.90	.90	.82
	GEP	.90	1.00	.90	.65	.86	.97
	CNC	1.10	.85	.85	.90	.93	.85
	DTH	.90	.90	1.00	.75	.89	.65
	Mean	.99	.93	.93	.85	.93	.87
Sea Level	JJC	1.50	.90			1.20	1.13
	RWM	.85	.85			.85	.80
	KJC	.75	1.00			.87	.82
	GEP	.85	.90			.87	.97
	CNC	.85	.85			.85	.85
	DTH	.90				.90	.65
	Mean	.95	.90			.93	.87

TABLE 8

VERTICAL PHORIA MEASURED IN PRISM DIOPTERS (FAR VISION)

Condition	Subj.	Test Time					
		6 hr.	24 hr.	48 hr.	72 hr.	Mean	Control
27,000 (1)	JJC		0	0	0	0	0
	RWM		0	0	0	0	0
	KJC		0	0	0	0	0
	GEP	0	0	0	0	0	0
	JNH	-1.0	-.5	-1.0	-.5	-.75	-1.5*
	Mean	- .50	-.10	- .20	-.10	-.15	- .30
27,000 (2)	JJC	0	0	0	0	0	0
	RWM	0	0	0	0	0	0
	KJC	0	0	0	0	0	0
	GEP	0				0	0
	JNH	- .5	-.5			-.5	-1.5
	Mean	- .10	-.13	0	0	-.07	- .30
18,000	JJC	0	0	0	0	0	0
	RWM	0	+.5	0	0	+.13	0
	KJC	0	0	0	0	0	0
	GEP	0	0	0	0	0	0
	CNC	0	0	0	0	0	0
	DTH	0	0	0	0	0	0
	Mean	0	+.08	0	0	+.02	0
Sea Level	JJC	0	0			0	0
	RWM	0	0			0	0
	KJC	0	0			0	0
	GEP	0	0			0	0
	CNC	0	0			0	0
	DTH	0				0	0
	Mean	0	0			0	0

TABLE 9

LATERAL PHORIA MEASURED IN PRISM DIOPTERS (FAR VISION)

Condition	Subj.	Test Time					
		6 hr.	24 hr.	48 hr.	72 hr.	Mean	Control
27,000 (1)	JJC		+2	+2	+2	+2	+2
	RWM		+2	0	+2	+1.3	+ .67
	KJC		+2	+1	+1	+1.3	+ .67
	GEP	+1	+1	+1	+1	+1	+1.33
	JNH	+1	+1	+1	+1	+1	+2
	Mean	+1	+1.6	+1	+1.4	+1.3	+1.33
27,000 (2)	JJC	+1	+2	+2	+1	+1.5	+2.0
	RWM	+1	+1	+1	0	+ .75	+ .67
	KJC	+1	+1	+1	+1	+1	+ .67
	GEP	+1				+1	+1.33
	JNH	+1	+1			+1	+2.0
	Mean	+1	+1.25	+1.33	+ .67	+1.07	+1.33
18,000	JJC	+2	+2	+2	+2	+2	+2.0
	RWM	+1		+1	+2	+1.33	+ .67
	KJC	+1	+1	+1	+1	+1	+ .67
	GEP		+1	+1	+1	+1	+1.33
	CNC	-1	-1	-1	0	- .75	0
	DTH	+1	+1	+1	+1	+1	+1.5
	Mean	+.8	+ .8	+ .83	+1.17	+ .91	+1.03
Sea Level	JJC	+2	+2			+2	+2.0
	RWM	+2	+2			+2	+ .67
	KJC	+1	+1			+1	+ .67
	GEP	+1	+1			+1	+1.33
	CNC	-1	-1			-1	0
	DTH	0				0	+1.5
	Mean	+.83	+1			+ .91	+1.03

TABLE 10

LATERAL PHORIA MEASURED IN PRISM DIOPTERS (NEAR VISION)

Condition	Subj.	Test Time					
		6 hr.	24 hr.	48 hr.	72 hr.	Mean	Control
27,000 (1)	JJC		-1	-1	-1	-1.00	-1.00
	RWM		0	0	-1	- .33	- .67
	KJC			-1	-3	-2.00	-2.33
	GEP	-1	0	-1	-1	- .75	-1.00
	JNH	0	-1	0	-1	- .50	-0.50
	Mean	- .50	- .50	- .60	-1.40	-0.81	-1.10
27,000 (2)	JJC	-1	0	-1	-1	- .75	-1.00
	RWM	-2	-0	-0	-1	- .75	-0.67
	KJC	-2	-2	-3	-2	-2.25	-2.33
	GEP	-1				-1.00	-1.00
	JNH	0	0			0	-0.50
	Mean	-1.20	- .50	-1.33	-1.33	-1.07	-1.10
18,000	JJC	0	-1	-1	-1	- .75	-1.00
	RWM	-1	-1	-2	-1	-1.25	-0.67
	KJC	-1	-2	-2	-2	-1.75	-2.33
	GEP	-2	0	-1	-1	-1.33	-1.00
	CNC	-2	-1	-2	-2	-1.75	-2.00
	DTH	+2	+3	+4	+3	+3.00	+3.00
	Mean	- .67	- .33	- .67	- .67	- .58	- .67
Sea Level	JJC	-2	-1			-1.50	-1.00
	RWM	-1	-1			-1.00	-0.67
	KJC	-2	-1			-1.50	-2.33
	GEP	-1	-1			-1.00	-1.00
	CNC	-2	-2			-2.00	-2.00
	DTH	+2				+2.00	+3.00
	Mean	-1.00	-1.20			-1.09	- .67

TABLE 11

TEMPORAL RETINAL FIELD IN DEGREES FOR THE HORIZONTAL MERIDIAN

Condition	Subj.	Test Time					
		6 hr.	24 hr.	48 hr.	72 hr.	Mean	Control
27,000 (1)	JJC		47	59	52	53	56
	RWM		61	62	62	62	58
	KJC		52	55	55	51	55
	GEP	65	56	57	60	59	64
	JNH	58	60	58	67	61	63
	Mean	62	55	58	59	58	59
27,000 (2)	JJC	53	54	57	58	55	56
	RWM	58	58	59	63	59	58
	KJC	53	50	50	58	53	55
	GEP	57				57	64
	JNH	59	62			61	63
	Mean	56	56	55	60	57	59
18,000	JJC	47	47	51	50	49	56
	RWM	60	57	56		58	58
	KJC	51	58	51	56	54	55
	GEP	57	58	57	54	57	64
	CNC	56	53	57	53	55	62
	DTH	44	52	50	52	49	54
	Mean	53	54	54	53	53	58
Sea Level	JJC	48	49			49	56
	RWM	57	56			57	58
	KJC	57	60			59	55
	GEP	55	63			59	64
	CNC	60	55			58	62
	DTH	54				54	54
	Mean	55	57			56	58

TABLE 12

NASAL RETINAL FIELD IN DEGREES FOR THE HORIZONTAL MERIDIAN

Condition	Subj.	Test Time					
		6 hr.	24 hr.	48 hr.	72 hr.	Mean	Control
27,000 (1)	JJC		87	86	87	87	85
	RWM		79	77	79	78	84
	KJC		88	79	84	84	90
	GEP	84	81	79	82	81	85
	JNH	85	78	82	86	83	86
	Mean	85	83	81	84	83	86
27,000 (2)	JJC	89	87	89	88	88	85
	RWM	88	85	84	84	85	84
	KJC	91	90	90	89	90	90
	GEP	89				89	85
	JNH	86	90			88	86
	Mean	89	88	88	87	88	86
18,000	JJC	79	84	89	83	84	85
	RWM	84	81	85		83	84
	KJC	88	90	88	90	89	90
	GEP	81	82	81	86	83	85
	CNC	80	75	81	81	79	87
	DTH	78	75	75	76	76	81
	Mean	82	81	83	83	89	85
Sea Level	JJC	90	89			89	85
	RWM	85	80			83	84
	KJC	89	88			89	90
	GEP	83	84			84	85
	CNC	81	80			81	87
	DTH	81				81	81
	Mean	85	84			85	85

TABLE 13

CRITICAL FLICKER FUSION IN DEGREES OF FILTER ROTATION

Condition	Subj.	Test Time					
		6 hr.	24 hr.	48 hr.	72 hr.	Mean	Control
27,000 (1)	JJC			52	54	53	59
	RWM			60	55	57	56
	KJC			43	38	41	46
	GEP	35	41	40	44	40	38
	JNH	33	36	42	58	42	35
	Mean	34	39	47	50	45	47
27,000 (2)	JJC	61	64	63	65	63	59
	RWM	60	565	60	57	58	56
	KJC	48	45	55	51	50	46
	GEP	37				37	38
	JNH	45	39			42	35
	Mean	50	51	59	58	54	47
18,000	JJC	59	63	59	63	61	59
	RWM	58	60	52	53	56	56
	KJC	41	45	41	45	43	46
	GEP	37	53	29	37	39	38
	CNC	29	28	28	35	30	33
	DTH	39	25	45	40	37	53
	Mean	44	46	42	46	44	47
Sea Level	JJC	61	64			63	59
	RWM	54	55			55	56
	KJC	53	58			55	46
	GEP	38	32			35	38
	CNC	36	35			35	33
	DTH	40				40	53
	Mean	47	49			48	47

TABLE 14

DIFFERENCES BETWEEN CONTROL AND EXPERIMENTAL VALUES DURING THE FIFTH MINUTE OF DARK ADAPTATION

	6th Hour					24th Hour				
Subj.	27,000	27,000	18,000	S.L.	Mean	27,000	27,000	18,000	S.L.	Mean
JJC	- 2.30	- 9.79	+ 0.58	-11.03	- 5.63	- 0.11	-16.55	- 3.82	-17.76	- 9.56
RWM		- 6.20	+ 3.83	- 6.56	- 2.98	+ 0.15	- 1.27	+ 0.07	- 2.56	- 0.90
KJC		- 4.39	+ 1.36	- 0.24	- 1.09	+ 1.70	+ 1.59	+ 3.33	+ 0.56	+ 1.79
GEP	+11.01	+ 5.91	+17.85	+10.80	+11.39	+13.11		+17.26	+10.11	+13.49
JNH	- 6.32	-12.85			- 9.59	- 9.18	-10.41			- 9.79
CNC			- 3.78	-23.35	-13.57			- 9.24	-10.24	- 9.74
DTH	--	--	--	--	--	--	--	--	--	--
Mean	+ 0.80	- 5.46	+ 3.97	- 6.08	- 1.97	+ 1.13	- 6.66	- 1.52	- 3.98	- 1.75
	48th Hour					72nd Hour				
JJC	- 6.69	-11.89	- 6.76	--	- 8.45	- 5.49	-15.54	-18.35	--	-13.13
RWM	- 4.75	- 4.19	- 0.93	--	- 3.29	+ 4.60	- 9.72	- 2.70	--	- 2.61
KJC	--	+ 3.54	+ 0.20	--	+ 1.87	+ 5.85	+ 7.66	+ 3.86	--	+ 5.79
GEP	+15.36	--	+16.38	--	+15.87	+14.11	--	+16.55	--	+15.33
JNH	- 8.10	--	--	--	- 8.10	- 9.22	--	--	--	- 9.22
CNC	--	--	- 4.24	--	- 4.24	--	--	- 3.69	--	- 3.69
DTH	--	--	--	--	--	--	--	--	--	--
Mean	- 1.05	- 4.18	+ 0.93	--	- 1.01	+ 1.97	- 5.87	- 0.87	--	- 0.93

TABLE 15

DIFFERENCES BETWEEN CONTROL AND EXPERIMENTAL VALUES DURING THE TENTH MINUTE OF DARK ADAPTATION

			6th Hour					24th Hour		
Subj.	27,000	27,000	18,000	S.L.	Mean	27,000	27,000	18,000	S.L.	Mean
JJC	+ 1.69	- 3.41	+ 2.76	- 6.85	- 1.45	- 0.07	-11.46	+ 4.90	-22.53	- 7.29
RWM	--	- 4.67	+ 4.62	- 7.13	- 2.39	+ 2.62	+ 5.17	+ 4.65	- 0.55	+ 2.97
KJC	--	+ 6.64	+12.39	+10.79	+ 9.94	- 2.59	- 2.08	- 1.88	- 1.62	- 2.04
GEP	+ 5.44	- 1.60	+ 8.27	+ 5.68	+ 4.45	+ 8.85	--	+ 7.54	+ 8.11	+ 8.17
JNH	- 7.44	-12.13	--	--	- 9.79	-10.44	-10.41	--	--	-10.41
CNC	--	--	- 6.82	--	- 6.82	--	--	- 7.43	- 9.24	- 8.33
DTH	--	--	--	--	--	--	--	--	--	--
Mean	- 0.10	- 3.03	+ 4.24	+ 2.49	+ 0.48	+ 0.33	- 4.69	+ 1.56	- 5.17	- 2.02
			48th Hour					72nd Hour		
JJC	- 2.29	- 5.93	- 1.53	--	- 3.25	- 2.83	-20.19	- 8.13	--	-10.38
RWM	- 0.13	- 1.58	- 2.58	--	- 1.43	+ 0.42	- 0.04	- 7.19	--	- 2.27
KJC	--	- 2.55	+ 0.99	--	- 0.78	+ 2.76	+ 1.20	- 5.21	--	- 0.42
GEP	+ 5.15	--	+ 6.90	--	+ 6.03	+ 7.15	--	+ 7.05	--	+ 7.10
JNH	- 7.11	--	--	--	- 7.11	- 7.53	--	--	--	- 7.53
CNC	--	--	- 1.36	--	- 1.36	--	--	+ 0.96	--	+ 0.96
DTH	--	--	--	--	--	--	--	--	--	--
Mean	- 1.09	- 3.35	+ 0.48	--	- 1.01	- 0.01	- 6.34	- 2.50	--	- 2.43

TABLE 16

DIFFERENCES BETWEEN CONTROL AND EXPERIMENTAL VALUES DURING THE FIFTEENTH MINUTE OF DARK ADAPTATION

	6th Hour					24th Hour				
Subj.	27,000	27,000	18,000	S.L.	Mean	27,000	27,000	18,000	S.L.	Mean
JJC	+ 3.86	- 2.37	- 1.03	- 0.92	- 0.11	+ 3.95	+ 0.12	+ 0.53	-14.13	- 4.68
RWM	--	- 5.63	+ 0.87	- 7.76	- 4.17	- 1.45	- 0.18	+ 0.17	- 2.00	- 8.65
KJC	--	- 4.08	- 7.16	- 2.64	- 4.62	--	- 4.04	--	- 3.85	- 3.95
GEP	- 4.05	- 8.91	- 2.24	- 3.12	- 4.58	+ 0.02	--	- 1.76	- 2.16	- 1.30
JNH	- 7.27	-13.70	--	--	-10.49	-10.12	-15.74	--	--	-12.93
CNC	--	--	- 5.29	- 5.92	- 5.61	--	--	- 8.84	- 8.29	- 8.57
DTH	--	--	--	--	--	--	--	--	--	--
Mean	- 2.49	- 6.94	- 2.97	- 4.07	- 4.30	- 1.90	- 4.96	- 2.48	- 6.09	- 3.99
	48th Hour					72nd Hour				
JJC	- 2.22	- 3.28	- 4.65	--	- 3.38	- 5.00	-17.25	- 7.65	--	- 9.97
RWM	+ 3.22	- 3.90	- 5.00	--	- 1.89	+ 3.09	- 7.33	- 3.16	--	- 2.47
KJC	--	--	- 4.95	--	- 4.95	- 1.07	- 0.78	--	--	- 0.93
GEP	+ 3.26	--	- 5.13	--	- 0.93	+ 1.42	--	- 5.13	--	- 1.85
JNH	- 5.78	--	--	--	- 5.78	- 7.50	--	--	--	- 7.50
CNC	--	--	- 5.24	--	- 5.24	--	--	- 2.46	--	- 2.46
DTH	--	--	--	--	--	--	--	--	--	--
Mean	- 0.38	- 3.59	- 4.99	--	- 3.06	- 1.81	- 8.45	- 4.60	--	- 4.40

TABLE 17

DIFFERENCES BETWEEN CONTROL AND EXPERIMENTAL VALUES DURING THE TWENTIETH MINUTE OF DARK ADAPTATION

			6th Hour					24th Hour		
Subj.	27,000	27,000	18,000	S.L.	Mean	27,000	27,000	18,000	S.L.	Mean
JJC	- 1.49	- 4.46	- 6.91	--	- 4.29	- 0.11	- 2.27	- 3.15	-11.18	- 4.17
RWM	--	- 5.05	- 1.15	- 4.01	- 3.40	+ 2.43	- 4.26	- 1.93	- 0.91	- 1.17
KJC	--	- 0.55	- 6.41	+ 1.80	- 1.72	- 3.53	- 0.05	--	- 6.57	- 3.38
GEP	--	- 6.63	+ 0.04	- 0.84	- 2.48	- 0.33	--	- 2.63	- 4.13	- 2.36
JNH	- 7.27	- 9.55	--	--	- 8.41	-10.29	- 9.03	--	--	- 9.66
CNC	--	--	- 9.93	- 7.88	- 8.90	--	--	- 7.09	- 6.63	- 6.86
DTH	--	--	--	--	--	--	--	--	--	--
Mean	- 4.38	- 5.25	- 4.87	- 2.73	- 4.39	- 2.37	- 3.90	- 3.70	- 5.88	- 3.98
			48th Hour					72nd Hour		
JJC	- 6.79	+ 0.24	- 4.76	--	- 3.77	- 3.99	-15.18	- 7.75	--	- 8.97
RWM	+ 2.87	- 3.96	- 6.63	--	- 2.57	+ 0.53	- 7.46	- 7.71	--	- 4.88
KJC	--	- 6.91	- 5.71	--	- 6.31	+ 0.09	- 1.41	--	--	- 0.66
GEP	+ 0.02	--	- 4.13	--	- 2.05	+ 3.52	--	- 3.99	--	- 0.23
JNH	- 6.29	--	--	--	- 6.29	- 7.91	--	--	--	- 7.91
CNC	--	--	- 3.48	--	- 3.48	--	--	- 3.17	--	- 3.17
DTH	--	--	--	--	--	--	--	--	--	--
Mean	- 2.55	- 3.54	- 4.94	--	- 3.74	- 1.55	- 8.02	- 5.66	--	- 4.54

TABLE 18

DIFFERENCES BETWEEN CONTROL AND EXPERIMENTAL VALUES OF INTRAOCULAR TENSION IN mm HG

Condition

Right Eye

Subj.	27,000 (1)	27,000 (2)	18,000	S.L.	Mean
JJC	+ 2.7	+ 2.4	0	--	+1.70
RWM	+ 4.3	- 3.8	-4.4	+6.0	+0.53
KJC	-10.2	+ 3.3	0	--	-2.30
GEP	- 9.5	--	-1.6	--	-5.55
JNH	- 3.70	--	--	--	-3.70
CNC	--	--	-2.4	+9.8	+3.70
DTH	--	--	--	-6.7	-6.70
Mean	- 2.13	+ 0.63	-1.68	+3.03	-0.86

Left Eye

Subj.	27,000 (1)	27,000 (2)	18,000	S.L.	Mean
JJC	0	0	+6.0	--	+2.00
RWM	- 1.4	-10.8	+1.6	-2.7	-3.33
KJC	- 3.7	- 1.3	-4.7	--	-3.23
GEP	+ 1.6	--	-5.1	--	-1.75
JNH	+ 5.1	--	--	--	+5.10
CNC	--	--	-4.4	+2.7	-0.85
DTH	--	--	--	0	0
Mean	+ 0.32	- 6.05	-1.32	0	-1.14

TABLE 19

PER CENT CHANGE IN DIAMETER OF RETINAL ARTERIES AND VEINS POST 27,000 FT. (2) CONDITION AND AFTER BREATHING AIR FOR ONE HOUR

Veins

Subj.	Post	1 hr. Post
RWM	-28.00%	0%
KJC	-28.23%	0%
JJC	-19.53%	0%
Mean	-25.25%	0%

Arteries

Subj.	Post	1 hr. Post
RWM	-23.30%	-3.30%
KJC	-21.44%	+3.64%
JJC	-13.30%	0%
Mean	-19.35%	+0.13%

APPENDIX A

HEMATOLOGICAL AND BIOCHEMICAL EFFECTS OF EXPOSURE TO AN ATMOSPHERE OF 100% OXYGEN

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HEMATOLOGICAL AND BIOCHEMICAL EFFECTS OF EXPOSURE TO AN ATMOSPHERE OF 100% OXYGEN

Lawrence J. Jenkins, Jr., and Robert Van Reen

Several reports have appeared in the recent literature describing physiological effects of an atmosphere of 100% oxygen at altitudes varying from sea level to over thirty thousand feet. Many of these papers, especially those describing pulmonary and visual changes, have already been discussed in this report. Several investigations have been concerned with functions that were other than pulmonary or visual and could be measured or detected in the peripheral blood of the subjects concerned.

Helvy _et al_. (1) exposed a group of medical student volunteers to an atmosphere of 100% oxygen at simulated altitudes of 18,000, 27,000, and 33,000 ft. for a period of two weeks. They found that the serum electrolyte levels, blood glucose, and urea nitrogen concentrations were essentially unchanged during the course of their experiments. They reported many hematological changes in their subjects, notably, a drop in hemoglobin concentration, an elevation of the reticulocyte count, hyperbilirubinemia, and in general, a picture that was compatible with erythrocyte hemolysis.

Hall and Kelly (2) carried on an experiment in which two 24-year-old Navy enlisted men were maintained in an atmosphere of 100% oxygen for a period of five days. They reported no significant changes in the blood constituents which they measured, including cell counts, hemoglobin

APPENDIX A

and hematocrit determinations, as well as the measurement of blood glucose and the serum electrolytes. They also included the determination of serum glutamic oxaloacetic transaminase as an index of tissue necrosis and found no alterations in the activity of the enzyme.

More recently, Zalusky _et al_. (3) conducted an experiment to further evaluate the effect of an increased partial pressure of oxygen on hematopoiesis. In the course of their investigations, they used an atmosphere approaching 100% oxygen (98.5%) and found a slight drop in the hematocrit of 9.1% in that group. They also report a drop in packed erythrocyte volume of approximately 6.7% in a group of subjects that was exposed to a slightly higher oxygen partial pressure but in an atmosphere of only 33% oxygen. Except for these deviations, the hematologic picture of their subjects was essentially unchanged. In order to determine if hemolysis was occurring, they subjected the erythrocytes of their subjects to the glutathione stability test and to the assay of glucose-6-phosphate dehydrogenase (G6PD). These criteria showed no change during the course of a thirty-day experiment, which led them to the conclusion that hemolysis was not occurring. The ages of their subjects were between 18 and 24 years.

Morgan _et al_. (4) (5) have conducted a series of experiments involving varying conditions of altitude and atmospheric oxygen. In the first series of experiments (4) involving two pilots, aged 30 and 36, at altitudes of 18,000 feet, breathing an atmosphere of 40% oxygen, and 33,500 ft. on 100% oxygen, they observed no changes in the blood constituents which they measured, including the electrolytes, glucose, urea nitrogen, lipids, protein electrophoresis, pH, and carbon dioxide. In their second series of experiments, they observed a slight drop in the hematocrit values of their subjects, which subsequently returned to the pre-exposure level. The blood electrolytes, calcium, phosphorus, and urea nitrogen remained constant. The ages of the subjects in the second runs were between 23 and 27 years and they were exposed to an atmosphere of 100% oxygen at an altitude of 27,000 ft. for a period of 14 days.

For the purposes of this study, and in view of the conflicting reports involving the hemolytic effects of this atmosphere, it was thought necessary to measure the glucose-6-phosphate dehydrogenase activity in the erythrocytes of our subjects. As a further index of hemolysis, the determination of total serum bilirubin as well as "direct" bilirubin was included in the experimental design. Hemoglobin and micro-hematocrit determinations were also done.

Of the enzymes that are normally present in the blood in readily measurable quantities, one of the more common classes is the dehydrogenases. Most of these enzymes are dependent on a nicotinamide-adenine dinucleotide as co-factor. In order to get a possible measure of an effect on metabolic processes, which included oxidation-reduction reactions catalyzed by enzymes of this type, the measurement of isocitrate dehydrogenase (ICD) and lactate dehydrogenase (LDH) in the serum were included. Isocitrate dehydrogenase is dependent on nicotinamide-adenine dinucleotide phosphate as a co-factor and lactate dehydrogenase is dependent on nicotinamide-adenine dinucleotide as a co-factor. There is a great deal of data available concerning the medical significance of these enzymes.

In order to further investigate this area, measurements were made of the oxidized and reduced forms of these co-enzymes in the erythrocytes. It was proposed several years ago that the steady-state ratios of the oxidized and reduced forms of these co-factors could presumably present an over-all picture of the general metabolic state of the organism, since these ratios were considered to be the result of substrate levels, competing dehydrogenases, and of such processes as oxidative phosphorylation (6).

Crits _et al_. (7) brought forth the possibility that there was an effect on the visual processes of subjects exposed to an atmosphere of 100% oxygen, particularly in their rate of dark adaptation. It is well known that the photochemistry of vision involves a series of reactions that are catalyzed by enzymes dependent on the nicotinamide-adenine nucleotides as co-factors, thereby giving further impetus to these measurements. It is also known that dark adaptation can be related to the level of blood glucose, and it was for this reason that glucose measurements were included in the experiment.

Methods

Glucose-6-phosphate dehydrogenase was measured in a system based on the method of Kornberg and Horecker (8) in which a hemolysate containing the enzyme is incubated with NADP at a pH of 7.6 and the rate of appearance of NADPH is followed at 340 mμ in a spectrophotometer following the addition of glucose-6-phosphate substrate.

Hemoglobin was determined by the well-known method based on the work of Drabkin and Austin (9) in which hemoglobin is oxidized to methemoglobin by potassium ferricyanide and is subsequently converted to cyanmethemoglobin by potassium cyanide.

Micro-hematocrit determinations were made in glass capillary tubes that were centrifuged at high speed in a specially designed centrifuge.

Bilirubin was determined by the method of Malloy and Evelyn (10) in which serum is treated with a diazotizing reagent and the subsequent color formed is measured spectrophotometrically.

Isocitrate dehydrogenase was determined by a method based on that of Wolfson and Williams-Ashman (11) in which NADP is incubated with isocitrate and manganese and the appearance of NADPH is followed in a spectrophotometer at 340 mμ after the addition of serum containing the enzyme. The reaction is carried out at a pH of 7.5.

Lactate dehydrogenases were measured by a method based on that of Wacker (11) in which NAD and lactate are incubated at pH 8.8 and the rate of appearance of NADH is followed in a spectrophotometer at 340 mμ following the addition of serum containing the enzyme.

The levels of oxidized and reduced NAD and NADP were determined by a method based on that of Jacobson and Astrachan (13) in which fluorescent complexes are formed with the oxidized forms and methyl-ethyl ketone. The reduced forms are oxidized enzymatically and then determined in the same fashion.

Lipase determinations were made by a modification of the Cherry-Crandall technique (14) in which serum is incubated with an olive oil substrate and the fatty acids liberated are determined by titration with standard alkali, following the titration with a pH meter.

Glucose determinations were performed by an automated method based on that of Hoffman (15) in which the reduction of potassium ferricyanide to ferrocyanide and the subsequent color loss is determined spectrophotometrically.

A series of four runs was carried out in a low pressure chamber with an atmosphere of 100% oxygen. One run was made at sea level for 24 hours, one at 18,000 ft. for 72 hours, and two at 27,000 ft. for 72 hours. The data from the two 27,000 ft. runs are combined.

Discussion

It is interesting to note that the glucose-6-phosphate dehydrogenase levels are essentially unchanged in all three runs. Although the duration of stay of the subjects was shorter than in the previously reported studies, the consistency of the enzyme activity indicates that there was no hemolysis during the period of time the subjects were in the chamber (Table 1).

The consistent levels of hemoglobin give further weight to the conclusion that no hemolytic processes were active, as do the consistent packed red blood cell values in the micro-hematocrit determinations.

There was no evidence of hyperbilirubinemia, as evidenced by the consistent bilirubin levels in the serum (Table 4,5,6). In the studies previously cited (1), hyperbilirubinemia began to occur as rapidly as the first 24 hours.

Marked changes in the activity of serum isocitrate dehydrogenase occurred in two of the subjects (Table 2). All of the other subjects remained relatively constant with respect to the activity of this enzyme. In the sea level run, subjects 2 and 3 showed slight transient elevations which returned to the pre-flight level by the end of the 24-hour run. However, in the 18,000 foot run, subject 2's activity remained consistently in the high normal to high range. In the same run, subject 3's activity achieved approximately a fivefold elevation.

In the final 27,000 foot run, subjects 2 and 3 had to be removed from the chamber because of pains that were consistent with dysbarism at the 24-hour point. At this time, they both showed slight elevations in ICD activity from the pre-flight level. The significance of this is rather hard to evaluate. Measurements of this enzyme are widely used in clinical medicine as an index of liver damage, however, neither subject showed an abnormality when a liver function work-up was done at the U. S. Naval Hospital, Philadelphia, Pa. Both were in the older age group, being 38 years of age, and had a history of moderate alcohol consumption.

The level of ICD in the red cell is approximately eighty times that of the serum (10). Scrupulous care was taken with all specimens to insure that there was no mechanical hemolysis due to the separation of the cells from the serum. It would seem that further studies will be necessary to determine the source of this elevated activity, in view of the possibility that it could have been from the liver, from the erythrocytes, or from some other source.

The activity of serum lactate dehydrogenase also remained constant throughout the course of all the chamber experiments (Table 3). There are many reports in the literature involving the iso-enzymes of lactate dehydrogenase, with respect to their origin, electrophoretic mobility, heat stability, and clinical or diagnostic significance. For the purposes of this study, no attempt was made to fractionate these iso-enzymes and determine their individual activities.

The levels of both the oxidized and reduced forms of the nicotinamide-adenine nucleotides remained essentially unchanged during the course of the experiments (Table 4,5,6). One discrepancy occurs in the table of results which must be explained. In the pre-flight determination of NADPH before the sea level experiments, the specimens were inadvertently allowed to thaw during transport from the laboratory where the experiment was carried out to the laboratory where the assays were performed. This thawing did not occur in any of the other specimens in any of the other runs.

The blood glucose levels (Tables 4,5,6) showed no change in the course of the altitude runs, which is in accordance with the studies previously cited.

There was also no change in the level of lipase in the serum (Tables 4,5,6). However, a relatively large volume of serum is required for this test, and consequently could be done on only a few specimens.

One unsuspected finding that must be reported is the incidence of a hyperlipemia in many of the subjects during the course of the chamber experiments. This was evidenced by the appearance of a turbid, lactescent serum. Because of the design of the experiment, it was not possible, except in the second 27,000 foot run, to insure that this was not of a dietary origin. However, in the final run, sufficient time (6 hours) was allowed between the time of food ingestion and blood sampling to lead to the conclusion that the appearance of an elevated lipid content of the blood was not due to absorption from the gastro-intestinal tract. This was an unsuspected finding, and consequently, it was difficult to obtain complete lipid analyses of the serum in order to elucidate which of the fractions were elevated. However, serum lipoprotein electrophoresis of the sera involved showed that there was an increase in the alpha/beta ratio of the lipoproteins. It is known that chylomicrons in the serum migrate in an electrophoretic analysis with the alpha fractions of the globulins. In view of the fact that a moderate degree of lactescence occurred in the final run in which sufficient time had been allowed between eating and blood drawing, it would seem that further studies should be carried out to further elucidate this observation.

Conclusions

Human subjects were subjected to three conditions of altitude in an altitude chamber breathing an atmosphere that consisted of pure oxygen for periods of time varying from 24 to 72 hours. During these exposures, no hemolytic episodes occurred as evidenced by constant activities of erythrocyte glucose-6-phosphate dehydrogenase and constant hemoglobin concentrations and packed red cell volumes. This is further evidenced by the fact that there was no hyperbilirubinemia. In two subjects, an elevation of serum isocitrate dehydrogenase was observed, the significance of which is not known. There were no alterations in the levels of serum lactate dehydrogenase. Serum glucose and lipase levels remained constant throughout the experiments. There were no alterations in the levels of either the oxidized or reduced forms of nicotinamide-adenine dinucleotide or nicotinamide-adenine dinucleotide phosphate. Hyperlipemia was observed in several of the subjects, as evidenced by a turbid, lactescent serum and an alteration of the ratio of the alpha/beta fractions of the serum lipoproteins. The significance of this is also unknown in view of the fact that it occurred when blood specimens were drawn as much as 6 hours following ingestion of food.

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REPORTING UNITS

G-6-PD	Micromoles of substrate oxidized per minute per milliliter of blood
ICD	Millimicromoles of substrate oxidized per hour per milliliter of serum
LDH	Millimoles of substrate oxidized per minute per milliliter of serum
NAD, NADH NADP, NADPH	Micrograms per milliliter of packed erythrocytes
Glucose	Milligrams per 100 milliliters of blood
Lipase	Milliliters of standard alkali required to titrate fatty acids liberated from substrate
Bilirubin	Milligrams per 100 milliliters of serum
Hematocrit	Volume of packed erythrocytes per total volume of blood, in per cent
Hemoglobin	Grams per 100 milliliters of blood

TABLE 1

GLUCOSE-6-PHOSPHATE DEHYDROGENASE

Micromoles of Substrate Oxidized per Minute per Ml. of Blood

			HOUR OF EXPOSURE				
	Subject	Pre	6	15	24	48	72
27,000 Ft.	1	0.24	0.34	-	-	-	-
	2	0.28	0.34	-	-	-	-
	3	0.28	0.38	-	-	-	-
	5	0.28	0.30	-	0.18	0.30	0.26
	6	0.32	0.32	-	0.30	0.32	0.34
	7	0.24	0.24	-	0.24	0.24	0.26
18,000 Ft.	2	0.40	0.40	-	0.32	0.30	0.38
	3	0.32	0.30	-	0.36	0.30	0.34
	5	0.24	0.28	-	0.34	0.22	0.30
	6	0.24	0.30	-	0.34	0.24	0.26
	7	0.28	0.30	-	0.26	0.18	0.34
	9	0.34	0.30	-	0.28	0.34	0.30
Sea Level	2	0.36	0.38	0.34	0.40	-	-
	3	0.24	0.36	0.30	0.40	-	-
	5	0.36	0.34	0.30	0.28	-	-
	6	0.34	0.46	0.28	0.30	-	-
	7	0.24	0.34	0.22	0.34	-	-
	9	0.28	0.36	0.40	0.30	-	-

TABLE 2

ISOCITRATE DEHYDROGENASE

Millimicromoles of Substrate Oxidized per Hour per Ml. of Serum

				HOUR OF EXPOSURE			
	Subject	Pre	6	15	24	48	72
27,000 Ft.	1	93	153	--	186	--	--
	2	192	450	--	--	--	--
	3	174	231	--	--	--	--
	5	66	72	--	69	54	63
	6	51	78	--	62	114	87
	7	93	81	--	75	69	72
18,000 Ft.	2	393	303	--	402	390	366
	3	279	252	--	621	1494	1135
	5	72	75	--	84	70	90
	6	69	84	--	60	72	75
	7	144	135	--	87	99	81
	9	114	117	--	129	132	135
Sea Level	2	240	324	336	218	--	--
	3	264	312	318	210	--	--
	5	72	69	69	57	--	--
	6	60	69	63	51	--	--
	7	96	81	78	72	--	--
	9	120	174	144	126	--	--

TABLE 3

LACTATE DEHYDROGENASE

Millimoles of Substrate Oxidized per Minute per Ml. of Serum

	Subject	Pre	6	15	24	48	72
		HOUR OF EXPOSURE					
27,000 Ft.	1	25.0	30.5	--	26.0	--	--
	2	45.5	33.5	--	--	--	--
	3	26.5	36.5	--	--	--	--
	5	12.0	14.5	--	16.5	16.0	15.5
	6	16.5	16.5	--	21.5	20.5	21.5
	7	21.5	--	--	19.0	22.0	23.5
18,000 Ft.	2	33.5	38.5	--	41.0	41.0	43.0
	3	33.5	36.0	--	41.0	55.5	43.0
	5	17.0	19.0	--	19.5	21.5	17.0
	6	26.5	29.0	--	26.5	29.5	31.5
	7	31.5	27.0	--	31.3	--	--
	9	28.5	33.5	--	36.5	34.0	36.0
Sea Level	2	34.0	36.0	28.5	28.5	--	--
	3	36.5	38.5	34.0	26.5	--	--
	5	16.5	16.5	16.5	12.0	--	--
	6	19.5	26.5	16.0	16.0	--	--
	7	26.0	19.5	21.5	17.0	--	--
	9	31.5	--	19.5	28.5	--	--

TABLE 4

SUMMARY OF ALL VALUES - 27,000 FT.

	Pre	6 Hr.	24 Hr.	48 Hr.	72 Hr.
G-6-PD	0.27	0.32	0.24	0.29	0.29
ICD	110	180	98	80	70
LDH	24.5	26.5	21.1	19.7	20.2
NAD	19.2	-	-	-	22.1
NADH	2.5	-	-	-	5.0
NADP	16.9	-	-	-	14.3
NADPH	6.6	-	-	-	5.5
Glucose	86	88	90	90	93
Lipase	0.18	0.17	0.29	0.27	0.27
Bilirubin, Total	0.43	0.29	-	0.60	0.36
Bilirubin, Direct	0.04	0.04	-	0.05	0.04
Hematocrit	42	43	42	41	41
Hemoglobin	13.7	14.1	13.8	14.2	14.0

TABLE 5

SUMMARY OF ALL VALUES - 18,000 FT.

	Pre	6 Hr.	24 Hr.	48 Hr.	72 Hr.
G-6-PD	0.30	0.38	0.32	0.26	0.32
ICD	170	168	235	365	315
LDH	28.5	30.6	32.6	36.2	34.2
NAD	20.6	-	-	-	20.2
NADH	10.4	-	-	-	5.4
NADP	17.8	-	-	-	17.3
NADPH	6.8	-	-	-	7.1
Glucose	91	91	94	88	90
Lipase	0.20	0.23	0.30	0.28	0.15
Bilirubin, Total	0.50	0.41	0.44	0.43	0.32
Bilirubin, Direct	0.08	0.04	0.05	0.05	0.03
Hematocrit	45	42	42	42	41
Hemoglobin	15.1	14.5	14.7	15.2	14.7

TABLE 6

SUMMARY OF ALL VALUES - SEA LEVEL

	Pre	6 Hr.	15 Hr.	24 Hr.
G-6-PD	0.30	0.37	0.31	0.31
ICD	140	170	170	125
LDH	27.3	27.5	22.9	21.7
NAD	16.2	-	-	17.1
NADH	4.0	-	-	4.8
NADP	16.6	-	-	13.5
NADPH	-	-	-	7.5
Glucose	95	85	89	93
Lipase	0.08	0.20	0.12	-
Bilirubin, Total	0.49	0.62	0.36	0.39
Bilirubin, Direct	0.03	0.07	0.05	0.04
Hematocrit	42	43	42	43
Hemoglobin	13.8	14.8	14.0	14.0

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Optics of Distilled and Natural Water

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INTRODUCTION

THE sea viewed in the daytime by an observer looking downward from a ship or an airplane has a certain color and brightness which, apart from the surface reflection, is caused by the portion of the daylight that has penetrated into the sea and has returned upward. The character and intensity of the up-welling light depends on the optical properties of the sea water. It is the purpose here to describe laboratory measurements of the absorption and scattering of distilled water and of the water of the Chesapeake Bay and the Atlantic Ocean, and to relate these through theory with observations of the Bay and the Ocean.

MEASUREMENTS IN THE LABORATORY

Apparatus was arranged for measuring the attenuation and scattering of samples of water for light of the visible spectrum. For the attenuation a glass tube was used 364 cm (12 feet) in length and 4.2 cm in internal diameter, closed with glass end-plates that were flat and perpendicular to the axis of the tube. A beam of light from a tungsten lamp, rendered parallel by a lens, passed through the tube being limited by diaphragms to a circular cross section of 2.5 cm so that it did not touch the walls of the tube. The beam passed through a Nutting photometer and came to a focus on the slit of a glass prism spectrograph. The long glass tube could be moved out of the beam and replaced by a short tube 20 cm in length, both tubes being filled with water from the same sample. In this way the attenuation κ of the water was determined throughout the visible spectrum from 420 to 700$\mu\mu$.

κ is defined by

$$i=i_0e^{-\kappa x}, \tag{1}$$

where i and i_0 are the respective intensities of a parallel beam of light of wave-length λ that enters and emerges from a thickness χ cm of the water.

Now

$$\kappa=\beta+\sigma, \tag{2}$$

where β and σ are the attenuations due to true absorption and to scattering, respectively.

In order to measure the scattering σ the water was placed in a spherical flask of 8 cm radius. A parallel beam of tungsten light was passed through the center of the flask and the brightness of the beam at various angles ϕ to the forward direction of the beam was measured with a Macbeth illuminometer. The flask was removed and replaced by a diffusing white plaque normal to the beam and in the position previously occupied by the center of the flask. The brightness of the white plaque was measured. From these measurements the values of σ_ϕ were determined, where σ_ϕ is the fraction of the light of the beam that was scattered per unit volume of water per unit solid angle in the direction ϕ.

The attenuation σ of parallel, or collimated, light due to scattering is given by

$$\sigma=2\pi\int_0^\pi \sigma_\phi \sin\phi d\phi. \tag{3}$$

Of the light that is scattered from the parallel beam portions σ_F and σ_B are scattered in the forward and backward directions, respectively, where

$$\sigma=\sigma_F+\sigma_B, \tag{4}$$

$$\sigma_F=2\pi\int_0^{\pi/2} \sigma_\phi \sin\phi d\phi, \tag{5}$$

$$\sigma_B=2\pi\int_{\pi/2}^{\pi} \sigma_\phi \sin\phi d\phi. \tag{6}$$

Quantities of interest here are η and $1-\eta$, the fractions of the light scattered in the forward and backward directions, respectively. Then

$$\eta=\sigma_F/\sigma, \qquad 1-\eta=\sigma_B/\sigma. \tag{7}$$

If the values of β, σ, and η are known throughout the visible spectrum for a sample of water the upcoming daylight from a uniform sea of such water may be calculated.

Distilled water was investigated first, because earlier measurements of its optical properties were not in complete agreement, and a knowledge of pure water was important to an understanding of natural waters. The preparation of approximately chemically pure water is relatively simple, but to prepare it free from optical impurities, that is, "dust free," is well known to be difficult. A good way is by slow distillation in quartz. There was no opportunity to do this in the case of the considerable quantity of water required in the present experiments. The procedure used was to allow distilled water to stand for several weeks in five-gallon bottles. The upper two-thirds of the water in a bottle was siphoned directly into the absorption tube and scattering flask for rinsing and finally for filling. Motes were visible in the settled-out distilled water in the tube and flask, especially when viewed by forward scattering, but after standing for several days many, but not all, settled out. After ten days $\sigma_{\pi/2}$, the scattering coefficient at right angles for tungsten light, diminished to

$$\sigma_{\pi/2}=1.44\times10^{-6},$$

and did not decrease any more with further standing in the flask.

The theoretical value for water for tungsten light viewed with the light adapted eye is

$$\sigma_{\pi/2}=1.21\times10^{-6},$$

as calculated from the density fluctuation expression with polarization defect.[1]

The observed values of σ_ϕ for distilled water for tungsten light are plotted as $(\sigma_\phi/\sigma_{\pi/2})\sin\phi$ as ordinate against ϕ as abscissa in Fig. 3. From these values the scattering attenuation σ_t for tungsten light and η were calculated from (3), (5) –(7). One obtained

$$\sigma_t=0.931\times10^{-4},$$
$$\eta=0.864.$$

The theoretical values for water[1] for tungsten light were

$$\sigma_t=0.194,$$
$$\eta=0.50.$$

It is seen that the dust content of the distilled water was reduced until the scattering at right angles was only about 20 percent in excess of the theoretical value. The total scattering, however, was over 4 times the theoretical value because of the forward scattering. However, there is no compelling reason why the scattering of water should conform with a simple theory.

From the observed value of $\sigma_t=0.931\times10^{-4}$ for tungsten light the values of σ, the scattering attenuation coefficient at wave-length λ, was derived by assuming that σ varied with the inverse fourth power of λ. Earlier measurements[2] supported the assumption and some experimental justification for it was afforded by the observation that the beam of tungsten light in the scattering flask was distinctly bluish. It would have been more satisfactory to have measured σ directly throughout the visible spectrum, but there was no opportunity for such a program. The values of σ are given in Table I, Column 3, and are plotted in the dotted curves of Fig. 1 and Fig. 2.

The values of $\kappa=\beta+\sigma$ for distilled water were measured throughout the visible spectrum. They

TABLE I. Absorption and scattering of distilled water and Chesapeake Bay.

	Distilled water			Chesapeake Bay		plankton
λ	κ	σ	β	κ	β	β
400μμ	8.0×10^{-4}	3.57×10^{-4}	4.4×10^{-4}	—	—	—
410	7.0	3.23	3.8	—	—	—
420	6.1	2.95	3.1	80.5×10^{-4}	62.5×10^{-4}	60×10^{-4}
430	5.3	2.69	2.6	70.5	52.5	49
440	4.6	2.45	2.1	62.8	44.8	43
450	4.0	2.25	1.7	55.6	37.6	36
460	3.6	2.04	1.6	51.2	33.2	31
470	3.6	1.89	1.7	47.5	29.5	28
480	3.65	1.72	1.8	44.7	26.7	25
490	3.7	1.59	2.1	41.9	23.9	22
500	3.8	1.47	2.3	38.8	20.8	18
510	3.9	1.35	2.6	36.8	18.8	16
520	4.0	1.25	2.8	35.1	17.1	14
530	4.2	1.17	3.0	33.7	15.7	13
540	4.4	1.09	3.3	33.1	15.1	12
550	4.7	1.00	3.7	32.8	14.3	11
560	5.3	.932	4.4	32.3	14.3	10
570	6.6	.868	5.7	32.3	14.3	9
580	8.4	.810	8.6	33.1	15.1	8
590	12.0	.756	11.2	36.5	18.5	7
600	19.7	.708	19.0	42.9	24.9	6
610	24.3	.662	23.6	46.5	28.5	5
620	26.5	.618	25.9	47.6	29.6	4
630	28.0	.581	27.4	48.8	30.8	4
640	29.2	.535	28.7	50.0	32.0	4
650	30.8	.507	30.3	51.8	33.8	4
660	33.5	.483	33.0	54.2	36.2	4
670	37.5	.455	37.0	56.3	38.3	2
680	40.6	.429	40.2	58.9	40.9	1
690	46.7	.404	46.3	63.	45.	0
700	57.6	.380	57.2	74.	56.	0

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[1] L. H. Dawson and E. O. Hulburt, J. Opt. Soc. Am. 31, 554–557 (1941).

[2] L. H. Dawson and E. O. Hulburt, J. Opt. Soc. Am. 27, 199–201 (1937).

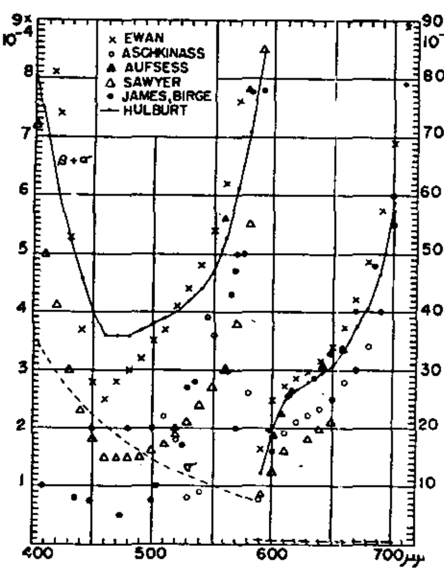

FIG. 1. Absorption and scattering of distilled water.

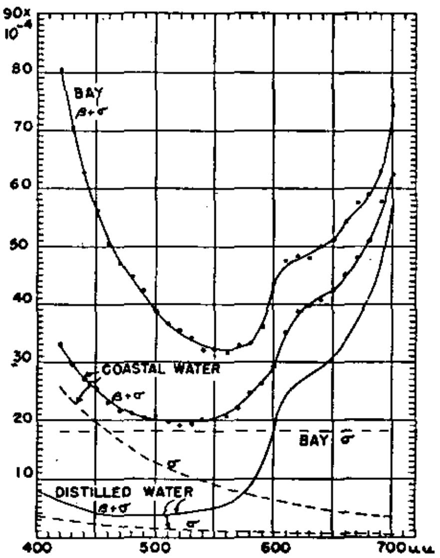

FIG. 2. Absorption and scattering of water samples.

are listed in Table I, Column 2, and are plotted in Fig. 1 in which for clarity the scale of ordinate for $\lambda < 580\mu\mu$ is 10 times the scale for $\lambda > 580\mu\mu$. By reflecting the beam of light back through the 12-foot absorption tube, so that the beam traversed 24 feet of distilled water, the shallow minimum of absorption in the blue green could be seen visually to lie in the region 460 to 470$\mu\mu$. For comparison, the values of κ obtained by a number of earlier observers[3] are plotted in Fig. 1. It is seen that there is considerable variance among the measurements. Whether the variations were caused by differences in preparation of water or in spectrographic and photometric techniques is not known.

Subtracting the values of σ, Table I, Column 3, from the respective values of κ, Column 2, gave the values of β, Column 4. These are the first data of the absorption coefficients of distilled water throughout the visible spectrum that have been obtained, for the present case is the only one in which σ was measured simultaneously with κ, thereby permitting β to be evaluated.

The sample of Atlantic Ocean water was taken on February 11 from the sea 2.5 miles east of the Florida coast near Hollywood.* The depth was about 70 fathoms and a 5-gallon bottle was used with an automatic stopper that opened about one fathom below the surface. The water might be described as "coastal Gulf Stream" water. The bottle was received at the laboratory on February 24. It was shaken vigorously and the water poured into the scattering flask and absorption tube. A few large heavy particles were visible which settled out almost immediately leaving motes visible for the most part only by forward scattering. The observed values of $\sigma_{\pi/2}$ for tungsten light are shown in Table II. Comparing these values with the value 1.44×10^{-6} for carefully settled out distilled water it is seen that the scattering of the coastal water was somewhat greater. But when compared with tap water, or with un-settled-out distilled water, the coastal water seemed astonishingly dust free.

TABLE II. Values of $\sigma_{\pi/2}$ of coastal water.

Date	$\sigma_{\pi/2}$
February 24	12.2×10^{-6}
27	8.8
March 1	8.6
5	6.7

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[3] N. E. Dorsey, *Properties of Ordinary Water-Substance* (Reinhold Publishing Corporation, New York, 1940), Table 161.

* Lieutenant E. R. F. Johnson kindly obtained the sample for me.

The values of σ_ϕ of the coastal water were measured on February 24 and are plotted as $(\sigma_\phi/\sigma_{\pi/2})\sin\phi$ in Fig. 3. From these values and $\sigma_{\pi/2}=12.2\times10^{-6}$ the scattering attenuation σ_t for tungsten light and η were calculated from (3), (5)–(7). One found

$$\sigma_t=8.69\times10^{-4},$$
$$\eta=0.866.$$

The scattered beam was bluish in color, justifying the assumption that σ was proportional approximately to λ^{-4}. With this assumption and with $\sigma_t=8.69\times10^{-4}$ the values of σ were calculated throughout the visible spectrum; they are plotted in Fig. 2.

The attenuation $\kappa=\beta+\sigma$ of the coastal water was measured on February 25 and 26, and is plotted in Fig. 2. In the absorption tube the ocean water was slightly, but distinctly, greener than the distilled water. In keeping with this was the fact that the κ or $\beta+\sigma$ curve of the coastal water showed relatively greater attenuation for the shorter wave-lengths than the curve of distilled water.

The sample of Chesapeake Bay water was taken on October 18 from the surface about a mile from Bloody Point, the depth being about 15 fathoms. Measurements were begun the following day. The water was shaken up and poured into the scattering flask and absorption tube. It showed considerable scattering especially in the forward direction, the beam being whitish in color with many motes. Some of the larger motes were alive and moved about; the larger ones soon settled out. Measurements on October 19 resulted in

$$\sigma_{\pi/2}=15.6\times10^{-6}$$

and the $(\sigma_\phi,\ \sigma_{\pi/2})\sin\phi$ curve of Fig. 3. From these data and (3), (5), and (6) one found

$$\sigma_t=18\times10^{-4},$$
$$\eta=0.93.$$

The whiteness of the beam indicated that σ was approximately constant with λ. Therefore the σ, λ curve is drawn in Fig. 2 as a straight line parallel to the X axis.

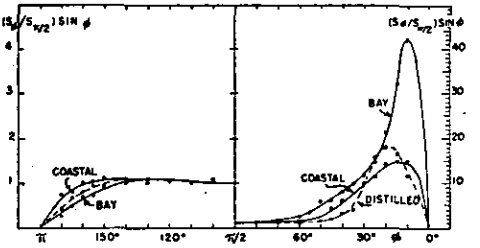

FIG. 3. Scattering of water samples. (The "*S*'s" in the figure should be σ's.)

The attenuation $\kappa=\beta+\sigma$ curve, measured on October 20, is given in Fig. 2, and shows a maximum of transmission in the yellow green. A white plaque observed through the Bay water in the 12-foot tube appeared yellow green. The values of κ for the Bay water are in Table I, Column 5. Subtracting $\sigma=18\times10^{-4}$ from these gave the absorption β of the Bay water in Column 6, which may be considered made up of two parts, one due to the water and the other due to the colored material in the water, the material being plankton. Subtracting β for distilled water from the respective values of Column 6 gave in Table I, Column 7, the absorption of the Bay plankton. The values are plotted in Fig. 4.

The Bay water remained in the absorption tube for several weeks. It gradually lost its green color and approached the color of distilled water, indicating that with lack of air and light the plankton material slowly changed and disappeared.

A filter whose absorption coefficient increased rapidly with decreasing wave-length, as that of the Chesapeake Bay plankton, would be yellow, or even amber. Thus we may say that the color of the plankton was yellow. When the plankton are in water, which absorbs the red end of the spectrum, the result is a green or yellow-green color. The fact that the color of the Bay material, which we have vaguely referred to as "plankton," is yellow is in keeping with an earlier conclusion[4] that pigments of a yellow color are present in water of the North Sea. The slight absorption in the blue of the coastal water of Fig. 2 may be regarded as due to a very slight amount of the yellow material, similar as far as color is concerned to that of the Chesapeake Bay considerably diluted. However, one cannot generalize too broadly, for not all planktonic materials are the same in color, various types being described as green, muddy, brownish, reddish, and so forth.

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[4] K. Kalle, Ann. d. Hydrogr. u. Mar. Met. 66, 1–13 (1938).

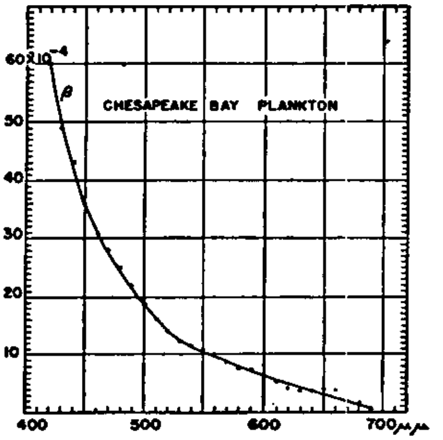

FIG. 4. Absorption of Chesapeake plankton.

THEORETICAL

A general expression for the light coming out of the sea in terms of the optical constants of the sea water was worked out for a sea of any depth in sunny and cloudy weather.[5] It is of interest to apply the expression to the present measurements. Let a_0 and i_0 be the illuminations from the sky and the sun, respectively, that fall on the surface of the sea, and b_0 the light that emerges from the sea outside of the sun path. The general expression is Eq. (16),[5] and may be written

$$b_0 = a_0\Gamma + i_0\Gamma', \tag{8}$$

where Γ and Γ' are functions of β, σ, η, ζ, the depth of the water and the reflectivity of the bottom; ζ is the zenith angle of the sun. All quantities of (8) refer to wave-length λ. In (8) no surface reflection is assumed. With surface reflection r_c for collimated light and r_d for diffuse light (8) becomes

$$b_0 = a_0[(1-r_c)(1-r_d)\Gamma + r_c] + i_0(1-r_c)^2\Gamma'. \tag{9}$$

For a calm surface of water $r_c = 0.021$ for $\lambda = 5600\text{A}$ and $\zeta = 0°$ and for other values of λ and ζ is given by Fresnel's equations. For $\lambda = 5600\text{A}$ $r_d = 0.066$. The reflectivity r_λ of the sea for wave-length λ is defined as the ratio of the downward light to the upward light seen by an observer looking vertically downward. Then

$$r_\lambda = b_0/(a_0 + i_0). \tag{10}$$

For skylight and sunlight seen with the eye, the visible reflectivity R is given by

$$R = \frac{\int b_0\psi d\lambda}{\int (a_0 + i_0)\psi d\lambda}, \tag{11}$$

where ψ is the visibility function and the integrals are taken over the visible spectrum.

In order to calculate from (11) the color of the up-welling light and the values of R for the three samples of water, we consider a simple case of an infinite depth and a uniformly cloudy sky. For no surface reflection R is given by (11) with

$$b_0 = a_0\Gamma, \tag{12}$$

and with surface reflection R is given by (11) with

$$b_0 = a_0[(1-r_c)(1-r_d)\Gamma + r_c]. \tag{13}$$

The b_0, λ curves were calculated for the three samples of water from (12) with the data of Fig. 2 and the observed values of η; they are plotted in Fig. 5 together with a_0 the spectral distribution of daylight for a cloudy sky.[6] Likewise, the b_0, λ curves from (13) were drawn. The $b_0\psi$, λ curves were then plotted but are not given here. From the areas under the curves and from (11) the reflectivities were determined and are given in Table III.

It appears from Table III that about 60 percent of the brightness of the Gulf Stream or Chesapeake Bay viewed in calm cloudy weather by an observer looking vertically downward is caused by light up-welling from the depths and about 40 percent is caused by surface reflection. The curves of Fig. 5 show that the light coming up from the Gulf Stream off the coast of Florida

TABLE III. Calculated reflectivity R of a calm sea of infinite depth for a cloudy sky.

	No surface reflection	With surface reflection
Distilled water	0.018	0.036
Gulf Stream	0.047	0.063
Chesapeake Bay	0.035	0.052

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[5] E. O. Hulburt, J. Opt. Soc. Am. 33, 42–45 (1943), Eq. (16).

[6] A. C. Hardy, *Handbook of Colorimetry* (The Technology Press, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1936), p. 17.

and from distilled water is very blue and from Chesapeake Bay is green. This is in agreement with familiar observation. The case of distilled water may be of interest in connection with observations of very pure fresh water lakes.

In order to bring out the change in the reflectivity of the sea with the state of the sky and the altitude of the sun, it is sufficiently accurate for the present purpose to use (11) with values averaged over the visible spectrum rather than to perform the indicated integrations. Let f define the state of the sky, where

$$i_0 = f a_0. \tag{14}$$

Values of f observed for various states of the sky are given in Table IV. Then (11) becomes

$$R = \frac{[(1-r_c)(1-r_d)\Gamma + r_c] + f(1-r_c)^2\Gamma'}{1+f}, \tag{15}$$

where now the quantities are values averaged over the visible spectrum for the spectral distributions of the illuminants and the visibility function. Average values for the Chesapeake Bay sample are

$$\sigma_c = 18 \times 10^{-4},$$

$$\beta_c = 16.7 \times 10^{-4},$$

$$\eta = 0.93.$$

With these the values of R were calculated from (15) for ζ from 0° to 90° for the values of f of Table IV. The R, ζ curves are plotted in Fig. 6; corresponding curves for the Gulf Stream were very similar to those of Fig. 6. The curves show the theoretical changes in the Bay and the Gulf Stream with the state of the sky and the altitude of the sun. For example, R increases by about 60 percent as the sky changes from cloudless to cloudy for altitudes of the sun above 50°.

OBSERVATIONS IN THE OPEN

Measurements of the reflectivity of Chesapeake Bay were made from a boat and from an airplane and of the sea from an airplane. Macbeth illuminometers were used and in each experiment three quantities were determined, the brightness W of the water surface outside of the sun path and the brightness P_1 of a horizontal, white, mat plaque exposed to the illumination of the sky plus the sun and P_2 to the sky alone. A pale blue, calibrated filter was placed over the illuminometer lamp in order to obtain a color match when bluish areas were observed. From W, P_1, and P_2, the reflectivity R and sun-to-sky ratio f were calculated by means of

$$R = W/P_1, \tag{16}$$

$$f = (P_1 - P_2)/P_2. \tag{17}$$

An interesting series of observations made from a boat on Chesapeake Bay is given in Table V. In this case the boat was becalmed in the middle of the Bay while dark clouds, which covered the sun and a portion of the sky, slowly moved away to expose the sun in a clear blue sky. During this time the altitude of the sun varied from 67° to 72°. The observed values of R are in Table V, Column 3, the theoretical values from Fig. 6 are in Column 4, and are in fair agreement with the observations.

Similarly, values of R of the Bay measured from an airplane changed from 0.025 to 0.06 when

TABLE IV.

State of Sky	f
All sun, no sky	infinity
Sunny, clear sky	7
Sunny, hazy sky	3
Sun through thin clouds	1
No sun, cloudy	0

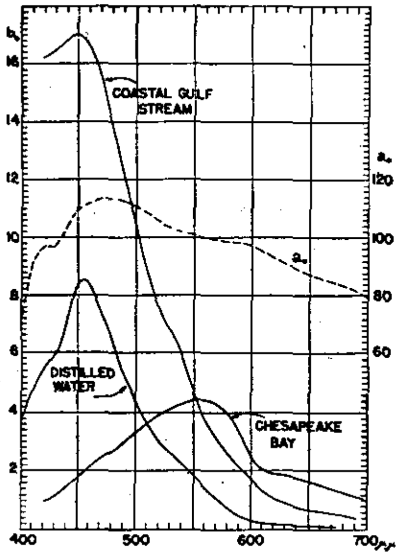

FIG. 5. Spectral curves of surface light from deep water.

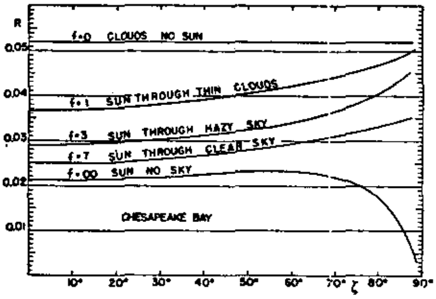

FIG. 6. Theoretical reflectivity of Chesapeake Bay.

the plane passed from sunshine into regions under clouds. In fact the decrease in *R* with the change in the illumination from diffuse, i.e., cloudy, to collimated, i.e., sunshine, was easily noticeable without accurate measurement. This was done with a large card painted a mat dark green and held horizontally against the Bay surface as background. The card matched the Bay surface approximately when the sun was behind clouds, and when the sun came out the card was observed to brighten much more than the Bay surface.

Observations of the reflectivity of the Atlantic Ocean made from an airplane on August 10, 1943, are recorded in Table VI. The sea was moderate and the air fairly clear. The plane flew at an altitude of about 1000 feet from the Maryland coast eastward about 150 miles out to sea. The plane passed under a cloudy area on the outward flight; on the return flight the sky became nearly cloudless. It is seen from Table VI that *R* was from 0.022 to 0.034 outside of the sun path for a sunny sky and about 0.05 for a cloudy sky for distances from shore beyond 12 miles where the depths were greater than 10 fathoms. The corresponding theoretical values, from Fig. 6, are 0.025 and 0.052. As the shore was approached, the depth decreasing from 8 fathoms to zero, *R* in sunshine increased from 0.025 to 0.05, due no doubt to the bottom and to considerable scattering material in the shoal water. A few observations indicated that *R* increased by one or two units in the second decimal place with the roughness of the sea. The above results are in approximate agreement with some earlier observations[7] off the coast of New England of the change in the reflectivity of the sea with the state of the sky. It was found that for the sun above

TABLE V. Reflectivity *R* of Chesapeake Bay.

State of sky	*f*	*R* observed	*R* theoretical
Cloudy	0	0.054	0.052
	0	0.056	0.052
Sun through edge of cloud	1.2	0.036	0.037
	1.7	0.023	0.035
	2.8	0.023	0.032
	5.3	0.017	0.027
Sunny	6.1	0.019	0.026

TABLE VI. Reflectivity *R* of the Atlantic Ocean.

Time EST	Altitude of sun	Distance from shore, nautical miles	Depth of sea, fathoms	*R* Sunny	*R* Cloudy
9.50	51°	4	5	0.033	
9.53				0.031	
9.56		17	16		0.037
9.58				0.023	
10.00		25	20	0.026	
10.05					0.047
10.07					0.052
10.09		45	40		0.052
10.23	60°	75	800	0.030	
10.25				0.028	
10.27		85	1100	0.029	
10.32				0.027	
10.35		100	1400	0.029	
10.52				0.026	
10.54		140	1800	0.025	
10.59	68°	150	1800	0.025	
11.33		110	1500	0.034	
11.35				0.033	
11.37				0.022	
11.56		70	600	0.030	
11.59	69°			0.025	
12.01		50	50	0.024	
12.02				0.024	
12.08				0.022	
12.09				0.025	
12.10		30	25	0.024	
12.11				0.024	
12.12				0.027	
12.13		20	15	0.025	
12.16				0.027	
12.17	68°			0.026	
12.18		10	8	0.025	
12.19		8	8	0.027	
12.20		6	7	0.030	
		5	6	0.032	
		4	5	0.032	
		3	5	0.037	
		2	4	0.040	
		1	3	0.044	
12.23		0	0	0.051	

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[7] W. M. Powell and G. L. Clarke, J. Opt. Soc. Am. 26, 111–120 (1936).

30° altitude the reflectivity was about 0.065 for cloudy days and 0.04 for clear days.

In general, it is seen that there was fair agreement between the observed values of the sea and the Bay reflectivity and the values of Table III and Fig. 6 which were calculated from the optical constants of samples of the sea and the Bay measured in the laboratory. This was not entirely anticipated, for the suspicion was entertained that the optical properties of samples, particularly the scattering, would change with time and with handling and would not be representative of the water from which they were taken. It appears that in the present case the suspicion was without much foundation. However, it is certain that the procedure of measuring samples transported to a laboratory is not a best procedure. Measurement of the water *in situ* is much to be preferred, or at least of samples *carefully taken and not more than a few hours old.*

In voyages on the Atlantic Ocean I have often observed that the color of the up-coming light of the open sea far from land is a beautiful turquoise blue in low latitudes, but in higher and colder latitudes is less blue in color, being a blue-black or a dark gray almost devoid of color. The explanation of the color difference is suggested in the results of the present experiments. A slight amount of yellow or green or brown coloring material in pure sea water will reduce the blue color and make the water appear less *blue and* more gray. Now it is well known that pelagic planktonic material is more abundant in the colder than in the warmer areas of the sea. For example the *Encyclopaedia Britannica*[8] states, "In general the temperate and cold waters are rich in plankton, while the tropical and warm waters are relatively poor. The richest plankton in any part of the world ocean is that found on the borders of the polar seas in the regions of melting ice." Therefore it is reasonable to suppose that the turquoise blue color of the ocean in low latitudes is that of nearly pure sea water, and that the blacker or grayer color of high latitude seas is to be attributed to a more or less amount of yellow or green or brown coloring due to the planktonic content.

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[8] *Encyclopaedia Britannica*, fourteenth edition, Vol. 17, p. 1004.

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Visual Function in Divers at 15 to 26 Atmospheres Pressure

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INCREASING interest in oceanographic research and exploitation on the continental shelf has yielded new techniques in deep sea diving.[1] By using these and other life-supporting techniques, man can live and work in high pressure environments for weeks or months.

Loss of vision may be caused by external factors: decreased natural illumination at depth; back-scattering of artificial illumination; limitation of visual field by the geometry of helmets and face masks; distortion or reflection of light at the glass faceplate.[2] During operational dives, the external visual limitations may obscure physiological abnormalities. Also, visual symptoms such as blurring, diplopia, or field constriction are common disorders reported during the post-dive period and may be related to decompression sickness, hypercarbia, anoxia, or hyperoxia.[3] The presence or absence of such changes at depth needs to be documented.

Our study consisted of a series of visual function tests conducted at the U. S. Navy Experimental Diving Unit, Washington, D.C., in 1968. This was carried out as part of the Navy SeaLab project during pressure chamber simulation of dive profiles, to be used on SeaLab III in the Pacific Ocean off the California coast.

Method

The human subjects were experienced deep-sea divers, attached to the U. S. Navy SeaLab, a part of the Deep Submergence Systems Projects. Three simulated dives were carried out, and at all depths, the gas mixture consisted of 0.3 atmospheres oxygen, 1.5 atmospheres nitrogen, and the balance helium. These dives were of a saturation type, that is, a bottom-time of more than 24 hours, sufficient to allow effective saturation of body tissues with inert gas.

After one week of training in visual testing, five men made each dive; one diver made the visual measurements and the other four served as subjects. Visual function measurements were made first on the surface in the pressure chamber, twice at depth during each dive, and again on the surface following the dive. One of the authors (J.S.K.) monitored the tests and was available for consultation at all times.

The first dive attained a saturated depth of 825 feet (26 atm.). During the saturation period of 48 hours, two divers went into a separate compartment of the pressure complex and made a "dive" of short duration to a simulated depth of 1025 feet (32 atm.), a record depth exposure at that time. Measurements of visual function were made after 24 hours at 825 feet (26 atm.), and during decompression at 600 feet (19 atm.), as well as on the surface as controls.

The second dive attained a saturation depth of 600 feet (19 atm.) for 48 hours. Visual measurements were made at 600 feet (19 atm.) and at 450 feet (15 atm.).

The third dive reached a saturated depth of 600 feet (19 atm.) with a saturation period of 60 hours. Visual measurements were made during decompression from 600 feet (19 atm.) to 340 feet (11 atm.).

Monitoring of pressure, temperature, humidity, oxygen level, and carbon dioxide level was continuous during each dive. Trace atmospheric contaminants were measured intermit-

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Tests performed at the U. S. Navy Experimental Diving Unit, Washington, D.C.

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TABLE I

PHYSIOLOGICAL FACTORS IN VISUAL FUNCTION STUDIES

Test	Surface Control (range)	Depth (range)
1. distance vision	20/15 to 20/20+2	20/15+5 to 20/20
2. near vision	0.5 D to 1.0 D	0.5 D to 1.0 D
3. accommodation	3.5 to 13 inches	3 to 11 inches
4. peripheral fields	725° to 855°	740° to 840°
5. central fields	normal	normal
6. color vision	normal	normal
7. ductions	normal	normal
8. ductions with red glass	no diplopia	no diplopia
9. Maddox wing	a. horizontal 1 to 2 scale units	a. horiz. 0 to 4 scale units
	b. vertical 1 to 2 scale units	b. vert. 0 to 2 scale units
	c. cyclo-0 to 1 scale units	c. cyclo-0 to 1 scale units
10. prism fusion	a. convergent 8 to 18 diopters	a. conv. 8 to 18 diopters
	b. divergent 14 to 40 diopters	b. diverg. 18 to 40 diopters
11. Worth 4-dot	fusion	fusion
12. Titmus Stereotest	40 seconds at 16 inches	40 seconds at 16 inches
13. optokinetic nystagmus	normal	normal
14. dark adaptation	39 to 55 correct	25 to 54 correct
15. subjective visual symptoms	none	none

tently. A complete life support system assured control of these variables and of the safety and comfort of the divers.

The visual tests employed are listed in Table I. Visual acuity in each eye was determined with an Armed Forces Clinical Test Chart at 20 feet at normal chamber illumination. Near vision was determined at 14 inches with an American Optical reading card. Maximum accommodation was measured by finding the near point at which the smallest print on the reading card was seen to blur.

Peripheral visual fields were measured in each eye with a Schweiger hand perimeter, using a one mm white test object in twelve meridians. The figures for peripheral fields are the total of the twelve measurements in each eye. Central field defects were looked for, utilizing an Amsler Grid. Color vision determinations were made with H-R-R Pseudoisochromatic Plates.

Ocular motility was observed in the primary, secondary, and tertiary positions of gaze. A red glass was used in an attempt to elicit diplopia in these positions. A Maddox Wing was utilized in determining horizontal, vertical, and cyclophorias. Subjective fusion ranges were measured with base in and base out prisms while the subject fixed on a hand light. A Worth 4-dot test was used to detect gross suppression. Stereopsis was quantitated with the Titmus Stereotest.

Pupil size was estimated with a comparator card. Horizontal and vertical optokinetic nystagmus were elicited with a striped tape.

All of the above determinations were made during the first two dives, so that visual function was measured in eight subjects. During the last dive, dark adaptation was determined with the MRL Night Vision Test in all five divers, with measurements both at depth and on the surface as controls.[4] In addition to these subjective and objective determinations, each subject was questioned about any visual symptoms during the dive.

Discussion

The primary objective of this study was to determine whether or not the sum of all the environmental changes imposed on divers under these conditions would induce visual changes sufficient to affect their safety or performance. Numerical data were analyzed according to the Wilcoxen Matched-pairs Signed-Rank Test.[5] The data summarized in Table I indicate that there was no significant change in any of the measured visual functions at the depths involved. The divers all denied subjective visual changes during the dives.

In the literature much attention has been given to the effect on the eyes of high oxygen partial pressures.[6,7] Whereas relatively high oxygen levels (one to two atm.) are required in some diving systems, the level during our studies was maintained at 0.3 atmospheres, a level of pressure said to be without measurable adverse effect. Carbon dioxide build-up has caused narcotic symptoms in some diving situations.[8] In our series, CO_2, CO, and trace contaminants were maintained at acceptable low levels of partial pressure by chemical purification systems, verified by gas chromatography.

The inert gas helium, which forms the balance of the mixture, was chosen as a relatively non-narcotic gas.[9] Bennett, however, has estimated that mild symptoms of helium narcosis would begin at a 450 foot depth (15 atm.).[10] Potential inert gas narcosis was a major reason for suspecting that changes in visual function might occur at depths beyond 450 feet.

Previous studies have shown that susceptibility to narcosis varies with the complexity of the neural pathway involved. Memory and judgment are affected more than spinal reflexes, which in turn are more sensitive than simple nerve conduction. Despite the fact that some of the performed visual tests represent at least an intermediate degree of complexity, no decrement in function was observed.

As noted before, visual testing was oriented toward safety and general performance. Tests were limited in complexity by the absence of medical personnel in the chamber during the dives. More specific tests for the effect of narcosis on ocular function would be of interest. However, it would appear from this study that visual function remains essentially normal during prolonged dives at these depths.

Summary

Multiple visual tests were made of 14 Navy divers during pressure chamber simulation of prolonged dives that ranged in depth to 1025 feet. During three dives, no significant changes in visual function were found when visual measurements at depth were compared with surface control values.

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Visibility of Colors Underwater*

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The underwater visibility of various colors, both fluorescent and nonfluorescent, was measured in four different bodies of water. The waters were selected to sample the continuum from very murky to clear. SCUBA divers observed with a horizontal path and other subjects on the surface looked down vertically. Fluorescent colors were always more visible than nonfluorescent, but the specific colors that were easiest and most difficult to see depended upon the body of water.

INDEX HEADINGS: Vision; Color; Oceanography.

THE increasing penetration of man into the sea has raised acute problems of visibility underwater. In some cases, the turbidity of the water is so severe that no visual signal can be used to assure the diver's return to his base of operations. At the other extreme, there are reported instances of divers seeing clearly for 200 ft in all directions. Between these two extremes lies the wide range of waters in which divers and small submersibles work and for which aids to visibility are possible.

The use of colored paints on objects is an obvious means of changing their visibility either by enhancing their contrast with the surround or by camouflaging them to merge with their background. The problem of determining which colors will be most and least visible underwater is, however, much more complicated than it is in air. Transmission of light through air does not appreciably change its spectral composition, but transmission through water can alter the distribution beyond recognition. Furthermore, both the quantity and quality of the change depend on the particular body of water involved.

Water selectively absorbs light of different wavelengths. Pure water has its greatest transmittance at 480 mμ in the blue-green region of the spectrum. Many natural contaminants of pure water, such as plankton, not only lower the total transmittance but selectively absorb more of the short- than of the long-wavelengths. The peak of the transmittance curve is thus moved from 480 mμ toward the longer wavelengths as the water becomes less clear. Similarly, as we move from open ocean toward the coast, the source of silt and pollution, the peak is moved further into the yellow-green and even yellow portions of the spectrum.[1] Thus, the relative visibility of paints of different colors can be expected to vary considerably with the body of water in which they are immersed. One of the most effective means of increasing visibility in air is the use of fluorescent paints, as evidenced by the expanding use of these paints in traffic signals, on aircraft, and for hunters' clothing. The advantage, of course, is the increased brightness and color contrast produced when energy of short wavelengths is converted to longer wavelengths to which the eye is more sensitive.[2] Thus reflectances higher than those of natural objects and often effectively in excess of 100% are possible as are high saturations similar to those of monochromatic light. The most effective colors in air are varieties of orange, which combine the advantages of great energy conversion, high sensitivity of the human eye, and good color contrast with natural backgrounds, which are often blue or green.

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* From Bureau of Medicine and Surgery, Navy Department, Research Work Unit MF011.99-9002. The opinions or assertions contained herein are the private ones of the authors and are not to be construed as official or reflecting the views of the Navy Department or the Naval Service at large.

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Most of these advantages are retained in water, and theoretically the use of fluorescent paint is a promising means of improving underwater visibility. Since the energy required for excitation is primarily in the violet, blue, and green portions of the spectrum, sufficient energy should be available at great depths in clear water.

This study is an empirical determination of the relative visibility underwater of paints of various colors, both fluorescent and nonfluorescent, in different bodies of water.

APPARATUS AND PROCEDURE

Fourteen paints were tested for underwater visibility; they were a blue, green, yellow, orange, and red in both fluorescent and nonfluorescent varieties plus white, gray, and black. Their characteristics are listed in Table I. Since fluorescent orange has been so effective in air, a number of hues are available and several were included. Paints were chosen to be representative of commercially available items and varied in reflectance as well as hue.

TABLE I. Specifications of paint samples.

Sample No.	Color	Luminance factor %T	CIE chromaticity coordinates x	y	z
FLOURESCENT					
1	Blue	20.3	0.1591	0.1756	0.6653
3	Green	60.4	0.2625	0.6005	0.1370
5	Yellow-Green	111.2	0.4138	0.5472	0.0392
7	Yellow-Orange	95.4	0.5558	0.4183	0.0258
9	Orange	70.4	0.6065	0.3853	0.0082
11	Red-Orange	49.2	0.6323	0.3364	0.0313
NONFLUORESCENT					
2	Blue	12.8	0.2199	0.2085	0.5715
4	Green	12.3	0.2755	0.5183	0.2063
6	Yellow	44.4	0.5052	0.4548	0.0401
8	Orange	16.6	0.6024	0.3535	0.0441
10	Red	9.0	0.6024	0.3047	0.0929
12	White	81.5	0.3080	0.3188	0.3732
13	Grey	13.6	0.3197	0.3325	0.3477
14	Black	3.7	0.3058	0.3209	0.3833

The paints were applied to spherical aluminum floats, 20 cm in diameter. Holes were drilled in each float and they were filled with sufficient water to reduce them to very slight positive buoyancy. The floats were submerged, one or two at a time, either from the surface by use of a pulley system or by a SCUBA diver on the bottom operating an anchor and snap-hook system. Viewing was done either on a horizontal path by SCUBA divers or on a vertical path from the surface. In each case the target was viewed against the natural water background.

Comparative visibility of the various colored spheres was generally assessed by a color-naming technique. Spheres were presented, singly, in a random order, and the subject was asked to name the color he saw. The distance between the subject and the ball was between that at which all of the colors could be perceived clearly and that at which none could be seen. This distance is referred to as the threshold or limit of visibility.

In addition to color naming, brightness comparisons between several combinations of two spheres were made to assess which, among the several most visible colors, was easiest to see.

For the vertical line of sight from the surface, data were obtained by color naming, as described above, and also by moving the sphere up from a depth at which it was not visible to the distance from the surface at which the color could be correctly identified.

Natural illumination was used throughout the experiment. Since each day's data consisted of relative comparisons among the various colors, no attempt was made to control the absolute illumination conditions. Instead, differences of absolute energy levels (caused for example, by a rainy vs sunny day) were compensated for by changing the subject's viewing distance for the day. While there are some variations of the spectral distribution of natural daylight due to atmospheric conditions, these should be minor compared to the selectivity of the water. This assumption was confirmed empirically by comparing runs on rainy and sunny days at the same location. Within the relative comparison of a single run, however, care was taken to exclude changing conditions which would affect visibility, such as variable cloud cover. (One run had to be omitted owing to visibility variations caused by intermittent schools of fish.)

Subjects for horizontal viewing were SCUBA divers attached to the Military Operations Branch of NSMC and to the Naval Mine Defense Laboratory in Panama City, Florida. For vertical viewing both divers and civilian members of the Vision Branch of NSMC were utilized. All subjects had normal color vision.

TYPES OF WATER INVESTIGATED

The same experiment was repeated in four different bodies of water, which were chosen to sample the continuum from very murky to clear. Water samples were taken, spectral transmittance was measured with a Beckman spectrophotometer; the data are summarized in Table II. The over-all transmittance of visible light by one meter of water varies from 5% for the Thames River to 91.5% for the fresh water in Morrison Springs. In addition to this sizable difference of over-all transmittance, the color of the water also varies, owing to quite different spectral transmittance characteristics of the samples.

Both of these points are illustrated in Fig. 1 which shows the transmittance of 1 m of the various waters as a function of the wavelength of light. The curve for Morrison Springs is the same as distilled water and has a maximum transmittance of over 90% at 480 mμ. The only difference between the samples from the Spring

TABLE II. Characteristics of various bodies of water investigated.

Body of water	Description	Transmittance of sunlight by 1 m of water	α
Thames River near Sub Base	extremely murky, polluted	0.05	2.3
Long Island Sound in Fort Pond Bay	moderately turbid	0.50	0.7
Gulf of Mexico off Panama City	clear	0.90	0.1
Morrison Springs fresh water	famous for clarity	0.92	0.09

and the Gulf of Mexico is a lower transmittance in the violet and blue portions, presumably due mainly to plankton. The Long Island Sound water shows less transmittance throughout the spectrum, with the greatest loss in the blue and blue-green portions. In the Thames River, very little light is transmitted at all and the shape of the curve has been completely transformed, with the greatest transmittance in the long wavelengths.

The difference among the spectral transmittance curves depicted thus far are for only 1 m of water; they become even more exaggerated when calculated for the actual viewing distances used in the experiment. Since transmittance is related to viewing distance by a power function, the wavelength selection becomes extreme as the distance the light travels through the water increases.

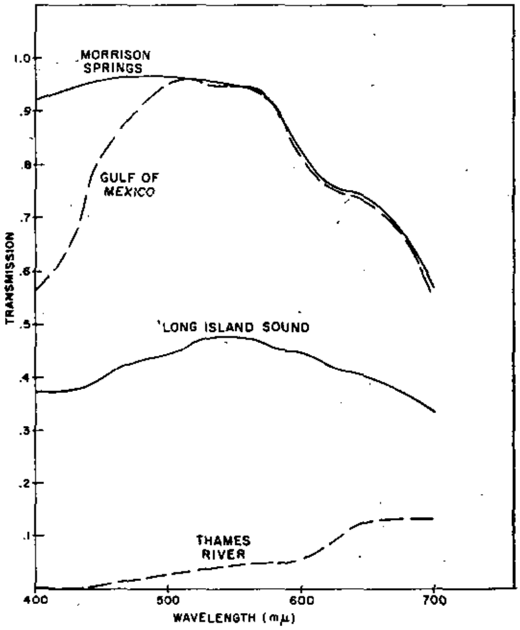

FIG. 1. Spectral transmittance of 1 m of various bodies of water.

Spectral transmittance curves have been calculated for the appropriate observing distances. The changes of the distributions are shown in the CIE diagram of Fig. 2. The tail of the arrow refers to the appearance of natural daylight through 1 m of the water sample; the head of the arrow shows the appearance through the

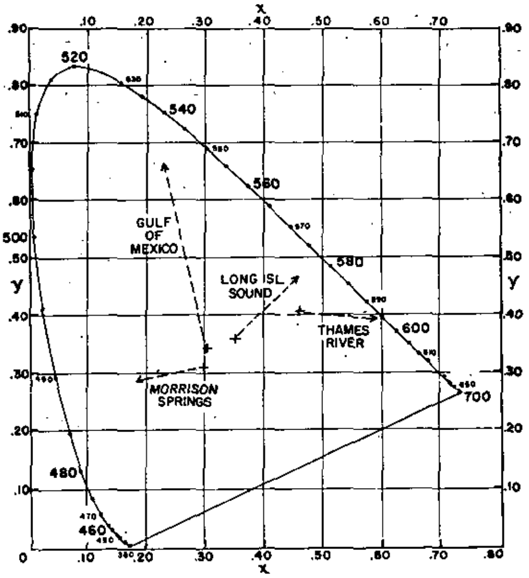

FIG. 2. Chromaticity values of 1 m of water compared with values calculated for distances actually used in experiment.

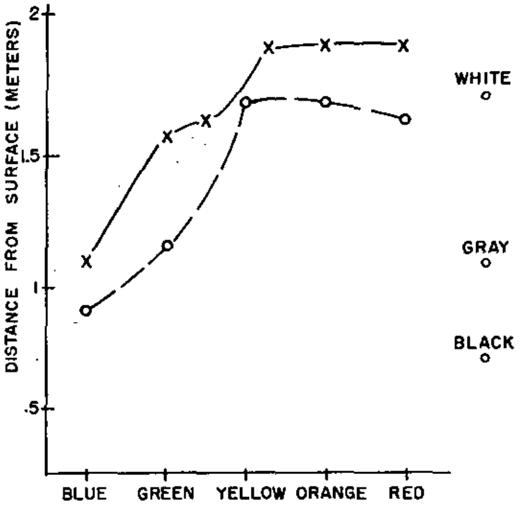

FIG. 3. Visibility of various colors in Thames River, Connecticut. Vertical viewing path, 15 subjects, fluorescent spheres ——, nonfluorescent - - - -.

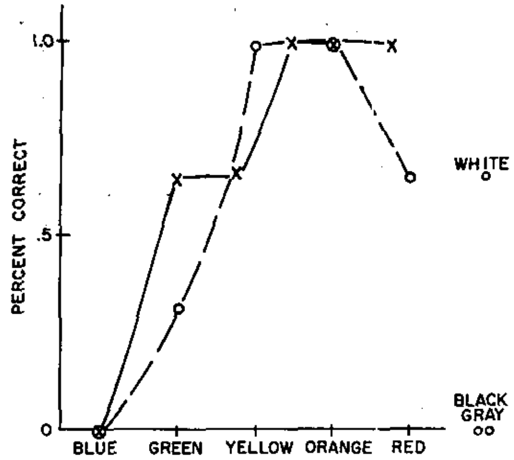

FIG. 4. Visibility of various colors in Thames River, Connecticut. Horizontal viewing path, 3 divers, depth 1.5 m, distance 1.8 m, fluorescent spheres ——, nonfluorescent - - - -.

distance that was actually used in each viewing situation. Thus, natural daylight becomes yellow-orange after filtering with 1.8 m of Thames River water, yellow-green with 7 m of Long Island Sound water, green through 34 m of Gulf water, and blue-green through 30 m of Morrison Springs water.

RESULTS

A. Visibility

Figures 3–9 present the data obtained in the different bodies of water. In each case, some measure of the visibility of the color is plotted as a function of the color. For the vertical or surface viewing condition, the visibility measure is the depth of the target when it was first seen. For the horizontal viewing condition, the measure is the proportion of correct responses obtained at a given distance from the target. Fluorescent and nonfluorescent colors are plotted separately in each figure, according to their dominant hue or hues on an arbitrarily spaced scale. (For example, yellow-green is plotted halfway between yellow and green.)

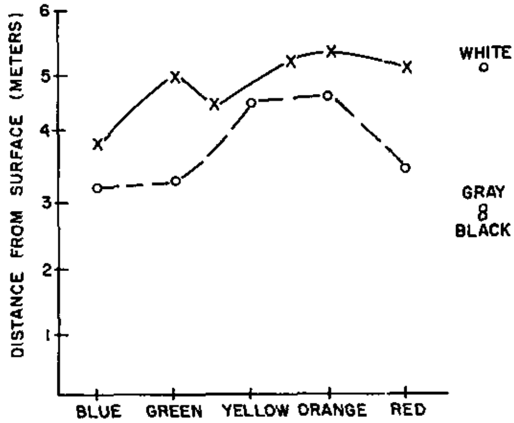

FIG. 5. Visibility of colors in Long Island Sound. Vertical viewing path, 5 subjects, fluorescent spheres ——, nonfluorescent - - - -.

Comparison of the various figures shows that visibility varies tremendously with the body of water, from 1.5 to 1.8 m in Thames River to 26 m in Morrison Springs. Furthermore, the colors found to be most and least visible are quite different in the different waters. Also, except for a few minor inversions, fluorescent paints are much more visible than non-fluorescent of the same color.

Specific results for each body are listed below:

Thames River

(1) The colors of highest visibility are: for the fluorescent paints, the oranges (yellow-orange, orange, and red-orange); for the nonfluorescent, white, yellow and orange.

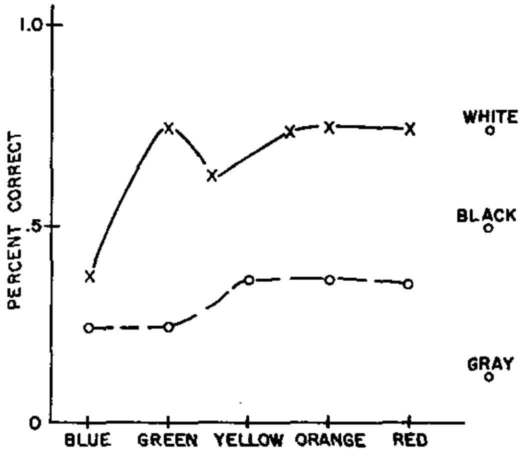

FIG. 6. Visibility of colors in Long Island Sound. Horizontal viewing path, 8 divers, depth 3.7 m, distance 3.4 m, fluorescent ——, nonfluorescent - - - -.

(2) The most difficult colors to see are black, gray, blue, and green.

Long Island Sound

(1) The most visible fluorescent colors are the oranges and fluorescent green. White and nonfluorescent yellow and orange are also readily seen.

(2) Lowest visibility scores are found for gray, blue, green, and black. Over-all differences among colors are smaller than in the other three bodies of water.

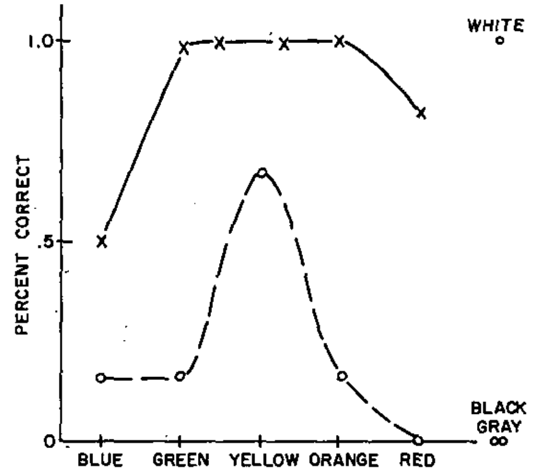

FIG. 7. Visibility of colors in Gulf of Mexico. Horizontal viewing path, 6 divers, depth 8.6 m, distance 11 m, fluorescent spheres ——, nonfluorescent - - - -.

Gulf of Mexico

(1) Fluorescent greens or yellow-oranges are the easiest to see, green at the longer distances and yellow-orange at the shortest. White is the best of the nonfluorescent colors, followed by yellow and finally green at the longer distances.

(2) Nonfluorescent red and orange join gray and black for the first time as the most difficult to see.

Morrison Springs

(1) Distinct differences among colors are found; the two fluorescent greens and white are highly visible, while all others are relatively poor.

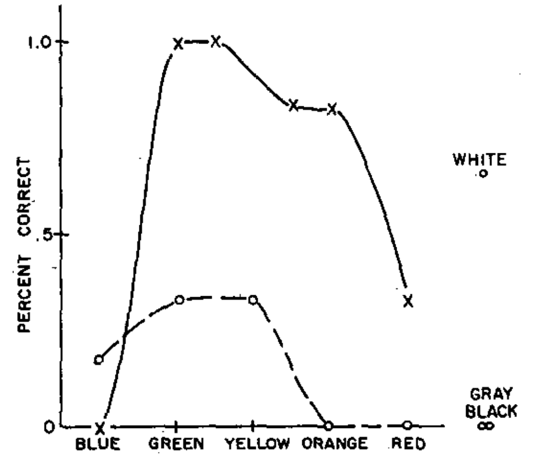

FIG. 8. Visibility of colors in Gulf of Mexico. Horizontal viewing path, 6 divers, depth 18 m, distance 16 m, fluorescent spheres ——, nonfluorescent - - - -.

(2) Black, gray, red, orange, and two of the fluorescent oranges were not seen at all. Blue, for the first time, is one of the easiest colors rather than the most difficult to perceive.

B. Comparative Brightness

The results of the comparative brightness measures were essentially the same as the visibility measures. In the Thames, simultaneous brightness comparisons revealed the three fluorescent oranges to be approximately equal to each other and considerably brighter in appearance than any other color. The judgments of the brightest colors gradually shifted toward the shorter wavelengths in clearer water until, at Morrison Springs, all subjects agreed that both fluorescent greens were much brighter than any of the oranges, and that fluorescent yellow-orange was much brighter than fluorescent orange.

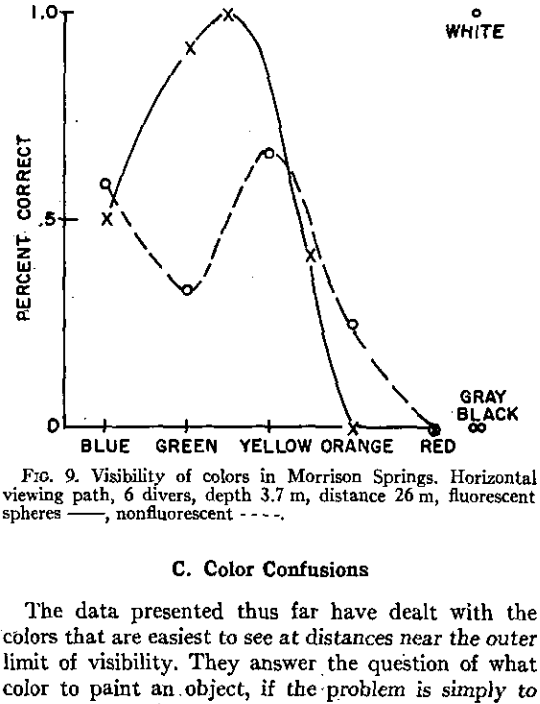

FIG. 9. Visibility of colors in Morrison Springs. Horizontal viewing path, 6 divers, depth 3.7 m, distance 26 m, fluorescent spheres ——, nonfluorescent - - - -.

C. Color Confusions

The data presented thus far have dealt with the colors that are easiest to see at distances near the outer limit of visibility. They answer the question of what color to paint an object, if the problem is simply to make it as visible or invisible as possible.

The question of which colors to use for color coding, or absolute identification of colors, is quite different but may be equally important in underwater salvage work. The data in Table III give answers to this question by listing the color names in order of frequency given to the various targets in the various bodies of water.

Certain very systematic changes take place. In water that transmits more of the long wavelengths than of short, e.g., the Thames, the perceived colors change

TABLE III. Color names given the targets in order of frequency in various bodies of water.

Color in air	Thames River	Long Island Sound	Gulf of Mexico	Morrison Springs
FLUORESCENT				
Blue	Green Green-blue	Blue Green	Blue	Blue
Green	Green	Green Blue Yellow	Green Yellow	Yellow Green
Yellow-Green	Gray White Yellow	Yellow Green White	Yellow Green White	Yellow Green White
Yellow-Orange	Orange Red	Orange	Orange	Orange Yellow
Orange	Orange Red	Orange Red	Orange Red	Orange
Red-Orange	Red Orange	Orange Red	Orange Red	...
NONFLUORESCENT				
Blue	Gray Green Blue	Blue	Blue	Blue
Green	Green	Green Gray	Green Blue	Green
Yellow	Yellow Orange	Yellow Orange	Yellow	...
Orange	Red Orange	Orange	...	Orange Yellow
Red	Red Red-Orange	Orange Red	Black	Black
White	White Yellow	Green White Yellow	White Green Blue	White Blue
Gray	Gray	Green Black	Blue	...
Black	Black	Black	...	...

toward the longer wavelengths. Blue thus is rarely reported as blue but rather green; yellow is seen as orange, orange is often called red. On the other hand, in the blue water of the Springs, the opposite tendency is seen. Among the neutrals, white often takes on the color of the water in which it is submerged. All of these differences are, of course, in accord with the spectral distribution of light from the target which reaches the eye after being filtered by the water.

Since the appearance of each color is almost always changed toward the ones closest to it on either side in the spectrum, the best solution for correct absolute identification is to use only two colors. One, chosen from the short wavelength portion of the spectrum, green, and one from the long, orange, should never be confused. Black is always correctly identified and can be added to green and orange as a third color. It will, however, be confused with red in clear water and with blue in murky water. White, while highly visible, is too often perceived as having a hue and should not be used where confusion among colors must be avoided. Any additional colors should be chosen for the particular body of water. For example, blue is perfectly identified in clear water and is a suitable addition there, while yellow and red could be easily discriminated and substituted for orange in murky water.

DISCUSSION

The data are in general agreement with theoretical predictions which can be made concerning visibility through the water. For adequate prediction, we must know (1) the absolute spectral distribution of energy falling on the target after transmission through a given distance d_1 of water, (2) the spectral reflectance of the target in the direction of the observer, (3) the spectral distribution of reflected energy reaching the eye after transmission through the distance d_2 to the eye, (4) the absolute spectral distribution of energy from the water background reaching the eye. From these values, we may calculate the contrast, both brightness and color, to the human eye and predict relative visibilties on the basis of the greatest and least contrast values.[3] For simplicity, d_1 and d_2 may be added for the nonfluorescent paint.[4] However, for the fluorescent paints, the distribution of exciting energy is completely distinct from the emitted energy and a variety of interactions are possible.

It has been pointed out that fluorescent paint has a theoretical advantage over nonfluorescent, since exceptional brightness and saturation are achieved by converting short wavelengths to long. This is particularly true of the oranges where reflectances close to 100% are possible. Thus, it is not surprising to find that fluorescent orange is frequently the most visible color.

In clear water an interesting interaction takes place. At depths where long wavelengths are normally poorly transmitted, the indispensable exciting energy for fluorescence, in the 400–520 mμ range, is well transmitted and should produce good fluorescent oranges. This is in fact true at moderate viewing distances; their appearance is both brilliant and of exceptional color contrast with the blue-green background. In clear water, however, the limits of visibility are pushed to such extreme distances that the orange fluorescent energy may be lost before it reaches the eye. This is clearly seen in Figs. 7–9 where the visibility of fluorescent orange drops dramatically as the viewing distance d_2, is increased from 11 to 16 to 26 m.

While some of the physical measurements necessary for precise calculation of underwater visibilities are rather difficult to obtain *in situ*,[5] the general picture can

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[3] S. Q. Duntley, J. Opt. Soc. Am. 53, 214 (1963); J. E. Tyler, Appl. Opt. 3, 582 (1964).

[4] This addition assumes that the attenuation of daylight in the sea is the same regardless of direction. While not strictly true (see, for example, Jerlov, in Ref. 1, p. 36–42), the assumption is adequate for purposes of this study.

[5] A suitable instrument recently developed by W. G. Fastie is described in J. E. Tyler, J. Opt. Soc. Am. 55, 800 (1965).

be obtained with fairly simple calculations from the relative spectral transmittances. Figures 10 and 11 illustrate this by comparing the chromaticities of several targets calculated in air and after filtering by water.

The changes produced by 1.8 m of Thames River water, in Fig. 10, are all toward the long-wavelength portion of the spectrum, thus accounting for the shifts of perceived colors in this direction. The largest shifts, for the blue and green, represent complete distortions of their normal reflectance values. There is less short-wavelength energy than long for these colors in the Thames and the over-all energy level is very low. The targets are correspondingly difficult to see, easily confused, and often called gray or black.

Transmission through water from the Gulf of Mexico produces chromaticity shifts in the opposite direction; calculations for a depth of 16 m plus the horizontal observing distance of 18 m show that all colors move toward the green portion of the spectrum (Fig. 11). For long-wavelength colors, the elimination of the most important part of the orignial reflectance curve, as evidenced by the sizable chromaticity shift, results in very low total reflectances and lack of visibility. Also illustrated in this figure is a basic advantage of the fluorescent paints. Since the energy conversion to longer wavelengths does not take place until after the energy has been transmitted through 16 m of water, calculations for fluorescent chromaticity are based upon a 18-m distance through water. The shift from the normal reflectance values is thus not nearly as great as for the nonfluorescent colors.

All of these calculations are based upon transmission through that distance and depth which represent the limit of visibility for that body of water. As these distances, either between the observer and the target or the target and the surface, are reduced, with consequent reduction in filtering action of the water, the chromaticities and reflectances will gradually revert toward their values in air.

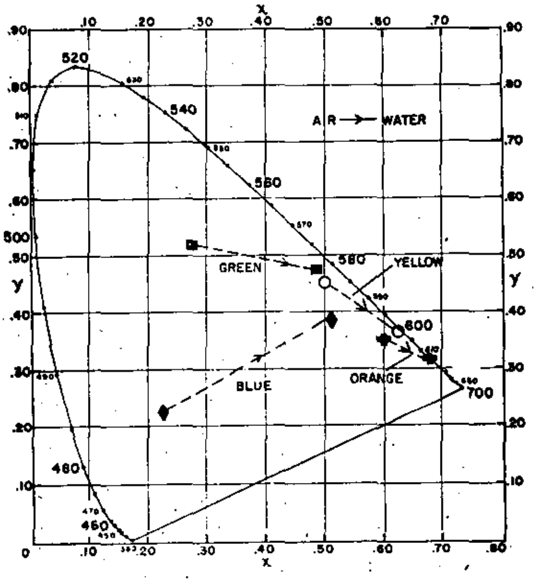

FIG. 10 Changes in chromaticity due to selective transmittance of water from Thames River, Connecticut, at depth of 1.8 m.

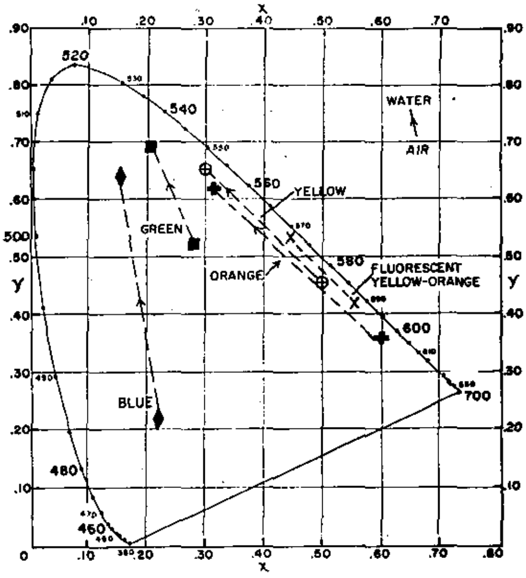

FIG. 11. Changes in chromaticity due to selective transmittance of water from Gulf of Mexico at a depth of 16 m and distance of 18 m.

It has been contended that black is a highly visible color underwater. This was never found in our studies (it was, indeed, the least visible), except in the sense that it was always correctly identified when it was finally perceived. The poor visibility is presumably due to the low contrast provided by black and gray against the dark water background obtained when the subject is at the maximum viewing distance. This conclusion is further supported by the fact that the hues which were not well transmitted by the water (i.e., red in clear water and blue and green in murky) were very difficult to see and were often perceived as black when they were seen. Certain situations can be anticipated in which black could be one of the easiest of non-fluorescent colors to perceive, such as against a white sand or a brightly lighted background. This, however, only serves to emphasize the care with which predictions of underwater visibility should be made.

SUMMARY

I. The colors that are easiest to see underwater at the limits of visibility with natural illumination and a water background are as follows:

(1) For rivers, harbors, and other turbid bodies of water, fluorescent orange is the most visible. Non-

fluorescent colors of good visibility are white, yellow, orange, and red.

(2) For coastal waters of mediocre clarity, fluorescent green and fluorescent orange are superior. White, yellow, and orange are the best non-fluorescent colors.

(3) For clear water, fluorescent greens and white are the best choice. As the clarity of the water is increased, with a consequent increase of viewing distance, the most visible color will change from yellow-green to green to blue-green.

(4) Fluorescent materials are superior to non-fluorescent materials of the same color in all bodies of water. White is the best non-fluorescent material in all bodies of water.

II. The most difficult colors to see at the limits of visibility under natural illumination and a water background are gray and black. Others that have poor visibility are those whose major spectral components are absorbed by the water; i.e., orange and red in clear water and blue and green in murky water.

III. Only a limited number of colors will not be confused with other colors underwater. To avoid confusions, if absolute identification is important, the following combinations are suggested:

(1) Green, orange and black.

(2) Blue, green, orange and black in clear water. (Avoid black and red together.)

(3) Green, yellow, red, and black in murky water. (Avoid blue and black together.)

ACKNOWLEDGMENTS

The authors wish to thank Capt. W. F. Mazzone, MSC, USN, who conducted the experimentation underwater and Michael Greenwood, who served as assistant and subject. We also gratefully acknowledge the help of all the Naval divers, from the Submarine Medical Center and the Naval Mine Defense Laboratory, who served as subjects and without whom the experiment would have been impossible.

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SCIENCE

Underwater Vision

The physical and psychological bases of the visual distortions that occur underwater are discussed.

S. M. Luria and Jo Ann S. Kinney

It is often said nowadays that man, after millennia of merely scratching the ocean's surface, stands on the threshold of returning to the sea. Many believe that the conquest of "inner space," as it is sometimes called, will prove to be far more important than the conquest of outer space. The oceans obviously contain incalculable treasures of food and minerals. A presidential commission has recently urged a vigorous and systematic investment in efforts to understand, exploit, and preserve the oceans (*1*). Nevertheless, the return is still more of a challenge than a temptation. Countless difficulties await man in the cold, bleak, and dangerous depths. Among them is simply seeing. In this article we review part of the research that we have recently been doing at the Naval Submarine Medical Center in Groton, Connecticut, on some of the problems of seeing underwater.

Alterations of the Physical Stimuli

Every aspect of vision appears to be altered underwater. These modifications in the appearance of the scene have a physical basis, for radiant energy is profoundly changed when it travels through water rather than air. First, water transmits far less total energy than air does. The fundamental equation describing the transmission of energy is the same for air and water:

$$P = P_0 e^{-\alpha d}$$

where P is the radiant power reaching a distance without loss, P_0 is the radiant power at the initial point, e is the base of the natural logarithmic system, α is the extinction or attenuation coefficient, and d is the distance (*2, 3*). The numerical value of α, however, is generally larger by a factor of 1000 or more for water than for air. The relatively large size of α means a rapid attenuation of light with increasing depth. If 90 percent of the incident energy is transmitted through 1 meter of water, 81 percent will be transmitted through 2 meters and only 37 percent through 10 meters.

The magnitude of α depends on the size of two components, (i) loss due to scattering of the energy by minute particles suspended in the water, and (ii) absorption of the energy by the water. Each of these has important visual consequences.

Scattering causes a loss of energy from the line of sight between the object and the eye, blurring of the outline of the object, and a decrease in the natural contrast between the object and its environment (*3*). As a rough rule of thumb, we can say that the luminance contrast between an object and its background must be at least 2 percent in order for the object to be visible (*4*). While rarely a problem in air (except in fog or smog), the loss of contrast does become significant in water, because of this scattering.

The interesting aspect of the loss of energy due to absorption is that it varies with wavelength and with the particular type of water involved. Figure 1 shows transmission curves measured through a distance of 1 meter of water for some of the different bodies of water in which

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we have worked. At the top is the transmission curve for water from Morrison Springs, Florida, a body of fresh water famous for its clarity. The curve is essentially the same as that for distilled water and has a maximum transmittance of over 90 percent at a wavelength of 480 nanometers. Water from the Gulf of Mexico (and the Caribbean) has a lower transmittance in the violet and blue, presumably because of absorption of these wavelengths by plankton. The water from Long Island Sound is typical of coastal water; it shows less transmittance throughout the spectrum, with the greatest loss in the blues and blue-greens. Finally, the Thames River in Connecticut is a fine example of a highly turbid, polluted body of water; it transmits very little light, and the shape of the curve is completely transformed, the greatest transmittance being at the long wavelengths. As a result of these variations, both the absolute and the relative visibility of colors underwater vary greatly at different distances and in different bodies of water.

Finally, light rays are refracted as they pass from water to air (*5*). This refraction displaces the optical image and causes distortions in the apparent size, distance, and direction of the object.

Thus, an underwater object is usually viewed by light that is insufficient and that has been scattered and drastically changed in wavelength, and the optical image has been modified in size and position. The object is, in short, less visible than it is in air, its size and color seem different, and it is not located where it appears to be. We turn next to an examination of some of the perceptual consequences of these physical distortions.

Visual Acuity

There are several different kinds of visual acuity—a term which refers to the fineness of detail that can be perceived. We can distinguish, for example, between resolution acuity and stereoscopic acuity ("stereoacuity"). The former is the ability to resolve small details; the latter is the ability, based specifically on binocular disparity, to perceive differences in the relative distance of different objects.

As a result of refraction of the light rays at the water-air interface, a virtual image of an underwater object is created at three-quarters of the distance from the interface to the object. The retinal image of the object is thus larger than the image from the same object in air (*6*).

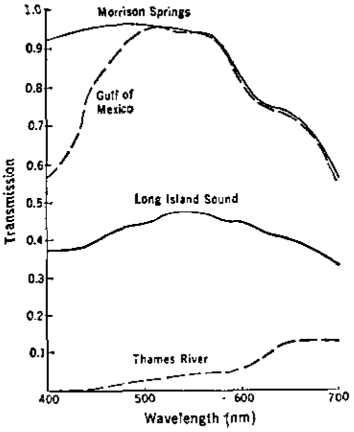

Fig. 1. Transmission of various wavelengths through a distance of 1 meter of various bodies of water. The water varies from exceptionally clear in Morrison Springs, Florida, to very turbid in the Thames River at New London, Connecticut. The peak transmission shifts toward the long wavelengths as turbidity increases.

As a result of this magnification, we would expect maximum resolution acuity and stereoacuity to be better underwater than in air. Indeed, Kent and Weissman (*7*) have found this to be true for resolution acuity under ideal conditions. By "ideal conditions" we mean very clear water, a clean face mask, and short viewing distances. Since these conditions are rare, it is more common to find that acuity is poorer underwater than in air.

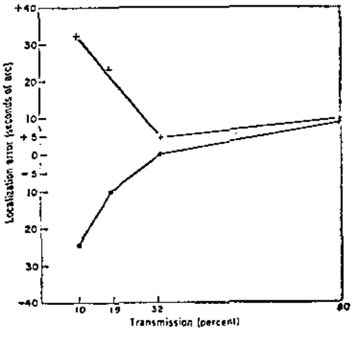

Fig. 2. Stereoacuity in water of various clarities. Typically in such an experiment, half the subjects, in attempting to set a movable rod at the same distance as a stationary rod, consistently set it too near, and half consistently set it too far. For both groups of subjects the magnitude of the localization error increases as the clarity of the water decreases.

Quite different results, on the other hand, have been found for stereoacuity. This is somewhat surprising, since most changes in physical conditions affect this form of acuity in much the same way that they affect resolution acuity (*8*). Yet we, working at short distances in an experimental pool (*9*), and Ross (*10*), working at much greater distances (up to 18 meters) in the Mediterranean, found stereoacuity very much worse underwater than in air. Furthermore, both the size of the error made by a subject attempting to set an object at the same distance from him as a test object and the variability of his settings increased as the clarity of the water decreased (Fig. 2). Since this drop in stereoacuity with decreasing clarity of water closely resembled the drop in stereoacuity with decreasing target contrast found by Lit (*11*), we have concluded that a major cause is the loss of contrast produced by the increasing turbidity.

However, this does not explain why stereoacuity is about three times poorer in the clearest water, where there appears to be no loss of contrast or of target visibility (*9*), than it is in air.

One aspect of the underwater scene that is distinct from the scene in air seems pertinent: the fact that there are few clearly visible objects: the world appears hazy, lacks definition, and approaches what is known in psychology as a *Ganzfeld*, an unstructured, homogeneous field of view. It is well known that a *Ganzfeld* distorts many visual functions (*12*), impairs target detection (*13*), and degrades other processes which are considered to be basically foveal, such as reading (*14*). We therefore tested the hypothesis that loss in the water of much of the usual peripheral stimulation is the cause of the drop in stereoacuity. We determined the effect of reducing the extent of the field of view on both resolution and stereoacuity. Grating targets or a Howard-Dolman three-rod apparatus were presented to subjects through binocular viewing ports which afforded fields ranging from 45 degrees to only 3.8 degrees. The visibility of the test apparatus was, of course, always unobstructed for both eyes.

Reduction in the size of the field of view did not systematically affect resolution acuity but it had a clearly delete-

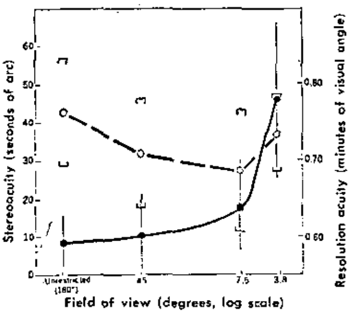

Fig. 3. Resolution acuity (dashed line) and stereoacuity (solid line) with various fields of view. The vertical lines give the average variability for the subjects with respect to the stereoacuity thresholds, and the horizontal brackets give the average variability with respect to the resolution acuity thresholds.

rious effect on stereoacuity (*15*). Under every condition of restricted view, there was an increase in both the error and the variability of the equidistance setting as compared to performance when the field of view was unrestricted (Fig. 3). The maximum reduction in stereoacuity was reduction to about one-fifth that of normal values, quite comparable to the reduction found in water. It appears likely, then, that it is the typical lack of peripheral stimulation in the underwater environment that causes the decrease in stereoacuity. This conforms to findings by Goldstein *et al.* (*16*) that individuals suffering from retinitis pigmentosa and a consequent loss of field down to a 10-degree visual angle also show a marked loss of stereopsis. It remains to be seen if underwater stereoacuity can be significantly improved by introducing clearly visible peripheral stimuli.

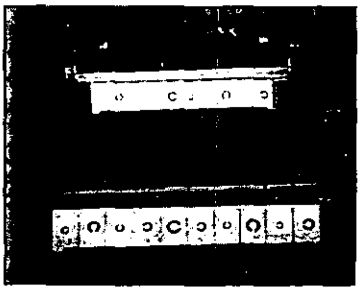

Fig. 4. Two photographs of the same target, both taken from a distance of 4.88 meters (top) in the air and (bottom) underwater.

Perception of Size and Distance

The magnification of the target image should also affect the perception of size and distance. Indeed, it is a common observation that underwater objects appear to be enlarged and closer than they really are, as shown in Fig. 4. This distortion is clearly seen when one stands with his head erect and looks at a partially submerged object with one's face mask half out of the water. Special techniques are needed to eliminate distortion in a photograph of an object half in and half out of the water (*17*). Divers report that it is a common occurrence to underestimate the distance of an object they are reaching for underwater.

We have made several studies on the perception of size and of distance underwater. Generally speaking, the perception of size can be predicted accurately from the magnification of the optical image. For example, subjects who were asked to judge underwater which disks were the same size as certain coins made selections that were much too small relative to the actual size of the coins. The size of the magnified retinal image of the selections did, however, correspond to the actual coin sizes (*18*).

On the other hand, the perception of distance is predictable from refraction data only within certain limited ranges. At very short distances and in clear water, distances are *under*estimated, as one would expect from the magnified retinal image. Figure 5 shows data obtained at short distances under two conditions of water clarity. In one, labeled "clear," transmittances ranged from 0.5 to 0.85 per meter of water; in the other, called "turbid," transmittances varied from 0.3 to 0.38 per meter. Target distances were underestimated when the target was closer than 1.2 meters; beyond that the median estimates were always too great. Moreover, the median estimates of distance were invariably greater under the more turbid condition (*19*).

Figure 6 is another example of the overestimation which occurred at all distances between 1.2 and 4.2 meters—virtually the limit of visibility in the lake in which the study was conducted (*20*). These results agree with those of Ross (*21*), who found similar overestimations in the Mediterranean at much greater distances.

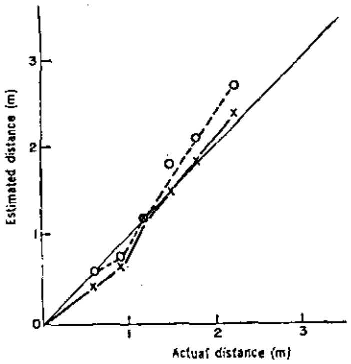

Fig. 5. Distance judgments made in water of different clarities and at relatively close distances. (*Dashed line*) *Turbid* water; (solid line) clear water. "Turbid" here means a transmission of 0.30 to 0.38 through 1 meter of water; "clear" signifies a transmission of 0.50 to 0.85 through 1 meter of water. The solid line indicates the locus of accurate judgments.

In the study depicted in Fig. 6, judgments of size and of distance were made by the same subjects. In air, both judgments were accurate, as is typically found when subjects have a full field of view and utilize binocular vision.

The overestimation stems in part from the loss of contrast underwater, due to the scattering of light by particles. Fry *et al.* and Ross have reported similar effects of reduced contrast in air (*22*), and the fact that the overestimations increase as turbidity increases lends further support. Overestimations are, however, more severe than would be expected solely on the basis of loss of contrast, for they do occur under conditions of fairly high contrast.

In order to determine whether or not the *Ganzfeld* characteristics of under-

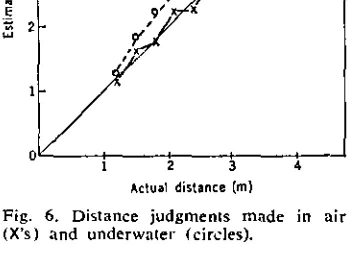

Fig. 6. Distance judgments made in air (X's) and underwater (circles).

water viewing were influential in depth perception, as they were in stereoacuity, the following control experiment was performed in air (*23*). Using the same targets and procedure as before, subjects estimated the distance to the target in three different environments. The first was an ordinary, well-lighted room about 6 meters square with all the usual apparatus and furniture in full view. Under this condition, the median estimates of distance were quite accurate (Fig. 7). When the experiment was repeated in the center of a large, empty, well-lighted gymnasium, the median estimate at every target distance was higher than in the first room; moreover, every estimate, except in the case of the shortest distance, was greater than the actual distance. Finally, the same procedure was carried out in a completely dark room with nothing visible except the target, at a constant, dim illumination. The distance of the target was now even more markedly overestimated, increasingly so as the actual distance increased. Thus, as fewer of the usual cues to distance were available, observers tended more and more to overestimate distance.

In short, both relative and absolute depth perception are less acute underwater. Various changes in the physical characteristics of the light underwater are responsible. Loss of contrast, which increases with increasing turbidity, and the typical lack of stimulation underwater cause increasingly larger errors in stereoacuity and increasingly larger overestimations of distances. Refraction results in underestimation at very short distances.

Perception of Color

The perception of color is another aspect of underwater viewing which is of considerable importance. Since the use of color is the most generally employed means of either enhancing or camouflaging an object, it is important to know which colors are most and least visible. We have already pointed out that water selectively absorbs electromagnetic energy, and that the degree of this absorption varies with the body of water (Fig. 1). Since a long column of water is one of the best monochromators that can be devised (*24*), the relative visibility of different colors can be expected to vary greatly with the body of water in which the colors are immersed.

Table 1. Amounts of underwater experience and original distortion.

Subjects	*N*	Amount of distortion* (cm)
Never used snorkel, mask	42	5.59
Occasionally used snorkel, mask	69	5.00
Frequently used snorkel, mask	20	3.30
Scuba class		
No scuba experience	14	3.23
Some scuba experience	12	2.64
Navy divers	8	2.03

* Group average.

Using scuba divers as subjects, we have investigated the relative visibility of colors underwater, in a number of different bodies of water which were selected for sampling a continuum from clear to murky. Natural illumination (*25*) and two of the most common underwater lights, a tungsten and a mercury light, were used (*26*). Spherical targets were painted black, gray, white, blue, green, yellow, orange, and red, with both regular and fluorescent paints. The latter have been widely used to increase visibility in air. They convert short wavelength energy, to which the eye is relatively insensitive, into longer wavelength energy, to which the eye is more sensitive. The converted energy is added to the reflected light, thus increasing the brightness and contrast of the painted object. In this way, reflectances in excess of 100 percent of the incident visible energy are often possible.

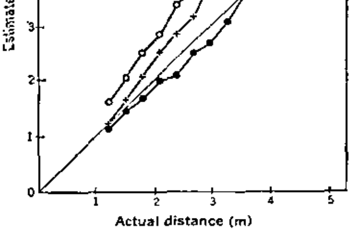

Fig. 7. Distance judgments made under normal conditions (solid circles), in the center of a well-lighted but empty gymnasium (X's), and in a dark room with nothing visible but the target (open circles).

The fluorescent paints were much more visible than nonfluorescent paints of the same color, and the visibility of the various colors was quite different in different bodies of water. In turbid water under natural light, red, orange, and yellow were the most visible colors (Fig. 8). With increasing clarity of the water, there was a shift in visibility toward the blue end of the spectrum. In water from Long Island Sound and the Gulf of Mexico, green, yellow, and orange were most visible. In Morrison Springs water, green was the easiest to see; red, which was the most visible in Thames River (Connecticut) water, was invisible, and blue, which heretofore had been the least visible, was now second only to green.

The fluorescent paints introduce an interesting interaction. The exciting energy for fluorescence is in the shorter wavelengths of visible energy. These wavelengths are well transmitted in clear water and produce good fluorescent oranges. The longer wavelengths that are thus produced, however, are relatively poorly transmitted. The result is that, in clear water, the oranges are brilliant at short distances but decrease rapidly in visibility as distance is increased.

Artificial lights introduce additional variables. For a given color to be visible, the wavelengths reflected by the paint must, of course, be present in the light source. Moreover, to activate the fluorescent paint, there must be short wavelengths present in the source, and they must be transmitted through the water to the target. Thus we found that with a mercury light, which is rich in short wavelength energy, the fluorescent paints are far superior to the nonfluorescent paints in every kind of water tested; with a tungsten light, the advantage of the fluorescent paints is lost in turbid water—there is too little short wavelength energy, and what little is available is poorly transmitted (Fig. 9). While the yellows and oranges were most visible with the tungsten light, yellow-green was most visible with the mercury light.

Thus, visibility can be predicted from a knowledge of the spectral sensitivity of the eye and the spectral distribution of energy reaching it. To specify the latter, we must know four spectral distributions: (i) the energy reaching the target, (ii) the reflectance of the target, (iii) the absorption of the water from the target to the eye, and (iv) the background. From these values, both the brightness and the color contrast can be calculated.

Color Coding

It is important to distinguish between the visibility of colors and their absolute identification. The question of which colors to use for color coding is an equally important problem, but quite different from the question of visibility. White, for example, while always highly visible, tends to take on the color of the water; for this reason, it is the easiest to confuse and should not be used for color coding.

In general, it is hard to distinguish a given color from the colors closest to it on either side of the spectrum. Where correct discrimination is important, it is best to use only two colors—one from each end of the spectrum—with black as a possible third choice. The choice of colors depends on the body of water and the type of illumination. We have found that use of green, orange, and black leads to the least confusion under most conditions. If four colors are needed, red and yellow may be substituted for orange in murky water in daylight or in any water with a tungsten light; blue may be used in clear water in daylight. However, with a mercury light—a commonly used underwater light source—we found no fourth color that was not confused with one of the other three.

Adaptation to Visual Distortion

It is clear that the visual distortion which afflicts the diver is extensive. Fortunately, there is a saving factor: human beings have a remarkable ability to adapt to changes in all kinds of stimulus conditions, such as illumination, color, and a wide variety of optical distortions.

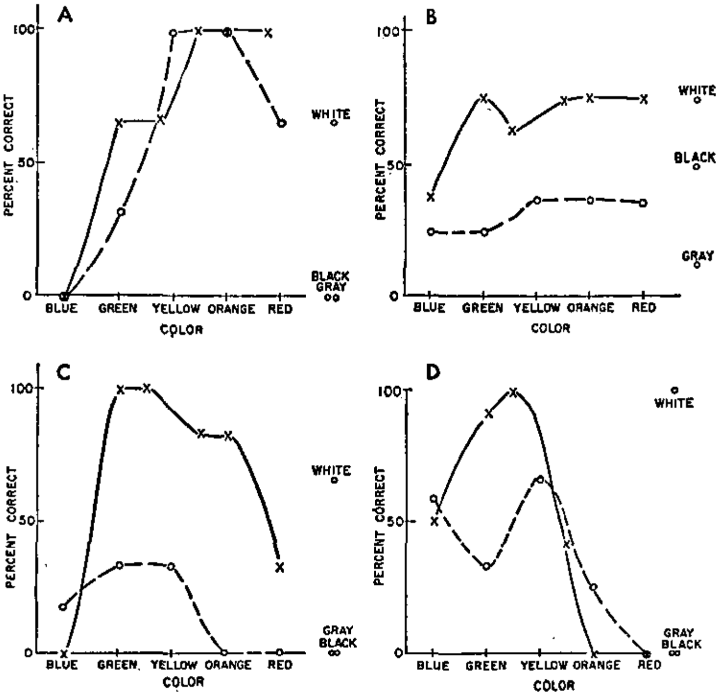

Fig. 8. The visability of various colors in (A) the Thames River, New London, Connecticut, (B) Long Island Sound, (C) Gulf of Mexico, and (D) Morrison Springs, Florida, for (solid line) fluorescent paint and (dashed line) nonfluorescent paint. Scuba divers viewed the colored targets one at a time at distances near the limits of visibility; these ranged from 1.8 meters in the Thames River to nearly 30 meters in Morrison Springs. The divers reported whether or not the target was visible, and if so, they attempted to identify its color. The two open circles shown on the abscissas of A, C, and D under "gray" and "black" indicate that these two colors were never visible.

Responses to distorted stimulation have been widely investigated in air (*27*), and our ability to adapt to even the most distorted situations has been recognized since Stratton wore inverting lenses, around the turn of the century (*28*). Recently there has been a great resurgence of interest in this type of adaptation (*29*). There have been some dramatic demonstrations, such as those of Kohler (*30*), whose subjects were able to ski, fence, and ride a motorcycle while wearing inverting lenses.

In all the studies of adaptation, the distortions have been produced artificially—by lenses, prisms, pseudophones, and the like. By "artificially" we mean that the subjects are fully aware that their perceptions are being manipulated by the experimenter and that distortions are being introduced. The underwater environment, on the other hand, provides a unique opportunity to study adaptation to perceptual distortions under natural conditions. That is, the subjects are not asked to wear unexpected and irrelevant equipment for the purposes of the experimenter, and the experimenter is clearly doing nothing to produce any distortions. Many subjects, in fact, are completely unaware that the distortions exist. Yet the distortions of size and depth are fundamentally the same as those produced in the laboratory; a diver's responses to the visual distortions underwater are at first the same as the responses of a subject wearing distorting lenses. When asked to pick up an object, both subjects will fail on the first attempt. Their errors in reaching are gradually reduced on successive attempts until both can make motor responses which are appropriate to the distorted display. When the distortion is removed, both will make errors in the opposite direction.

Using the apparatus shown in Fig. 10 (*31*), we have made extensive measures of hand-eye coordination of subjects with various amounts of underwater experience. If the subject has not adapted, his responses to the test objects underwater should reflect the fact that (i) they appear closer to him than they actually are, and (ii) they also appear displaced toward the edges. If the subject has adapted, his responses should agree more closely with the actual location of the targets than with the optical appearance.

The amount of theoretical optical

displacement on this particular test averages 5.6 centimeters toward the subject. The amount of apparent displacement is measured empirically by relating the marks made on the underside of the table in the water to those made in air. A value of zero indicates perfect correspondence between the two sets of marks; that is, the water produced no difference in the apparent location of the test objects. A positive value indicates a shift in the apparent position toward the subject; a negative value, a shift away from the subject, relative to the apparent position on the preliminary test in air.

Table 1 is a compilation of the data from many subjects tested over the past 2 years. There is excellent agreement between the amount of prior underwater experience and the amount of compensation for distortion. Only inexperienced subjects show complete reliance on the optical image; the average amount of displacement for them is the theoretical maximum of 5.6 centimeters toward the subject. For the others, there is increasing correspondence between their determination of the apparent location of the test object and its actual location. Those entering a Navy scuba class did well on the hand-eye coordination test even without prior scuba experience, presumably because of the extensive experience in the water required to qualify for the class.

Navy divers, while clearly showing the greatest amount of adaptation to the visual distortion, did not achieve zero distortion for a group average. There were, however, sizable individual differences, and it is noteworthy that the rank order correlation between the proficiency scores for the individual divers by their commanding officer and their results on this test was .85.

These differences in the test results for experienced and for inexperienced subjects suggest that considerable adaptation occurs naturally as a consequence of underwater experience. In an effort to measure this adaptation and its time course, a battery of underwater visual tests was given every week for 4 weeks to the men of a scuba class undergoing daily scuba training. During these 4 weeks the men adapted to the visual distortion to some extent, but the amount of adaptation was surprisingly small. At the end of 4 weeks of intensive work underwater, the divers exhibited an amount of adaptation sufficient to compensate for only 20 percent of their original visual distortion.

The failure to find sizable amounts of adaptation after a 4-week training period is in sharp contrast to the results obtained with prisms in air and undoubtedly resulted, at least in large measure, from two things: (i) visual stimulation underwater is minimal, and (ii) the distortion in water is symmetrical, rather than all in one direction. Furthermore, this failure suggests that specific activities should be provided for inexperienced scuba divers, to facilitate their adaptation.

Facilitating the Adaptation Process

We have carried out several experiments to determine the most effective way of training inexperienced subjects. Different groups of subjects were assigned different activities underwater and were tested for hand-eye coordination before and after these activities, both in air and in water. The difference between the two sets of underwater measures gives the measure of compensation; the difference between the measures in air gives the size of the aftereffect.

Some of the underwater activities were chosen on the basis of predictions from several theories that have resulted from extensive work on adaptation to distortion in air (*32–35*). For example, one activity involved repeatedly placing a small weight on different locations on a checkerboard grid. Some subjects moved their own hand, while, in the case of others, their hand was moved for them by the experimenter (*33*); other subjects were allowed to see the results of their movements only after the movement had been completed (*34*); another group consisted of pairs of subjects (Fig. 11) one of whom was blindfolded and directed in his movements by his partner (*35*).

Other activities were based on more practical considerations or on well-used educational techniques: some subjects

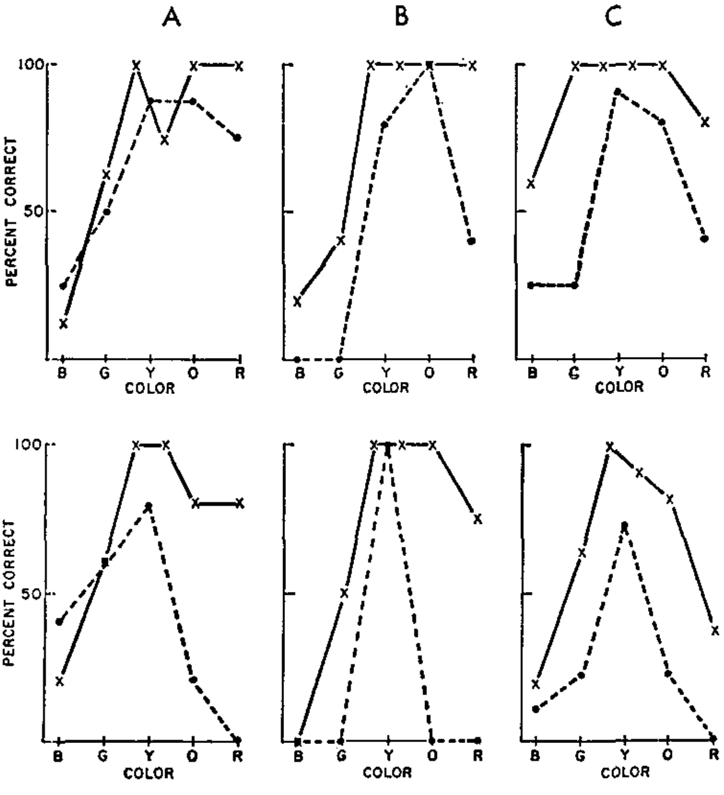

Fig. 9. The visibility of various colors in (A) the Thames River, (B) Long Island Sound, and (C) the Caribbean Sea, under illumination by (top row) a tungsten and (bottom row) a mercury light source. (Solid lines) Fluorescent paints; (dashed lines) nonfluorescent paints.

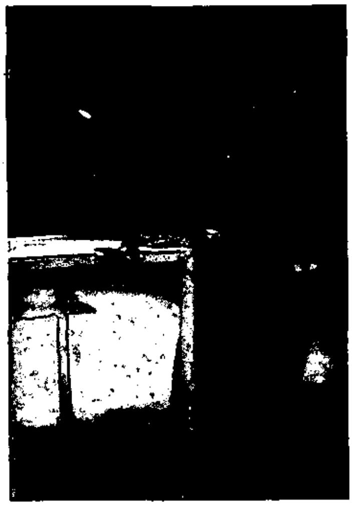

Fig. 10. Testing for hand-eye coordination underwater. The subject is directed to make a mark on the underside of the table directly under a given point on the top.

were given a lecture on distortion and then allowed to practice placing the test object; other subjects played games which involved the same type of placing response.

Finally, some subjects obtained all their underwater experience in one underwater session; for others, the same total training time underwater was divided into three periods separated by activity out of the water. Adaptation periods of two different lengths were tried, 3 to 4 minutes and 15 minutes. The former is very brief, of course, but is comparable to adaptation periods used by many investigators in air.

The results of these experiments were quite clear. Three to 4 minutes of underwater activity yielded about 20 percent compensation—a small but significant amount. The type of activity, however, made no difference; all subjects achieved the same compensation as long as they were in the water for that length of time with their eyes open.

Fifteen minutes in the water, however, produced not only greater amounts of compensation but distinct differences among the groups of subjects as well. Subjects who played various games underwater for three 5-minute intervals did significantly better than subjects in any of the other groups; they achieved 60 percent compensation on one test and 100 percent on another. Explaining the distortions to subjects and then allowing them to practice placing the test object did not help; in fact, this group did considerably less well than the group that played games. The control subjects, who simply swam around, showed the least compensation.

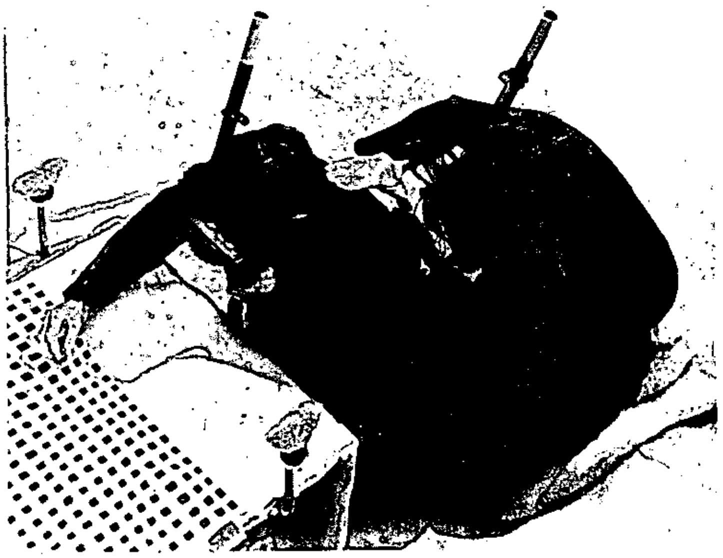

Fig. 11. Team practice in the placement task. The subject actually placing the weight is blindfolded. His teammate is signaling where to put the weight by tapping him on the shoulder.

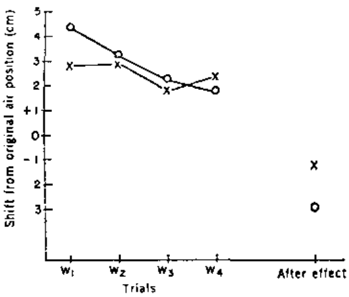

Fig. 12. Changes in the apparent position of targets with repeated testing underwater (tests W_1 to W_4) and on final testing in air (*after effect*). Positive values indicate a shift in apparent position toward the subject; negative values, a shift away from the subject relative to the apparent position of the object in air on the preliminary test. The total time in the water during the course of the experiment (W_1 to W_4) was 3 weeks for the scuba class (X's); for the inexperienced subjects (open circles) the total time in the water was 30 minutes, which included three 5-minute periods of practice and four test periods of about 4 minutes each.

Figure 12 illustrates our results. It shows four consecutive measures of compensation for the scuba class and for our most successful group. This group initially exhibited greater visual distortion than the scuba class and at the end of the test exhibited less. Moreover, it should be remembered that between the "Water$_1$" and "Water$_4$" tests, *the scuba class had had* 3 *weeks of* underwater activity, while our group had had only 30 minutes—including four testing periods of about 4 minutes each.

The factors underlying the success of this underwater activity in promoting adaptation in our subjects are not all known, but they undoubtedly include the active placing of the test object, the use of spaced rather than massed trials, and the fact that the activity held the interest and attention of the subjects. Further refinements and more time in the water should result in complete compensation for all subjects.

Summary

Both physical and psychological factors act to produce a wide variety of perceptual distortions underwater. The image of an underwater object is altered in apparent size and distance; the color and brightness of the object are changed, and its outline becomes less distinct. Decrements in a scuba diver's performance which result from these distortions, however, may be considerably lessened by adaptation to the underwater environment. Our involvement stems from a need to improve the visual performance of divers. But in the course of this work we have become increasingly aware of another great opportunity that the underwater world provides: It is a unique laboratory for the investigation of countless perceptual problems which bear on the most fundamental theories of perception.

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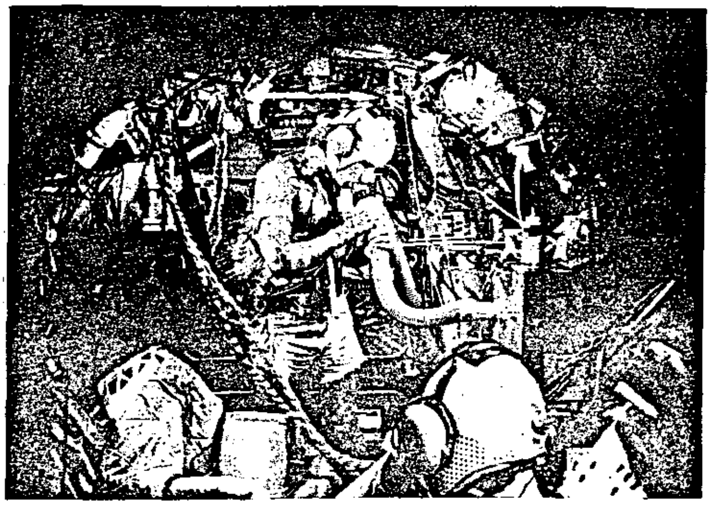
PREDICTIVE STUDIES IV

WORK CAPABILITY AND PHYSIOLOGICAL EFFECTS IN $He-O_2$ EXCURSIONS TO PRESSURES OF 400-800-1200 AND 1600 FEET OF SEA WATER

A COLLABORATIVE INVESTIGATION

EDITED BY
C.J. LAMBERTSEN, R. GELFAND AND J.M. CLARK



TECHNICAL EDITOR
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1978

E-8. VISUAL FUNCTION

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Studies of visual function during prolonged exposures to simulated depths over the range of 0 to 1200 fsw have not reported inert gas or hydrostatic pressure effects on vision (2-4). However, exposures in which vision has been studied have involved slow rates of compression. It was considered in planning the present study that the neural influences produced by rapid compression might have a demonstrable effect on the visual system. The present studies provided opportunities for both subjective and objective evaluation of visual function during exposure to hydrostatic pressures of 0-800-1200-1600 fsw and at rates generally faster than previously employed in compressions to the higher pressures. For this reason, repeated measurements of visual function were made both during stages of compression and during the protracted exposures at stable elevated pressures. Of the four visual function tests which were used, two (measuring central visual acuity and accommodation) were self-administered by the supervised subjects at saturation pressures and during the stable pressures at the extremes of transient excursions. Two (measurement of color discrimination and peripheral visual fields) were administered only at saturation pressures on days when transient compressions did not occur. These four measures of visual integrity provided useful indicators of specialized central nervous system function and are relevant to performance in diving operations.

METHODS

The specific tests selected for use in compression states were in addition to the comprehensive clinical

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ophthalmological evaluations of visual function performed before and following the pressure exposures.

EXAMINATIONS PRIOR TO COMPRESSION

Prior to the start of the study all subjects underwent an ophthalmological examination which included measures of muscle balance, ocular pressure, applanation tonometry and refraction, as well as slit lamp and full external examinations. All were found to be normal both clinically and perceptually.

MEASUREMENTS DURING PRESSURE

In addition to the clinical examinations, psychophysical measures of visual function provided baseline controls prior to compression and were performed during actual exposures to pressure.

CENTRAL ACUITY

Three copies of the chart were used, each having one of the three test columns uncovered. There were six possible test instructions (the order of reading letters or numerals), providing eighteen different tests to minimize complications due to learning.

A general instruction required the subjects to read and record the finest possible set of letters or numerals first, followed by the next coarsest acuity level. This procedure assured that a score would not be lost if a subject made all incorrect responses on a single set. The test chart was located on a modified MacBeth illuminator stand as shown in Fig. 1. The subject was seated in front of the chart with his eye position maintained at a fixed distance of 35.3 cm from the chart surface by means of a restraining device which rested on the bridge of his nose and cheekbones. Chamber lights were dimmed and the chart was viewed under the illumination of the MacBeth source which provided 0.95 log lux illuminance (the source was that of Illuminant C which is approximately equivalent to average daylight, having a color-correlated temperature of 6750° K). Measurements were taken monocularly, first for the right eye (left eye patched), and then for the left eye (right eye patched), since results of binocular measurements would represent only the better of the two eyes. The patch was translucent to prevent changes in the subjects' level of light adaptation.

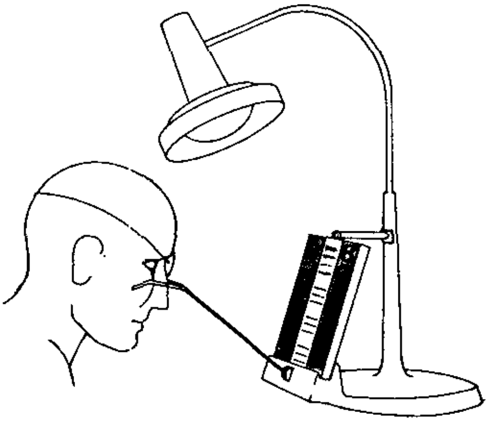

FIG. 1. Drawing of the modified MacBeth illuminator stand used for acuity measurements. The head restraining device ensures accurate placement of the subject's eyes at a fixed distance from the test chart.

ACCOMMODATION

A modified Adler Near-Point Rule (6) was used to measure accommodative ability by determining the closest distance at which the subject could accommodate. A fine-letter target (4 x 4 array of letters) attached to a millimeter rule was initially positioned to be in sharp focus; it was then slowly moved toward the eye (with the rule angled inward toward midline to avoid the problem of convergence of the eyes) while the subject was actively accommodating to the decreasing distance until blurring began at the near-point. Accommodative near-points were measured separately for each eye, recording a total of five readings per eye. All trials were performed with the chamber lights on and with the eye not being tested, occluded with a translucent eye patch. Baseline measurements were obtained for each subject several days prior to compression. Following one-half hour of practice during which no scores were taken, 20 or more trials over a two-day period were scored to establish control values.

COLOR VISION

Three different measures of color vision were obtained. The Farnsworth-Munsell 100-Hue Test of Color Discrimination (1) served as a preliminary comprehensive screening examination for color deficiency. All subjects scored normally in this test. The two tests of color vision administered during the actual pressure exposures were the Farnsworth Dichotomous Test (D-15 Panel) and the Farnsworth Tritanopic Test Plate. Both were presented monocularly to each eye under the MacBeth light source at the same illuminance level employed for the acuity test.

PERIMETRY

Peripheral visual field measurements were made monocularly for each eye with one subject (acting to perform the measurement) presenting the stimuli in a fully darkened chamber. Perimetric fields were plotted every 30^o on a Rodenstock Projection Perimeter employing the 1.12 mm test spot (13' visual angle). Field luminance of the hemisphere was fixed at 0.50 log mL while test luminance was maintained at 2.0 log mL. To assure that proper fixation was maintained throughout each test, the subject was continuously monitored by the subject-experimenter with the viewing device built into the perimeter. The stimulus was presented randomly in any one of 12 field locations, with each presentation being from the "not seen" to the "seen" mode.

TEST CIRCUMSTANCES

For Phases I and II of the overall study program, the measurements of acuity and accommodation were performed on only the rest subjects (Phase I: subjects LJ and FS; Phase II: subjects MP and FS) just before compressions and during maximum pressures of the excursions. Periods of one and one-half minutes were allotted for measurements, first of visual acuity and then visual accommodation. These measurements were also made at one atmosphere, before and after the pressure exposures. Additional measurements were made in Phase II at the stable saturation pressure of 1200 fsw.

Color vision and peripheral visual field measurements were made on all subjects in both Phases I and II, at one atmosphere before and after the exposures, and at the saturation pressures.

SUBJECT TRAINING

Each subject was trained to measure and record acuity, accommodation and color vision. During four separate training sessions, the tasks were repeated until the test package could be completed efficiently and with reproducible results within the allotted three minutes. The subjects were trained in pairs for the perimetry measurements, with each member of each team acting as subject and experimenter until consistent levels of performance were reached.

RESULTS

At no time in either the active compression or the stable periods at increased pressure during Phase I or II were visual manifestations such as scintillations or other subjective phenomena reported by any of the six subjects.

The data obtained from all subjects in both phases are summarized in Tables I, II and III.

VISUAL ACUITY

Phase I (0-800-1200), subject LJ (Fig. 2A). Visual acuity showed virtually no change from pre-compression control levels either during the stable pressure periods on the first compression day or on succeeding days. The only exception was an apparent change in the left eye from 20/20 to approximately 20/25 while at the 1200 fsw highest excursion

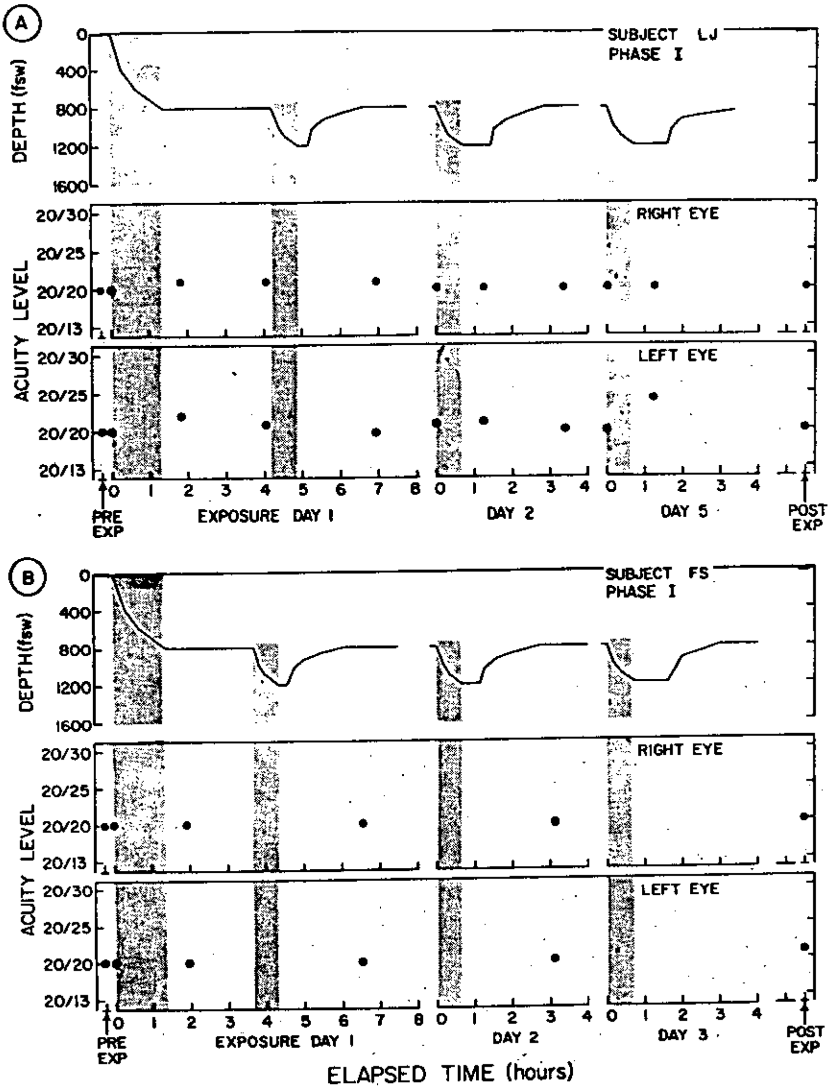

FIG. 2. Visual function (acuity) during exposure to pressures equivalent to 800 and 1200 fsw. Acuity level is given in standard Snellen numbers. (Phase I; A, subject LJ; B, subject FS.)

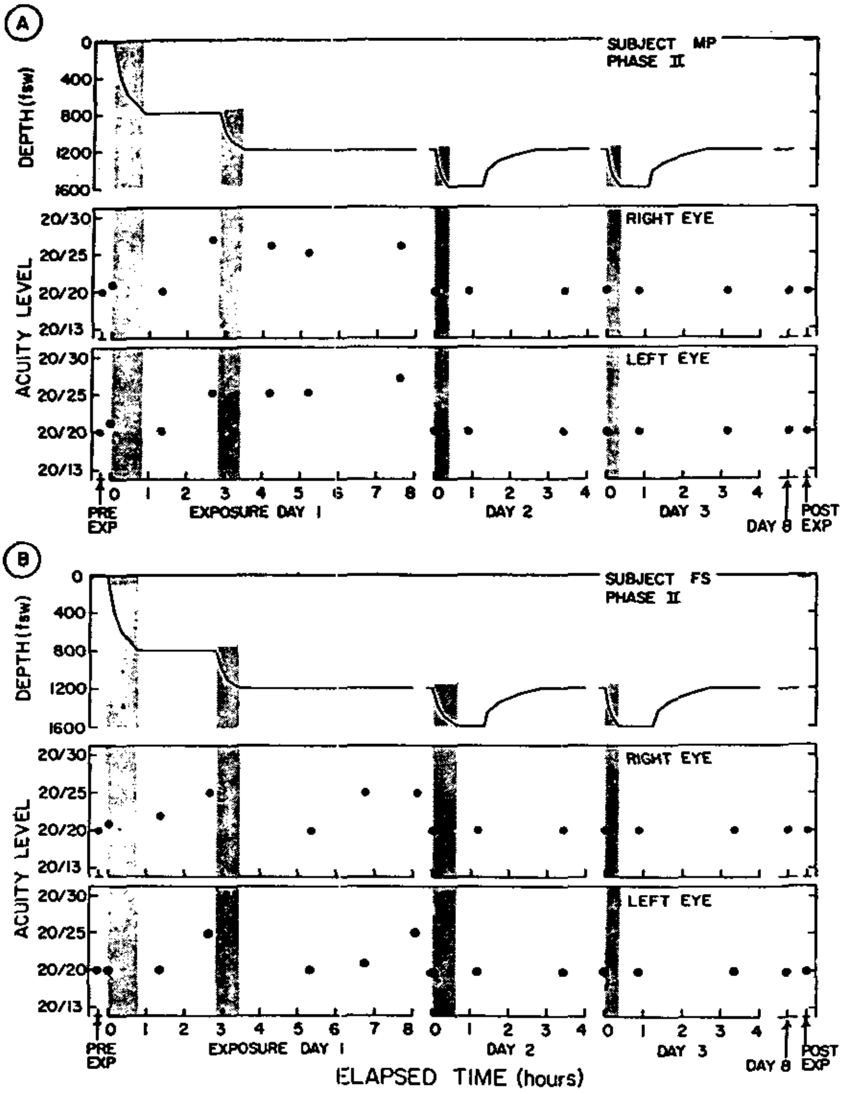

FIG. 3. Visual function (acuity) during exposure to pressures equivalent to 800, 1200 and 1600 fsw. Acuity level is given in standard Snellen numbers. (Phase II; A, subject MP; B, subject FS.)

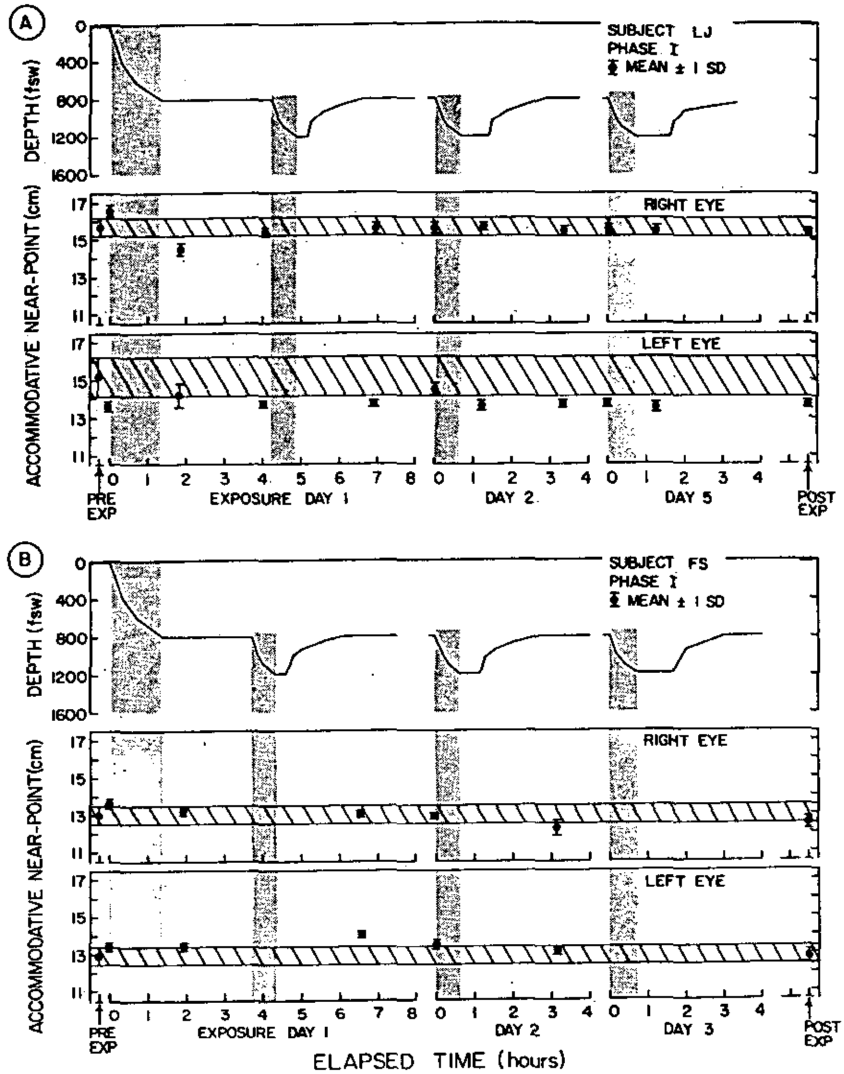

FIG. 4. Visual function (accommodation) during exposure to pressures equivalent to 800 and 1200 fsw. Near-point measurements are the average of five trials. (Phase I; A, subject LJ; B, subject FS.)

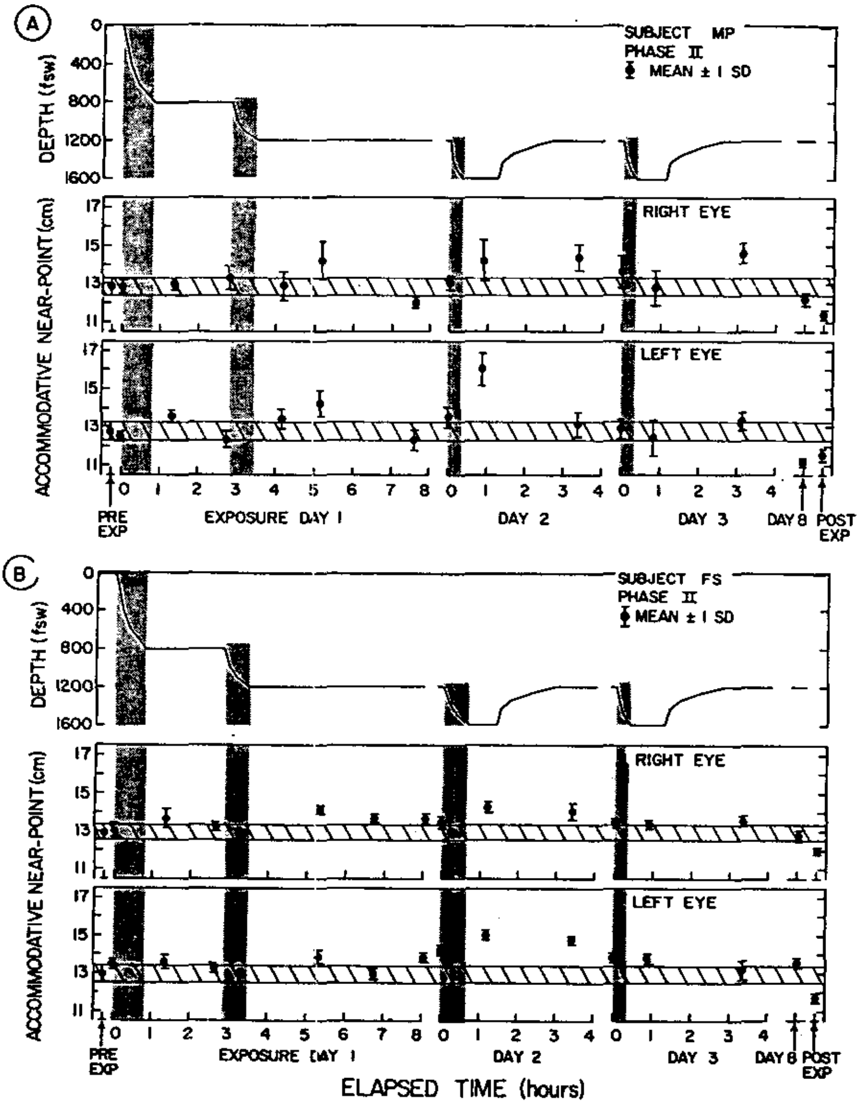

FIG. 5. Visual function (accommodation) during exposure to pressures equivalent to 800, 1200 and 1600 fsw. Near-point measurements are the average of five trials. (Phase II; A, subject MP; B, subject FS.)

TABLE I. Visual Function Tests During Exposure to Pressure (Subject LJ, Phase I)

Exposure Day	Depth (fsw)	Acuity		Accommodation			
		Right Eye	Left Eye	Right Eye		Left Eye	
				Mean	SD	Mean	SD
Pre-exp. baseline	0	20/20	20/20	Mean	15.7	Mean	15.2
				SD	0.5	SD	1.0
				N	30	N	25
1	0	20/20	20/20	16.6	0.22	13.6	0.20
	800	20/20-1	20/20-2[a]	14.5	0.27	14.2	0.54
	800	20/20-1	20/20-1	15.4	0.20	13.7	0.10
	800	20/20-1	20/20	15.6	0.26	13.7	0.10
2	800	20/20	20/20-1	15.6	0.26	14.5	0.23
	1200	20/20	20/20-1	15.7	0.10	13.6	0.16
	800	20/20	20/20	15.5	0.20	13.7	0.09
5	800	20/20	20/20	15.6	0.13	13.7	0.10
	1200	20/20	20/20-4	15.5	0.24	13.5	0.20
Post-exp.	0	20/20	20/20	15.4	0.16	13.7	0.10

[a] The number following the standard Snellen figure indicates the number of errors made by the subject.

TABLE II. Visual Function Tests During Exposure to Pressure (Subject MP, Phase II)

Exposure Day	Depth (fsw)	Acuity		Accommodation			
		Right Eye	Left Eye	Right Eye		Left Eye	
				Mean	SD	Mean	SD
Pre-exp. baseline	0	20/20	20/20	Mean SD N	12.8 0.4 20	Mean SD N	12.6 0.6 20
1	0	20/20-1	20/20-1	12.8	0.36	12.4	0.16
	800	20/20	20/20	13.0	0.25	13.5	0.33
	800	20/25-2	20/25	13.3	0.62	12.3	0.39
	1200	20/25-1	20/25	12.9	0.71	13.4	0.49
	1200	20/25	20/25	14.2	0.93	14.2	0.69
	1200	20/25-1	20/25-2	12.0	0.28	12.3	0.56
2	1200	20/20	20/20	13.0	0.33	13.5	0.52
	1600	20/20	20/20	14.2	1.03	16.0	0.87
	1200	20/20	20/20	14.4	0.63	13.1	0.65
3	1200	20/20	20/20	13.6	0.85	12.9	0.49
	1600	20/20	20/20	12.8	0.90	12.4	0.92
	1200	20/20	20/20	14.6	0.56	13.3	0.48
8	1200	20/20	20/20	12.2	0.29	11.1	0.20
Post-exp.	0	20/20	20/20	11.4	0.17	11.5	0.29

TABLE III. Visual Function Tests During Exposure to Pressure (Subject FS, Phases I and II)

Exposure Day	Depth (fsw)	Acuity		Accommodation			
		Right Eye	Left Eye	Right Eye		Left Eye	
				Mean	SD	Mean	SD
Pre-exp. baseline	0	20/20	20/20	Mean SD N	13.0 0.4 37	Mean SD N	13.0 0.4 36
Phase I							
1	0	20/20	20/20	13.6	0.24	13.4	0.19
	800	20/20	20/20	13.2	0.16	13.4	0.14
	800	20/20	20/20	13.0	0.11	14.0	0.13
2	800	-	-	12.9	0.09	13.5	0.23
	800	20/20	20/20	12.2	0.39	13.1	0.15
Post-exp.	0	20/20	20/20-1	12.5	0.28	12.7	0.38
Phase II							
1	0	20/20-1	20/20	13.1	0.36	13.5	0.19
	800	20/20-2	20/20	13.7	0.49	13.6	0.34
	800	20/25	20/25	13.3	0.22	13.3	0.20
	1200	20/20	20/20	14.2	0.18	13.9	0.32
	1200	20/25	20/20-1	13.7	0.22	13.0	0.26
	1200	20/25	20/25	13.7	0.24	13.9	0.21
2	1200	20/20	20/20	13.5	0.32	14.3	0.19
	1600	20/20	20/20	14.3	0.23	15.1	0.16
	1200	20/20	20/20	14.1	0.37	14.8	0.19
3	1200	20/20	20/20	13.5	0.15	13.9	0.09
	1600	20/20	20/20	13.4	0.18	13.8	0.23
	1200	20/20	20/20	13.6	0.24	13.2	0.45
8	1200	20/20	20/20	12.8	0.26	13.6	0.20
Post-exp.	0	20/20	20/20	12.0	0.04	11.7	0.13

pressure on day 5, which occurred while the subject reported feeling nauseous and lightheaded.

Phase I, subject FS (Fig. 2B). This subject showed no changes in acuity in the relatively few measurements made on him in this phase.

Phase II (0-800-1200-1600, subjects MP and FS (Fig. 3A,B). Both subjects showed a mild decrease in acuity after their compressions from 0 to 800 fsw and from 800 to 1200 fsw. The visual changes were associated with effects such as "mental slowness," "shakiness," "spinning" and fasciculations of thigh and abdominal muscles in subject MP, while subject FS had headache, nausea and coarse tremor (Section E-1). No changes in acuity for either subject were associated with subsequent excursions to 1600 fsw.

VISUAL ACCOMMODATION

Standard deviations (SD) of 20 or more pre-exposure trials were used to establish the regions of variation of controls for this measurement.

Phase I, subjects LJ and FS (Fig. 4A,B). No systematic changes in accommodation were associated with exposure to pressure. Almost all measurements which were outside their control regions deviate by less than 1/2 cm and show closer near-points than the controls.

Phase II, subject MP (Fig. 5A). The standard deviation for the measurement sequences of five trials was larger for this subject than for subjects LJ or FS and was usually larger during the pressure exposures than at sea level. Measurements which were outside the variation established by individual controls occurred at 1200 fsw following compression from the surface, during and after the first 1200-1600 fsw excursion, and at 1200 fsw following decompression from the second excursion. These deviations occurred in the presence of previously described symptoms on the first two exposure days and in the absence of symptoms on the third day (Section E-1).

Phase II, subject FS (Fig. 5B). Although exposure of FS to pressure in Phase II had slightly greater effects on accommodation than he experienced in Phase I (Fig. 4B), the magnitude of these effects was small, Minor deviations from control measurements occurred on each of the first three exposure days with the largest changes found during and after the first 1200-1600 fsw excursion on day 2. These deviations occurred in the presence of more numerous symptoms on day 1 than on days 2 or 3 (Section E-1).

COLOR VISION AND PERIMETRY

Phase I, subjects CC, LJ, FS, WS. Both the D-15 panel and Farnsworth Tritanopic Test Plate measurements were made at 800 fsw on exposure day 4 for CC and LJ and on day 5 for FS and WS. Color vision of all four subjects was completely normal. Visual fields (both eyes, all four subjects) were well within normal limits, both at one atmosphere and at 800 fsw.

Phase II, subjects CC, GM, MP, FS. Measurements made at 1200 fsw on exposure day 4 showed that all four subjects had normal color vision. Visual fields were within normal limits (both eyes, all subjects) both at sea level and at 1200 fsw.

DISCUSSION

The tests employed provided objective information concerning visual function before and just after each stage of rapid compression to high pressure. Although these tests were not done during dynamic stages of compression, the subjects did perform various perceptual, memory, cognitive and psychomotor function tests during compression (Section E-10) which involved the visual system, including reading and eye-hand coordination. There was no indication that visual disturbances per se impeded the performance of these tests. Nor did any of the subjects report visual disturbances of any kind either during rapid compression or at stable pressures equivalent to depths of 800, 1200 and 1600 fsw.

While there were essentially no changes in visual acuity or accommodation throughout Phase I, changes in these measures were noted in the more rapid pressurizations and the higher pressure of Phase II (Figs. 3 and 5). Changes in acuity observed in Phase II were associated only with compression from the surface, while changes in accommodation occurred during excursion to 1600 fsw and upon return to 1200 fsw. Although many of these changes occurred concomitantly with severe compression or hydrostatic pressure effects—which may have indirectly influenced test reliability, some were associated only with minimal symptoms of discomfort. Deviations from control levels were greater in Phase II than in Phase I, coincident with the increased rate of compression, greater saturation pressure and increased severity of symptoms.

Most changes in acuity and accommodation were bilateral. Even minor fluctuations almost always affected both eyes in parallel. Such responses are consistent with direct hydrostatic effects on vision by a common pathway in the central nervous system. However, attentional distractions induced by symptoms could also cause bilateral changes in vision test results.

The observed changes in accommodation (usually less than 2 cm) are considered to be functionally insignificant. While the greatest lengthening (from an average of about 12.5 to 16 cm) was noted to be unusual by subject MP as he recorded it, he commented that he did not sense any change in vision at that time. The greatest change in acuity (from 20/20 to 20/25) is considered to be functionally insignificant.

SUMMARY

No subjective visual disturbances were reported in these exposures to compression and prolonged residence at stable high pressure. Complex tasks involving vision and eye-hand coordination were performed throughout, without interference due to visual difficulties.

Relatively small, transient, and functionally insignificant changes in visual accommodation and acuity were observed in Phase II, but none were observed in Phase I. Most but not all of these changes coincided with the greater severity of discomfort reported by the subjects in Phase II as compared to Phase I.

Color vision and peripheral visual fields were normal at the stable pressures of 800 and 1200 fsw.

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Environmental Effects on Consciousness

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Effects of High and Low Oxygen Tension on the Visual System

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This review of the effects of hyperoxia and hypoxia upon the visual system, which summarizes much of our own work in this area, will be restricted to the retina. We will discuss, in particular, effects of oxygen upon the visual cells—those retinal cells which mainly determine the unique properties of the retina.

The visual cells of all vertebrates have the same general structure (Fig. 1). Each comprises a rod or a cone, divided into an outer segment and an inner segment, a nuclear region, and a "fiber" which synapses with the bipolar cell (Sjöstrand, DeRobertis, and others). The outer segment contains the photosensitive pigment, but it lacks, so far as we know, the ordinary metabolic activities such as those of the respiratory and the glycolytic systems. The inner segment contains cytoplasm rich in enzymes of general cell metabolism (Lowry *et al.*, 1956). Its distal part, near the origin of the cilium (which connects the inner segment with the outer segment) is filled with large mitochondria. In the rabbit—on which most of our experiments have been performed—this part is the only region of the visual cell which contains mitochondria and, therefore, is the principal, and probably the only region capable of reducing oxygen. In the mouse and in the rat, one additional mitochondrion is located within the synaptic region. For large parts of the visual cell, therefore, glycolysis may be the main source of energy. A uniquely high glycolytic activity of the mammalian retina in the presence of oxygen has long been known.

The unique structure and function of the visual cell and its separation into large compartments of different metabolic activities conceivably may be associated with a responsiveness to poisons or abnormal environmental conditions which differs from that of other cells, including the other retinal cells.

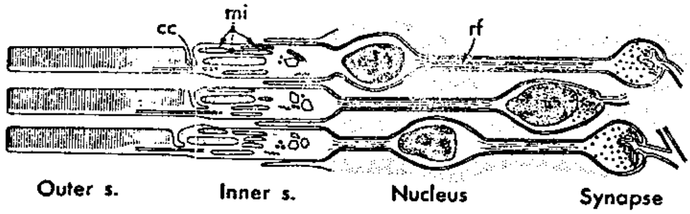


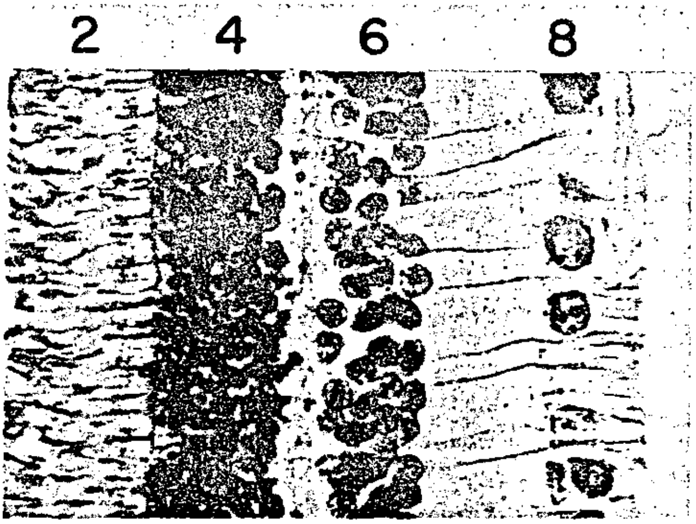
FIGURE 1.
Rod cell of the mammalian retina: Outer s—outer segment; Inner s—inner segment; cc—connecting cilium (De Robertis 1956); mi—mitochondria; rf—rod fiber. The shaded area denotes Müller cells which, like the glia cells of brain, fill the spaces between the neuronal elements of the retina.

VISUAL CELL EFFECT OF HYPEROXIA

Hyperoxia is one of several conditions to which the visual cell is more susceptible than the other retinal cells. This is manifested by the selective death of the rabbit's visual cells resulting from the exposure to a high oxygen pressure. In a normal rabbit retina (Fig. 2) the visual cells occupy about half the thickness of the retina. Their nuclei form the broad outer layer where they are arranged in 4 to 6 rows. It is this layer which most readily indicates the death of the visual cells. Figure 3 shows a section of a rabbit's retina 4 days after the rabbit had been exposed to 3 atmospheres of oxygen for about 4 hours. The outer nuclear layer is markedly reduced in thickness and in the number of nuclei. Those nuclei which are still evident show pyknosis, that is, clumping of their chromatin, indicative of cell damage beyond repair. If the eye had been removed a few days later, these pyknotic nuclei would have disappeared by autolysis. Consistent with the damage in the outer nuclear layer, there is deterioration and depopulation of the layer which contains the outer and inner segments. The inner layers of the retina, however, show no significant difference from normal. Even when all visual cells of a retinal section have undergone autolysis and disappeared, the ganglion cells and bipolars are fairly well and permanently preserved (Noell, 1952; Noell, 1953; Noell, 1958a; Noell, 1958b).

ELECTRORETINOGRAPHIC EFFECT OF HYPEROXIA AT 3 TO 7 ATMOSPHERES

The retina provides unusual advantages for the study of effects of agents upon cell life processes. The great uniformity and its remarkably ordered arrangement in distinct layers, each representing a different neuron or a part thereof, enables very accurate evaluation of any histological effect. However, it also provides one with a very simple measurement of certain of its functional capacities. This is the electroretinogram (ERG), the electrical response to a



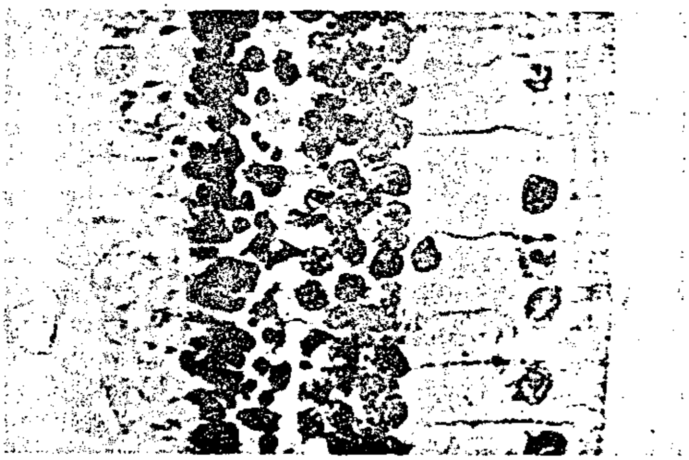


FIGURE 2 (*top*).
Section of normal rabbit's retina (hematoxylin-eosin, × 620). Retina is detached from pigment epithelium. 2—layers of the rods and cones with the outer and inner segments; 4—outer nuclear layer, comprising the nuclear regions of the visual cells; 6—inner nuclear layer, comprising mainly the (round) nuclei of the bipolar cells; 8—layer of the ganglion cells.

FIGURE 3 (*above*).
The retina of a rabbit exposed to 3 atmospheres of O_2 (30-lb chamber pressure) for 3.5 hours. The chamber pressure was kept at 18 lb for the following 2 hours, and thereafter at 10 lb for 3.5 hours. *During exposure, the animal was anesthetized* by urethane. The photographed section is from approximately the same retinal area as shown in Fig. 2. (Hematoxylin-eosin × 620.)

flash of light, recorded by an electrode in contact with the cornea or inserted in animals into the anterior eye chamber (Noell, 1958b; Noell, 1959). The origin of the ERG is still a matter of dispute. The ERG does not compound the activities of all elements of the retinal pathway in response to light stimulation. It certainly does not record the excitation of the retinal ganglion cell. It may contain components which depend upon the function of the second neuron, the bipolar cell. However, its greatest dependence is understandably upon the first neuron of the pathway, the visual cell. Although the visual cell may not be the actual site of generation of any component of the ERG, a failure of the visual cell function, nevertheless, must become evident in a light-induced reaction, such as the ERG. With no exception, all agents known to impair ultimately the structural integrity of the visual cell, while leaving unaffected histologically the bipolar cells and the ganglion cells, also affect readily the ERG in one or the other characteristic way (Noell, 1958a; Noell, 1958b).

Continued exposure of the rabbit to an oxygen pressure of one atmosphere or more resulted in a severe attenuation or the disappearance of the ERG whether or not systemic effects were evident. At pressures of several atmospheres, when oxygen poisoning developed rapidly, the cornea-positive *b* wave was the most susceptible component of the ERG (Fig. 4).

We utilized the reduction of the *b* wave for the quantitation of the retinal effect of oxygen poisoning. A *b*-wave index was computed from the responses to 3 different intensities of light as shown in Fig. 5. The value of this index prior to oxygen exposure was taken as 100%. The experiments were performed on restraint adult albino rabbits. The steel chamber for exposure to high oxygen pressures was equipped with windows through which the light flash reached the eyes. The ERG was recorded intermittently by inkwriter and cathode-ray oscilloscope. Records of the electrocardiogram and the electroencephalogram were simultaneously obtained. Respiratory carbon dioxide was absorbed by soda lime in bags around and in front of mouth and nostrils or tracheal canula. Oxygen at 10–20 liters per minute was flushed through the chamber at all times after it had been closed.

Experiments at 1 atmosphere of oxygen and at lower pressure were performed in sealed plastic chambers. Temperature, humidity, carbon dioxide, and oxygen concentrations were continuously monitored. The ERG was recorded during brief interruptions of exposure or after exposure had been terminated.

Typical relationships between oxygen pressure and its effect upon the *b* wave are illustrated by the curves of Fig. 6 which relate the *b*-wave amplitude to the time of exposure at different pressures. These curves show that the *b*-wave decline started after a characteristic latent period which was a function of the oxygen pressure. Once this decline had started it progressed without interruption, and unless exposure was terminated, it proceeded to complete *b*-wave disappearance. The rate of the decline was dependent upon the oxygen pres-

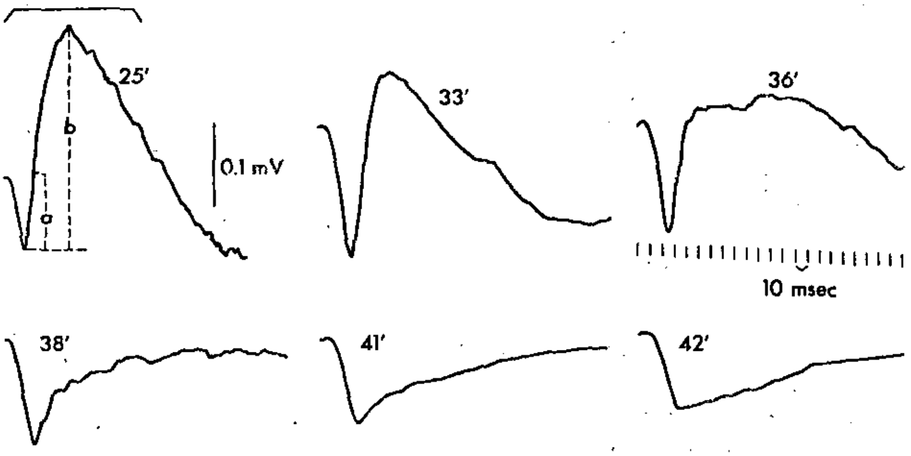


FIGURE 4.

ERG during exposure to 7 atmospheres O_2 (rabbit, urethane anesthesia). The increase in pressure from 1 atmosphere O_2 to 7 atmospheres O_2 occurred during 25 minutes; all time notations (in minutes) refer to the start of compression. No significant change *in the ERG was observed until the* chamber pressure reached 90 p.s.i. Respiratory arrest ensued 39 minutes after the start of compression; electrical brain activity disappeared at 45 minutes.

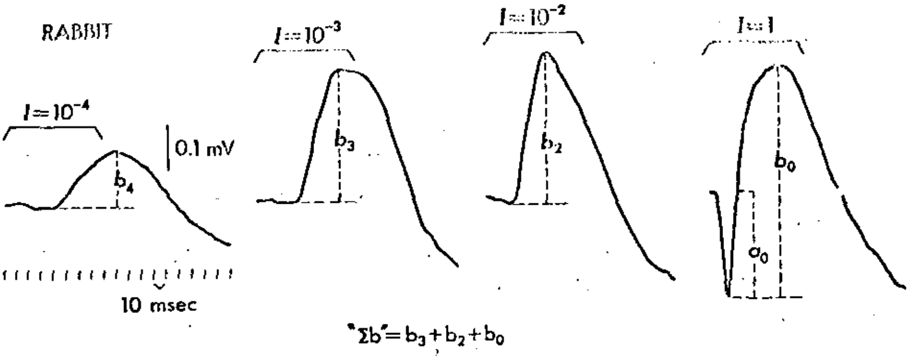


FIGURE 5.

Control ERG recorded by cathode ray. The beam is triggered by the "on" of the light flash of 120 msec duration. *I* indicates intensity of flash in arbitrary units. The *interval between* flashes is 4 seconds; the test begins with 3 stimuli of the lowest intensity, continues with three flashes of each higher intensity, and terminates with one flash of the highest simulus strength. The *b*-wave index (see text) refers to Σb.

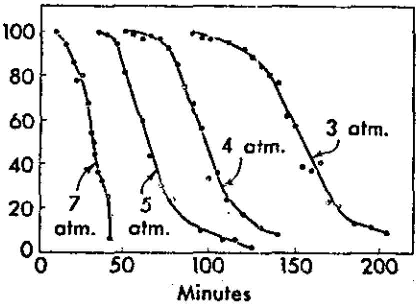


FIGURE 6.
Decline of the ERG at different pressures of O_2. Time is measured from onset of compression, 1.5 minute per one atmosphere above ambient pressure.

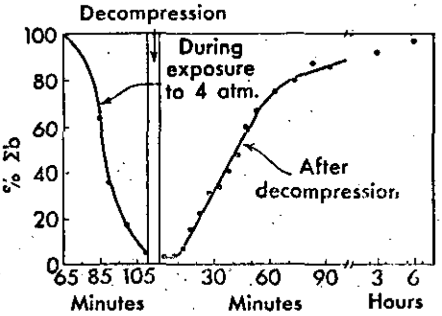
sure, and start and rate of decline changed about proportionately with the oxygen pressure. Except for the effect of very high pressure, when rapid systemic failure occurred, the ERG decline resembled a typical S-shaped survival curve. The average latency of the retinal effect, including the time needed to attain the nominal pressure, ranged from 20 minutes at 7 atmospheres to 100 minutes at 3 atmospheres. The average time from the start of the decline to the 50% amplitude level was 14 minutes at 7 atmospheres and 54 minutes at 3 atmospheres.

The toxic effects upon the brain manifested by convulsions appeared slightly earlier than the first change of the ERG if they appeared at all. However, at 3 atmospheres of oxygen only 40% of the animals showed convulsive activity at all; the ERG effect nevertheless developed. The occurrence of the death of the animal also did not obey the same dose-effect relationship as the ERG. At lower pressures, death was delayed much more than the appearance of the retinal effect. These differences seem to point out that convulsions and death are complex manifestations of oxygen poisoning, whereas the retinal effect measured by the ERG is determined by the susceptibility of a rather homogeneous cell population. We assume that this population is the visual cell population, but it may be any other population upon which the generation of the ERG depends.

Recovery from the effects upon the ERG occurred unless exposure was extended for several hours beyond the occurrence of the first effect. It was not possible to test the capacity for recovery at very high pressures because of the close association of ERG effect with the death of the animal. However, at 3 or 4 atmospheres, the systemic effects of oxygen poisoning were late compared to the ERG effect and recovery could be studied. When the transfer to normal oxygen environment immediately followed the decline of the *b*-wave, recovery started in a few minutes (Fig. 7). It proceeded at almost constant rate until 75% of the control amplitude had been regained. This required from 30 to 90 minutes. Recovery of the remaining deficit occurred slowly, and 3 to 6 hours were generally needed until the ERG was the same as prior to the exposure. Recovery was delayed when the exposure was prolonged beyond the

FIGURE 7.

Recovery of the ERG after exposure to 4 atmospheres of O_2. The rabbit was breathing room air after decompression.



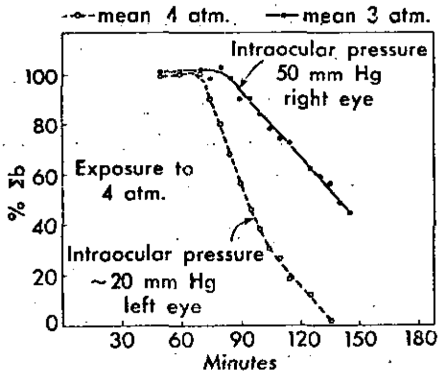
time of occurrence of a marked decrease in the *b* wave. It then often required more than 24 hours and it was occasionally incomplete. Of 6 animals exposed to approximately 3 atmospheres for 5 to 6½ hours (*b*-wave decline starting at about 2 hours), 4 showed death of a small fracture of the visual cell population indicating the irreversibility of the changes incurred during exposure.

CIRCULATORY AND HORMONAL FACTORS AFFECTING OXYGEN EFFECT

If one postulates that oxygen at high pressures produces its effect by a direct action upon the visual cells, the severity of the effect should be determined mainly by the oxygen tension within the tissue and all factors which influence tissue oxygen tension should be parameters of oxygen toxicity. Hence, one would expect that a reduction in ocular blood flow diminishes the toxic effect of oxygen. In order to test the validity of this argument, the intraocular pressure of one eye was kept continuously increased at 50 mm Hg during the exposure of the animal to 4 atmospheres of oxygen while the other eye served as control. As shown in Fig. 8, the decline of the *b*-wave was delayed in the experimental eye and proceeded slower than in the control eye. On the average,

FIGURE 8.

ERG decline during exposure to 4 atmospheres of O_2 at different intraocular pressures: right eye—50 mm Hg; left eye—control.



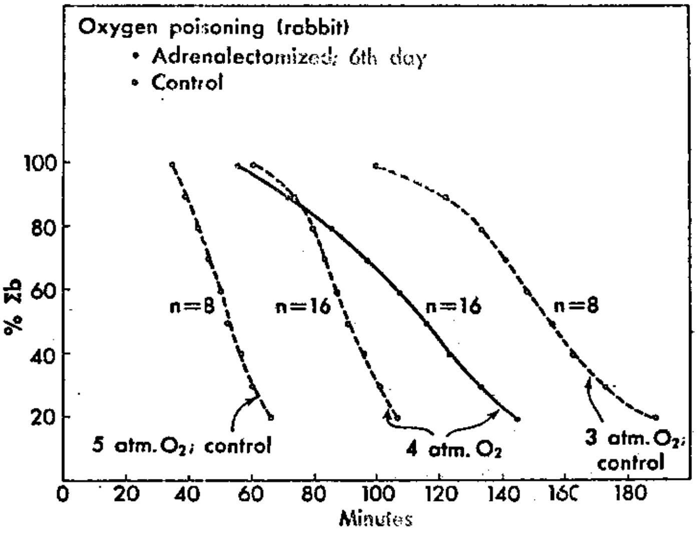


FIGURE 9.
Effect of adrenalectomy on ERG decline during exposure to 4 atmospheres O_2.

the 50% *b*-wave amplitude level was reached 120 minutes after the start of exposure as compared to 90 minutes for the control eye. In order to attain this effect (50% *b*-wave decline) in 120 minutes, control animals would have to be exposed to about 3½ atmospheres, i.e., to ½ atmosphere less than in the experiment as performed. Hence, the increase in intraocular pressure and the resultant reduction in blood flow provided a protection of about ½ atmosphere. This amount of protection was the same as computed on the basis that the increase in intraocular pressure provided a 30% reduction in the blood flow through the chorioidal capillaries and that the hemoglobin remained fully saturated with oxygen as the blood passed through the eye. The experiment virtually proves that the oxygen tension within the retinal tissue determines the effects of the exposure.

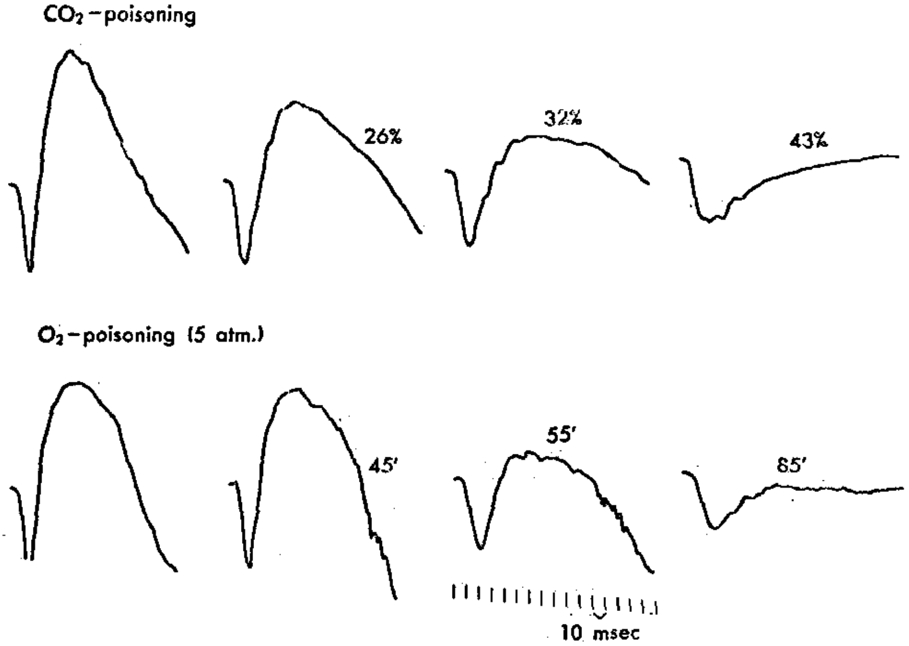
Adrenalectomy is known to reduce the systemic effectiveness of oxygen (Gerschman and Fenn, 1954). In experiments at 4 atmospheres of oxygen performed on rabbits 6 days after removal of the adrenals, we tested whether adrenalectomy affected protection to the retina as well (Noell and Baker, 1956). Figure 9 shows that the ERG began to decline at about the same time as in the control animals. However, once started, the decline proceeded slower and deviated progressively more from that of the controls, as if the protective effect of adrenalectomy developed during the exposure to oxygen and if such protection had been absent during the initial part of the experiment. We are inclined to assume that this effect of adrenalectomy, rather than being a true protection against oxygen, resulted from a fall in tissue oxygen tension in the adrenalectomized animals owing to a more rapid failure of the cardiovascular system.

COMPARISON OF HYPEROXIA WITH CARBON DIOXIDE POISONING AND X-IRRADIATION

The impairment of carbon dioxide transport during hyperoxia has often been considered a contributing factor in oxygen toxicity. Indeed, as shown in Fig. 10, high inspiratory carbon dioxide concentrations produced virtually the same ERG abnormality as oxygen poisoning. However, there were important differences as indicated by Fig. 11. Firstly, the CO_2 concentration required to reduce the ERG by a significant amount is very high. In order to depress almost completely the *b* wave, a concentration of 50% inspiratory CO_2 is required. Secondly, the carbon dioxide effect is not cumulative in contrast to oxygen poisoning. Thirdly, recovery from CO_2 poisoning is much faster than from oxygen. The experiment from which this figure was taken was conducted in such a manner that the time course of the ERG decline approximated as much as possible the decline during exposure to 4 atmospheres. Nevertheless, the recovery of the ERG from CO_2 followed almost instantaneously a reduction in CO_2 concentration. Nothing of this kind was ever observed after termination of exposure to high oxygen pressures.

In its striking cumulative action, oxygen poisoning resembles x-irradiation, and Gerschman *et al.* (1953) postulated that ionizing radiation and oxygen may have a common basis of action. Indeed, x-irradiation, just as oxygen poisoning, effects visual cell death without destroying simultaneously the other cells of the retina. Figure 12 shows that continued exposure to x-radiation produces ERG decline curves very similar to those resulting from oxygen poisoning, and it is probable that any ERG decline observed in oxygen poisoning can be simulated by continuous irradiation at a certain rate and of a certain x-ray quality. The x-ray dose needed to simulate the oxygen effect is very high; for instance, to simulate the ERG failure measured in 7 atmospheres of oxygen, each visual cell must be exposed to about 400–600 rad tissue dose per minute. A total retinal dose of 4000 to 6000 rads is required for the cytocidal effect upon the rabbit visual cells (Baily and Noell, 1958). More important and in contrast to oxygen poisoning, the x-radiation effect upon the ERG is practically irreversible and almost inevitably associated with visual cell death. X-irradiation, much more than oxygen poisoning, seems to act on the visual cell at a site or system critical to both sensory function and visual cell life.

It appears likely that oxygen produces its effect by poisoning essential cellular enzyme systems (Stadie *et al.*, 1944). From this point of view the high sensitivity of the visual cell to oxygen would indicate that either such an enzyme system is more readily accessible in the visual cell to the effect of oxy-



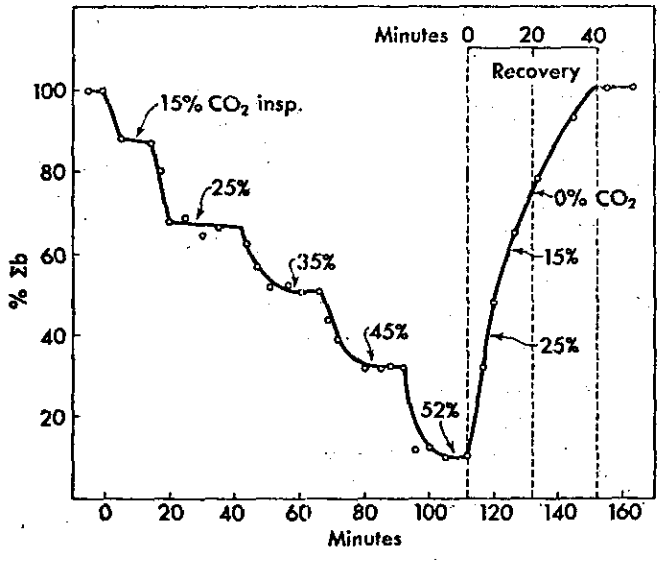


FIGURE 10 (*top*).
ERG during CO_2 poisoning (in percentage of inspiratory CO_2) in comparison with O_2 poisoning (two different experiments).

FIGURE 11. (*above*).
ERG decline in relation to stepwise increases in inspiratory CO_2 and ERG recovery from exposure to 52% CO_2.

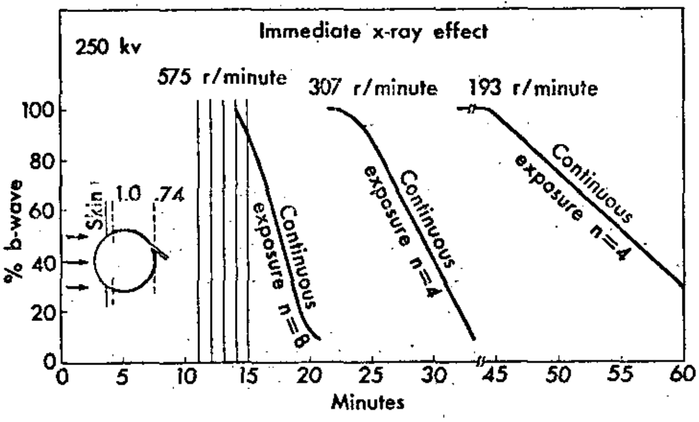


FIGURE 12.

X-irradiation effects upon ERG. The x-ray beam entered through the cornea. The dose rates refer to the dose delivered to the anterior rim of the retina; 74% of this dose from 250 krp x-radiation is delivered to the posterior retina.

gen than in other cells, or that the visual cell has a lower margin of safety with respect to certain enzymatic activities. The peculiar metabolic organization of the visual cell seems to be the reason for the selective effectiveness of intravenous iodoacetate, an inhibitor of glycolysis, which in rabbit, cat and monkey readily destroys function and viability of the visual cells, particularly of the rod cells (Noell, 1951b; Noell, 1952a; Noell, 1959). It is assumed that a vital region of the visual cell depends upon glycolysis and that glycolytic inhibition is poorly compensated for by other metabolic activities such as the oxidation of noncarbohydrate substrates. Preliminary *in vitro* experiments on isolated retinas indicate, however, that glycolytic enzymes are not the target of the action of oxygen upon the visual cells. With several atmospheres of oxygen, lactic acid production was little affected whereas glucose oxidation measured by the conversion of uniformly labeled C^{14} glucose to CO_2 was markedly reduced, this reduction increasing with the duration of exposure. Similar metabolic changes were measured in retinas after *in vivo* x-irradiation which affected the ERG.

EFFECTS OF HIGH CONCENTRATIONS OF O_2 AT AMBIENT PRESSURE

The most selective and the most severe effect of oxygen upon the visual cells was observed at a pressure of 1 atmosphere or lower. At these pressures and with prolonged exposure oxygen destroyed visual cell life without necessarily affecting the animal in other ways. Visual cell death was noted in practically

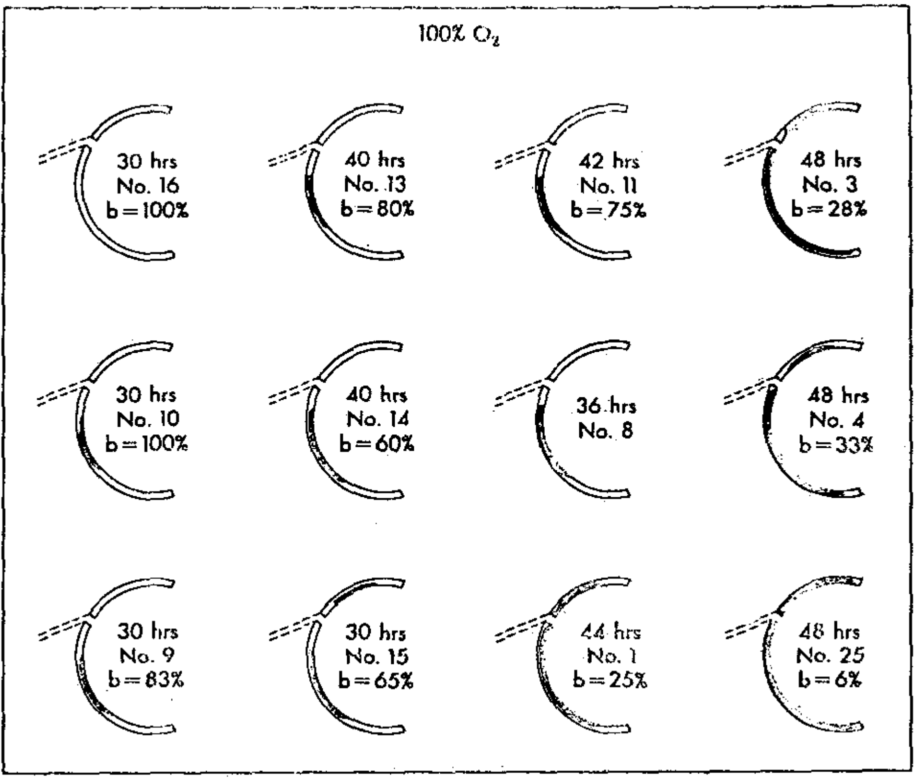


FIGURE 13.

Extent of visual cell death resulting from exposure to 100% O_2 at ambient pressure for the specified times in hours.

all animals exposed for 40 hours to 100% of oxygen. Its incidence was 82% with an exposure time of 36 hours and even as short an exposure as 24 to 30 hours produced death of a fraction of the visual cell population in about 50% of the animals. Exposure to 80% of oxygen was 100% effective in producing visual cell death when the duration of exposure was approximately 4 days. Exposure to 55–60% O_2 for 7 days was effective in slightly less than half the animals and no evidence for visual cell death was obtained with 50% oxygen for 12 days. The amount of visual cell death over the cell population varied considerably. It ranged from the death of one or two rows of cells in a small area to the death of almost all cells over most of the retina.

The extent of visual cell death in 12 experiments after exposure to 100% O_2 at ambient pressure is indicated schematically in Fig. 13 using a sagittal section through the eye. The area between the two open circles represents the nuclear layer of the visual cells which normally contains 4–6 rows of nuclei.

The most sensitive visual cells—those most likely affected—are close to the center of the retina. From this region the effect spreads peripherally with gradually decreasing effectiveness. It is perhaps significant that these most sensitive visual cells are those which differentiate first (Noell, 1958a; Noell, 1958b) during the early postnatal life of the rabbit.

A significant attenuation of the ERG during exposures to high oxygen concentrations at ambient pressure preceded the manifestation of visual cell death. It occasionally became manifest as early as 15 hours after the start of exposure to 100%. Our data permit us to conclude that visual cells are irreversibly affected when exposure to 1 atmosphere of oxygen exceeds the onset of the electroretinographic change by 5 to 8 hours.

Visual cell death from exposure to high oxygen tensions is especially noted in experiments with rabbits. In the mouse, rat, and cat, pure oxygen at ambient pressure for a duration of time compatible with the survival of the animal rarely effected visual cell death.

Cell death is an unusual phenomenon of oxygen poisoning. Cancer growth and viability are said to be affected by high oxygen tension (Stadie *et al.*, 1944). Warburg recently reported that Ehrlich's ascites cells are reduced in viability after *in vitro* exposures to oxygen pressures higher than 2½ atmospheres. The spermatogenic cells are sensitive to iodoacetate (Karli, 1952) and De Almeida found that they are selectively damaged by high oxygen pressures.

The retina of the young rabbit proved to be more resistant to oxygen than that of the adult (Noell, 1958b). With 2 to 5-day-old animals exposure of 72 hours to 100% oxygen at ambient pressure killed only a few visual cells, whereas in the adult animal 30 hours of oxygen breathing sufficed to produce widespread visual cell death. Pulmonary pathology developed during exposure of adult rabbits to 1 atmosphere for 40 hours; none occurred in the young ones. Exposure of the adult animal to 1⅔ atmospheres of oxygen produced the death of almost all visual cells within 24 hours, whereas animals 3 to 5 days old, exposed for 30 hours to the same pressure, occasionally showed only visual cell death in a restricted area. Even at the age of 20 to 60 days the resistance to oxygen poisoning was still higher than in the adult. Apparently the susceptibility to oxygen poisoning develops simultaneously with the growth of the visual cell to the adult size and with the maturation of the sensory function. A similar increase in visual cell susceptibility was also observed for the effectiveness of intravenous iodoacetate.

Isolated young retinas in a tissue culture medium have been shown to be susceptible to high concentrations of oxygen at ambient pressure. Lucas and Trowell, in culturing intact retinas of 8- to 10-day-old mice, found survival of the retinal cells impaired when the oxygen concentration was higher than 50%. No other tissue behaved in a similar manner.

It should be noted at this point that the oxygen-induced retinal disease of prematurely born infants, *retrolental fibroplasia*, is initiated by a constriction of the immature retinal blood vessels from exposure to an oxygen tension above the physiological range. The pathology of this effect is clearly different from that previously discussed. The rabbit lacks the retinal blood vessel system typical for mammals, and our experiments on young rabbits, therefore, did not produce phenomena of retrolental fibroplasia which are well documented in the literature by experiments on mice, rats, and kittens. Like the visual cell effects of oxygen, the development and incidence of retrolental fibroplasia is a function of oxygen tension and duration of exposure. Oxygen is much more toxic with respect to the initiation of retrolental fibroplasia than it is on function and structure of the rabbit's visual cells. It would be a strange coincidence if the striking effects of oxygen on the immature retinal blood vessels and on the adult visual cells were unrelated. It rather seems that the retina as such has certain properties which make it more susceptible to oxygen.

There is no evidence that the mature retina of man is adversely affected by breathing high concentrations of oxygen at ambient pressure. However, the resistance of man's retina to oxygen has its limits. Behnke *et al.*, found distinct visual disturbances when subjects were exposed to 3 atmospheres of oxygen. There was a progressive failure of peripheral vision with maximal constriction of the visual field to 10°. Central vision was not seriously impaired; it failed only temporarily during impending collapse or during the transfer from oxygen to air. The authors emphasize that visual disturbances are the most consistent sign of oxygen toxicity at several atmospheres.

Donald confirmed these observations in a large series of experiments. He also states that visual field constriction can be marked while other manifestations of oxygen poisoning are absent. Visual field constriction occurred during the fourth hour of exposure to 3 atmospheres of oxygen. Recovery from this effect after termination of exposure required about one hour. These times are about the same as noted for the effects of 3 atmospheres of oxygen on the rabbit's ERG. These ERG effects became maximal between 3 and 5 hours after the start of exposure and they disappeared 45 to 90 minutes after return to normal oxygen tension.

It is quite possible that the visual disturbances in man result from effects upon the visual cells rather than from effects upon other cells of the retina such as the bipolar cells and ganglion cells. We have no evidence on the relative susceptibility of rod and cone cells to oxygen poisoning, but intravenous iodoacetate administered in monkeys has its main action upon the rod cell population; the cone cells of the central retina and central vision survive when practically all rod cells have died and peripheral vision has permanently vanished (Noell, 1952b; Noell, 1953; Noell *et al.*, 1954). Electroretinographic examinations of subjects during exposure to oxygen probably would permit the localization of the oxygen effect responsible for the visual disturbances in man.

Since oxygen has been shown to affect human vision, caution should be exercised against the prolonged exposure to unphysiological oxygen pressures on subjects with a family history of retinal degenerative disease. Visual cell degeneration on a hereditary basis occurs in man and in animals with signs similar to those discussed above for oxygen (Noell, 1953; Noell, 1958a; Noell, 1958b). Conceivably a latent hereditary factor could render the retina abnormally susceptible.

EFFECTS OF ISCHEMIA

In comparison to brain cells and in contrast to the effect of hyperoxia, the visual cells withstand lack of oxygen rather well (Noell and Chin, 1950; Noell, 1951a; Noell, 1952a; Turnbull, 1950). Complete recovery of the rabbit's ERG has been reported to occur after ischemia lasting as long as 75 minutes (Papst and Heck, 1955; Popp, 1955). In order to produce a complete disappearance of the ERG in rabbit, cat, and rhesus monkey ocular ischemia must last from 5 to 20 minutes. However the first ERG changes may develop within a few seconds. The familiar "black-out," the very rapid loss of vision in man when ocular circulation is impaired, seems to result from effects of hypoxia upon the neuronal network of the retina, particularly upon the retinal ganglion cells (Noell, 1951*a*; Noell, 1952*a*). Nevertheless, and in striking contrast to forebrain and cerebellum, irreversible effects of transient or systemic anoxia upon the retinal cells are virtually unknown. Wegner in 1928 found that up to 30 minutes of ocular ischemia do not lead to permanent damage in man. Although I would not take such an optimistic attitude concerning the retinal effects of anoxia, the resistance of the retinal cell to anoxia is undoubtedly much higher than that of most brain cells. This may be related to the high anaerobic capacity of the retina which to some degree may be possessed by all retinal cell layers.

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STUDIES ON THE EFFECT OF HIGH OXYGEN ADMINISTRATION IN RETROLENTAL FIBROPLASIA*

I. Nursery observations

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In the Gallinger Municipal Hospital from January, 1948, to January, 1951, 18 of 21 infants who developed retrolental fibroplasia received prolonged oxygen therapy at high concentrations. High oxygen therapy could not be accepted as a causal factor, however, since the smaller infants generally received more oxygen. To evaluate the possible role of oxygen therapy in retrolental fibroplasia, a controlled oxygen-administration program was instituted. An analysis of the first of this three-year study is presented.

Subjects and Methods

All infants included in this investigation were delivered in the Gallinger Municipal Hospital obstetrical division. Infants with birth weights under 3.5 lb. were placed in one of two groups on admission to the premature nursery. Group I was maintained in high oxygen (65 to 70 percent) for four to seven weeks. Group II received lower oxygen (under 40-percent concentrations). The nursery routine was otherwise identical in the two groups.

Infants were placed in high or lower oxygen levels on an alternate admission basis regardless of birth weights. Oxygen tensions were controlled by incubator samplings at eight-hour intervals with the electronic analyzer (accurate within two-percent concentrations).

In general, approximately, seven liters for the high-oxygen levels and approximately two liters for the lower levels gave the desired concentrations in the isolette-type incubators. However, when the incubator concentration was found below 60 percent, the flow rate was raised, or when above 35 to 40 percent in the lower oxygen group, the flow rate was reduced.

The infants in high oxygen were maintained at these levels constantly for from four to seven weeks. Weaning off from high oxygen was done by gradually reducing the incubator concentrations over a period of one week. The infants in lower oxygen tensions were kept in incubators for from 24 hours up to two weeks at levels under 40 percent. Weaning off from lower oxygen was done over one to three days. The infants in each group were examined ophthalmoscopically

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TABLE 1
RESULTS OF STUDY OF 65 CASES

Oxygen Levels	Total Number of Infants	Normal Eyegrounds	Retrolental Fibroplasia Grade I	II	III	IV
High	28	11	3	7	2	5
Low	37	31	4	2	0	0

at regular intervals and followed after discharge in a special clinic until they were six months of age.

A brief resume of pertinent nursery routine shows that 5.0 mg. of vitamin K were administered routinely on the first day. The smaller infants usually received nothing by mouth for the first 36 to 48 hours, at which time they were started on sterile water. The larger infants were started at 12 to 24 hours.

On about the third day a half-skimmed milk formula with cartose syrup was begun and increased gradually. When the infant weighed about 4.5 lb., a straight evaporated-milk formula was started. Starting at two weeks of age, 20 drops of visynerol multivitamin preparation was given daily to all infants. This water-miscible preparation contains vitamins A, B complex, C, and D. Starting at 30 days, 60 mg. of ferrous sulfate was given twice daily.

Transfusions were administered during this study in only two cases, neither of which developed retrolental fibroplasia. One infant in the high-oxygen group who developed retrolental fibroplasia was given ACTH and is not included in the analysis of cases. No vitamin E was administered in this study.

ANALYSIS OF CASES

In the first year of this investigation, 76 infants with birth weights under 3.0 lb. 8.0 oz. were studied. Eight cases are deleted in this analysis because incubator oxygen levels were not sufficiently constant. None of these eight infants progressed beyond Grade-II changes. Three infants who were normal in the nursery did not return for follow-up examinations after discharge and are deleted. The results in the remaining 65 cases are tabulated in Table 1.

Owens and Owens'[1] classification of retrolental fibroplasia was slightly modified to include a fourth stage of completely arrested disease with residual retrolental membranes. Stage I represented marked dilatation and tortuosity of the retinal vessels with occasional areas of mild retinal edema. Stage II showed vascular changes, increased retinal edema, retinal hemorrhages, and vitreous clouding and opacities. Stage III represented detachment of the retina, new vessel formation, retinal hemorrhages, and vitreous opacities. Stage IV represented the arrested phase of the disease at total or almost complete permanent retinal membrane behind the lens.

Grade III and Grade IV retrolental fibroplasia occurred in seven cases (25 percent) receiving constant high oxygen. None of the 37 infants in the lower oxygen group progressed beyond Grade II changes. It is significant that infants who received prolonged high-oxygen levels were not necessarily the smaller infants. A continuous high or lower oxygen regime was administered on an alternate admission basis instead of the usual procedure of giving more oxygen to the smaller infants.

Early in our study, Gordon[2] pointed out to us that a similar investigation being carried out at the University of Colorado showed that premature infants thrive with much lower oxygen-environment concentrations than had been commonly advocated.

DISCUSSION

To evaluate oxygen administration critically it is essential that incubator oxygen concentration be measured frequently with an accurate oxygen analyzer. Flow rates as recorded in liters per minute do not necessarily indicate the incubator oxygen levels.[3]

Graham and associates,[4] in a carefully performed experiment on 44 premature infants, found a close correlation between incubator oxygen levels and arterial oxygen saturations. It is significant that at room oxygen (20 percent), they found arterial oxygen saturation to average 93 percent; at 30 to 55 percent, it averaged 96 percent; and at 70- to 79-percent oxygen concentrations, 100 percent arterial saturation was recorded.

Theoretically a gross pulmonary or circulatory anomaly could lower arterial oxygen values; however, careful clinical examinations should reveal these exceptional cases. In the remainder of our studies, hemoglobins, hematocrits, and simultaneous arterial oxygen saturations and incubator concentrations will be performed.

The toxic effects of hyperoxia in man and animals are well established and the monographs of Stadie and associates[5] and Bean[6] review the extensive studies that have been performed. Adult animals in 80-percent oxygen typically show oxygen poisoning with acute pulmonary edema developing in from three to eight days. Young rats, rabbits, and mice have been reported to be relatively immune to sustained high oxygen levels. It is significant, however, that in dogs maintained at 80-percent oxygen level, Paine[7] noted acute oxygen poisoning occurring in young puppies as readily as in adult dogs.

The following observations suggest mechanisms by which increased oxygen tensions might influence the developing premature retina.

1. In four cases of retrolental fibroplasia we have noted marked attenuation of the retinal vessels occurring prior to the development of dilatation and tortuosity. This narrowing has also been observed by Lamott[8] in approximately one third of his cases that developed retrolental fibroplasia. We have also noted in premature infants a visible narrowing of the retinal arteries and veins after one hour when increasing oxygen from 20 to 80 percent.

This is consistent with the report of Cusick and others[9] who reported an average of 25-percent constriction both in the retinal arterioles and retinal veins in adults after breathing pure oxygen.

Tinel,[10] Wolff and Lennox,[11] Cobb and Fremont-Smith,[12] and Schmidt,[13] describe a constriction of the pial or superficial cerebral vessels in animals breathing high oxygen. Bernthal[14] and Bronk and Gessell[15] found in animals that administration of 50-percent oxygen decreased the carotid blood flow. Ketty and Schmidt,[16] using the nitrous-oxide technique, demonstrated a reduction in cerebral blood flow in humans breathing 85-percent to 100-percent oxygen.

By diminishing retinal blood flow high oxygen might diminish the supply of other necessary metabolites to the premature retina.

2. There are considerable experimental data[17, 18] pointing to a destruction of intracellular enzymes, particularly dehydrogenase systems of the brain, in oxygen poisoning. Cusick[9] suggested that the retinal vessel constriction noted on breathing high oxygen is a mechanism to reduce retinal blood flow in an attempt to protect the retina from excessive oxygen levels. The mechanism is apparently inadequate as the color of the retinal veins approximates that of the arterioles when breathing high oxygen. Conceivably prolonged high oxygen administration might alter retinal enzyme systems in the premature.

3. Studies on the fetus in utero show that oxygen saturation of arterial blood is approximately 50 percent.[19] After birth, the arterial oxygen saturation rises in a few hours to approximately 90 percent in room atmosphere.[19] The final maturation of the premature infant, therefore, occurs at arterial oxygen saturations of 90 percent plus; whereas, in normal gestation, the fetus would have continued to develop in utero at considerably lower oxygen tensions.

Abnormal proliferation of the developing retina might result from these relatively higher oxygen tensions. The transfer of incubator oxygen across the cornea to the premature retina is an undetermined factor that may further increase oxygen tensions in the retina.

It must be realized that there is no experimental proof to show that diminishing the retinal blood flow, altering the retinal enzyme systems, or exposing the developing retina to relatively higher oxygen tensions can produce the changes of retrolental fibroplasia. These mechanisms only suggest possible methods by which elevated oxygen tensions might influence the developing premature retina.

Szewczyk[20] removed prematures from incubators and recorded dilatation of retinal vessels, hemorrhages, and edema within the first few days out of oxygen. On replacing infants with early retrolental fibroplasia in oxygen he observed a uniform regression of the disease.

Our cases in continuous high oxygen seemed good subjects to test his observations. Two infants were studied.

Infant A weighed 2.0 lb., 7.0 oz. at birth and Infant B, 2.0 lb., 9.0 oz. Each had been in approximately 70-percent oxygen for 32 days.

Examination immediately prior to removal from the incubator revealed dilation and tortuosity of the retinal vessels, vitreous haze, and an index myopia of approximately six diopters in each infant. Infant B showed in addition localized areas of retinal edema along the vessels.

Instead of being gradually weaned off from oxygen, as is done routinely, these infants were suddenly removed from constant 70-percent oxygen to room oxygen (20-percent). Infant A required supplements of oxygen for one-half hour after meals for the first 48 hours due to slight respiratory distress. Infant B required supplementary oxygen on two occasions after feeding.

The eyes were examined daily for four days, then at two-day intervals to the 10th day, then once weekly for 60 days.

Infant A showed essentially no change in the eyegrounds in the first four days. In subsequent examinations, a regression of the retrolental fibroplasia with clearing of the vitreous and attentuation of the dilated vessels was observed.

Infant B showed a slight but definite increase in caliber and tortuosity of the arteries and veins during the first four days out of high oxygen. One solitary hemorrhage was noted in the nasal periphery of the left eye on the third day out of high oxygen. This hemorrhage cleared and the retinal vessels gradually had resumed normal size 21 days after removal from the incubator. The eyes have remained normal in both cases up to the age of three months.

These two infants demonstrate a spontaneous regression of mild retrolental fibroplasia to normal in spite of the anoxic insult that resulted from sudden withdrawal from a continuous 70-percent oxygen environment. These observations raise the question of how many of Szewczyk's[20] cases with early retrolental fibroplasia would have regressed to normal regardless of the oxygen environment.

Retrolental fibroplasia changes were detected in some of our cases while still in incubators with high oxygen. Also weaning off from high oxygen was done gradually over seven to eight days. These observations suggest that prolonged high oxygen, if injurious, results from a direct effect instead of from the relative anoxia that might result from the too rapid withdrawal from oxygen as cited by Szewczyk.[20]

If prolonged high oxygen therapy can be conclusively correlated with the incidence of retrolental fibroplasia, other factors may play a basic role in the disease's pathogenesis. Six cases of mild retrolental fibroplasia were recorded in our lower oxygen group. A theory based upon increased arterial oxygen tensions relative to those sustained in utero could, however, provide for occasional cases of retrolental fibroplasia developing when no supplementary oxygen is administered postnatally.

The data cited here together with the surveys of Campbell,[21] Ryan,[22] Kinsey and Zacharias,[23] and Crosse,[24, 25] suggest strongly that high oxygen administration is a factor in the pathogenesis of retrolental fibroplasia. However, in view of the bizarre manner in which the incidence of the disease fluctuates, additional rigidly controlled observations are necessary to establish this concept. There are now sufficient data to question the advisibility of the "routine" use of prolonged high oxygen concentrations in the nursery.

SUMMARY

1. The results of the first of a three-year controlled oxygen nursery study are cited. Seven of 28 infants receiving prolonged high oxygen levels progressed to Grades III and IV retrolental fibroplasia. Of 37 infants in the lower oxygen group none progressed beyond Grade II changes.

2. Mechanisms by which prolonged high oxygen administration might influence the premature retina are discussed.

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