The Technical Guide to

Gas Blending

By Nicos Raftis

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The Technical Guide to Gas Blending

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Finally, I am grateful to all my gas blending students, from whom I have never ceased to learn new things, and with whom I have had the chance to apply critical thinking and discuss numerous situations for setting up gas blending stations, sizing air banks, doing logistics planning, and developing the critical spirit that a gas blending technician must have.

Preface

The role of the gas blender is multiple and varied. A good understanding of gas blending and air fill station issues is very important for the business success of a dive facility.

This book is written to be a comprehensive reference and guide. The material in some chapters goes far beyond the level which the average gas blender may be capable of comprehending. This is the ultimate guide for the gas blender, the technician, and the instructor. Use it as a "how to" guide, as a reference, and as a planning aid.

Section 1

1. Introduction

1.1 The Responsibilities of the Gas Blender

The role of the gas blender is more than mixing gas. A good gas blending technician must be able to:

- ✓ Help the owner/ manager in equipment selection
- ✓ Plan and execute the layout of the blending station
- ✓ Do logistics planning and calculations
- ✓ Help in calculating the cost of nitrox fills
- ✓ Plan and carry out equipment preparations
- ✓ Do the mixing and safely dispense the gas to the customer

1.2 Mixed Gases and Their Production

Normally when we refer to mixed gases, we actually refer to a mixture of two or more gases. Air is also a mixture. It consists of 21% oxygen and 79% nitrogen by volume or molar fraction. The most popular mixed gas is nitrox, or EANx (Enriched Air Nitrox). This is a mixture of nitrogen and oxygen, with an oxygen percentage higher than 21%.

Trimix is a mixture of three gases (in Greek "tria" means "three"), and the term is used in the diving industry for a mixture of helium, nitrogen, and oxygen. The term "Helair" is also used to describe trimixes where no additional oxygen is required, other than what is already present in the air. Heliox is another mixed gas and consists of helium and oxygen only.

1.3 A Brief Description of Blending Methods

There are five available methods to produce nitrox:

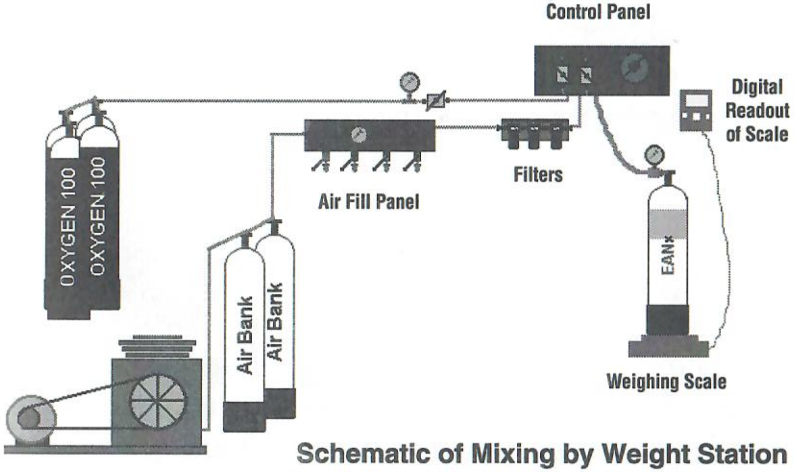
1. Mixing by weight
2. Partial pressure mixing
3. Automatic mixing
4. Continuous blending
5. Permeable membrane gas separation

One can also dispense nitrox to the customer's scuba tanks by use of pre-mix.

1.3.1 Mixing By Weight

With this method, one measures the weight of the cylinder and gas in order to determine how much oxygen and air is added to the scuba tank. Tables are used that are based on the molar weight of the gases, rather than on pressures. Weight and pressure are essentially equivalent and they are related by the state equation for a gas. Weight measurement is the most direct way of determining the quantity of gas in the scuba tank. This method involves placing an empty scuba tank on an accurate scale (most often digital), zeroing the scale to take out the weight of the scuba tank, and adding oxygen until a given weight is reached. Then air is added.

This method is neither more accurate, nor does it involve any expensive equipment or special training. However, it does have problems similar to partial pressure blending. The diagram below will make this more obvious.



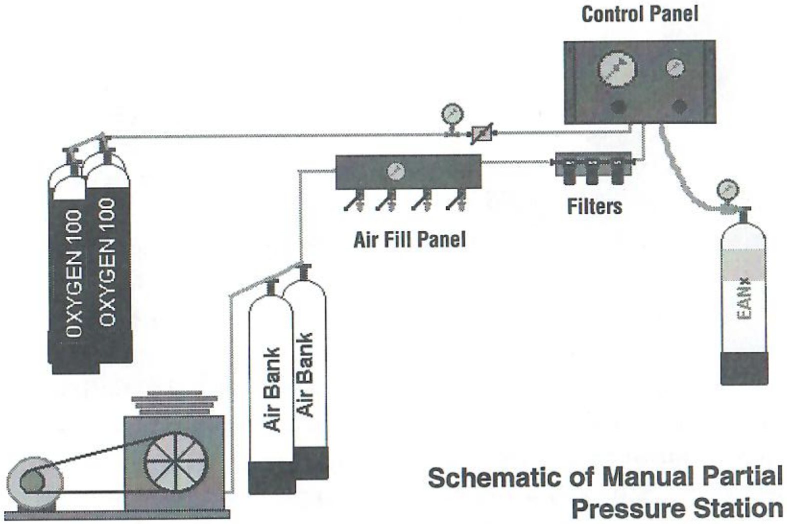
Schematic of Mixing by Weight Station

The hose connected to the scuba tank does have some weight. At the same time, when the hose is pressurized, and as gas flows to the tank, there is a torque created (think of a compressor fill whip when you open the compressor valve) and a force is exerted with a downward component, thus affecting the scale reading. So, adjustments need to be made here as well. These depend to a large extent on the positioning of the hoses, and are therefore specific to a given set-up.

Another problem with mixing by weight is that it is difficult to deal with half-full cylinders. This is because it is difficult to determine how much of the weight measured is the weight of the cylinder itself, and how much is the weight of gas in the cylinder. This could be overcome by either keeping record of weights of cylinders used (measured precisely and logged with serial numbers), or measuring the pressure of the residual gas and its oxygen percentage, and doing some calculations of mass. This makes the whole process more complicated.

1.3.2 Partial Pressure Mixing

Partial pressure mixing is by far the most common method in the production of nitrox with more than 70% of facilities using this method. This is largely due to the low initial investment required, and the simplicity of this method.



Schematic of Manual Partial Pressure Station

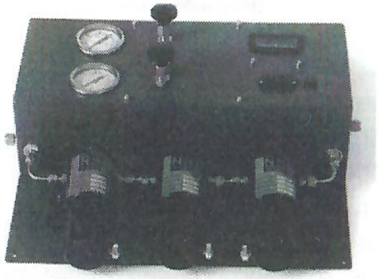
Pressure is a convenient and easy (although indirect) way to measure the quantity of oxygen, air, or helium added to the scuba cylinder. The pressures are calculated using simple equations, or mixing tables.

Because of the relatively simple equipment necessary, the initial investment required is low. In fact, many instructors have been constructing their own systems for many years. Lack of good understanding of design issues and flow characteristics makes this practice dangerous.

Integrated Expedition Mixing System

One other advantage of manual partial pressure mixing is that it can use truly portable equipment to suit the needs of expeditions in remote locations.

Although the calculations are not complex or difficult, the accuracy of the mix depends, to a large extent, on the skill and care of the operator to make the necessary adjustments for temperature increase and for the different compressibility of the gases.

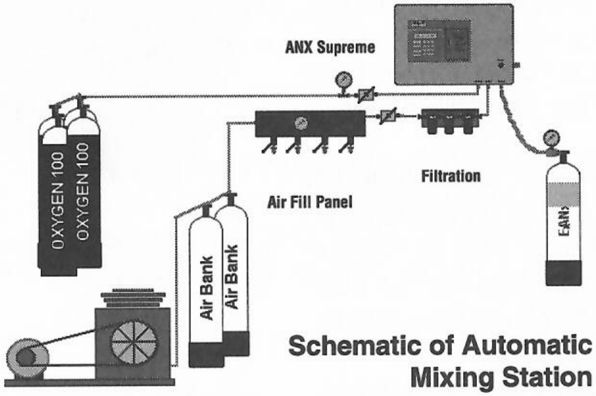


Integrated Manual Partial Pressure Mixing System

From a business point of view, this means that a dive business depends on a small number of key individuals who have, over time, acquired the necessary experience and skills to do the mixing safely and accurately. Depending on a small number of individuals means lack of flexibility as well as other operational difficulties.

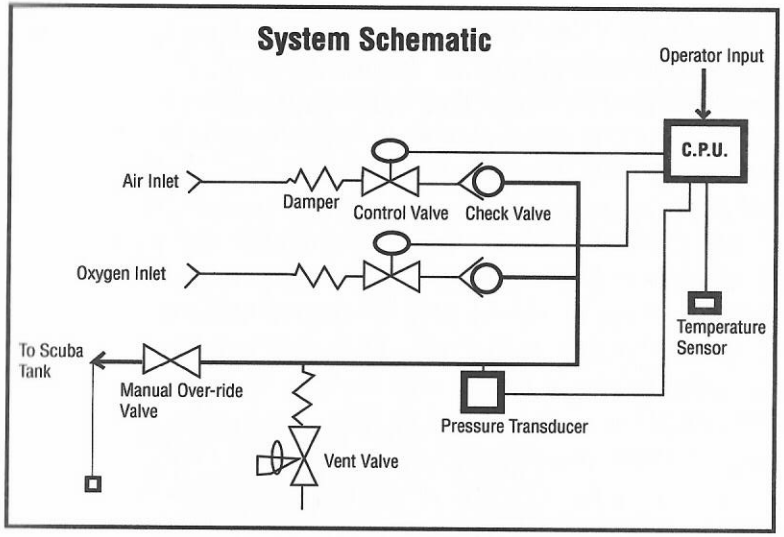
Because oxygen or oxygen-rich mixtures are used, the system needs to be oxygen service rated (be clean and use oxygen compatible materials).

1.3.3 Automatic Mixing



Schematic of Automatic Mixing Station

Automatic Blending Station at Facility of Holdive International, Amsterdam



Automatic mixing is based on the principle of partial pressures but, in this method, the process is fully automated. The process is microprocessor controlled, and the user has no access to valves or gauges. The user only has to connect the scuba tank, enter the mix specifications through a keypad/LCD display, and start the process. At the end of the filling, the system will give an audio and visual message prompting the user to analyze and verify the mix. A sophisticated thermodynamic model calculates temperature profiles, compressibility factors of the gases, generates accurate pressure profiles, and delivers very accurate mixes. The process no longer depends on the skill and the care of the operator. This gives extra safety by eliminating the human error, offers flexibility because the business no longer depends on one or two key individuals for the production of nitrox, and operating cost is kept very low because the system can work unattended, thus minimizing labor cost.

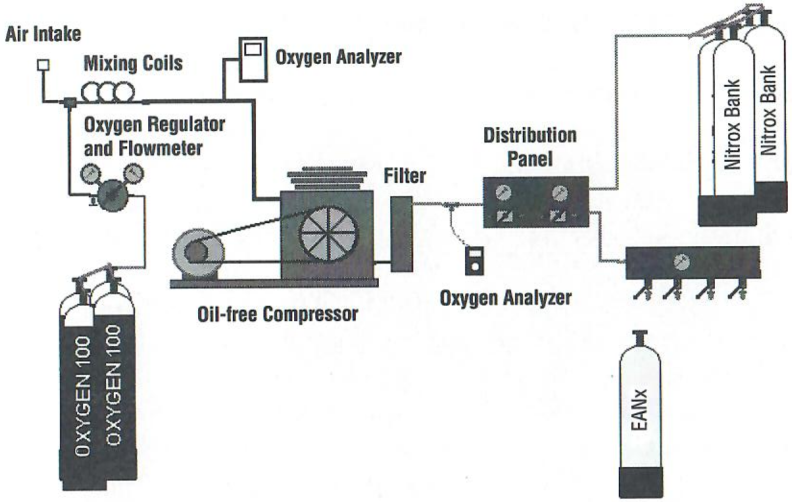
The ANX Supreme offered by NS Research is the first automatic system that was introduced to the market in 1996. The mechanics of the system are very simple.

A Central Processing Unit (CPU) takes information from the user via a keypad and the measurements of a pressure transducer and an ambient temperature sensor to calculate the pressures to open and close the control valves for air (or nitrox mix 21% - 40%) and oxygen (or nitrox mix 50% - 100%). The system can produce mixes for the full range of oxygen percentages (21 - 100 %).

1.3.4 Continuous Blending

Continuous nitrox blending was developed in the mid-1980s by the National Oceanic and Atmospheric Administration (NOAA). The main characteristic of continuous blending is that air and oxygen are being mixed at atmospheric pressure and temperature. The mix is analyzed to verify and correct its composition, and then passed to an oil-free compressor to compress it up to 230 bar (3300 psig). Usually the mix is restricted to a maximum 40% oxygen, although mixes higher in oxygen can be achieved. Because the gas is already homogeneous as it is being compressed, both storage nitrox banks and multiple scuba tanks can be filled simultaneously, similar to filling air cylinders. The system is shown schematically below.

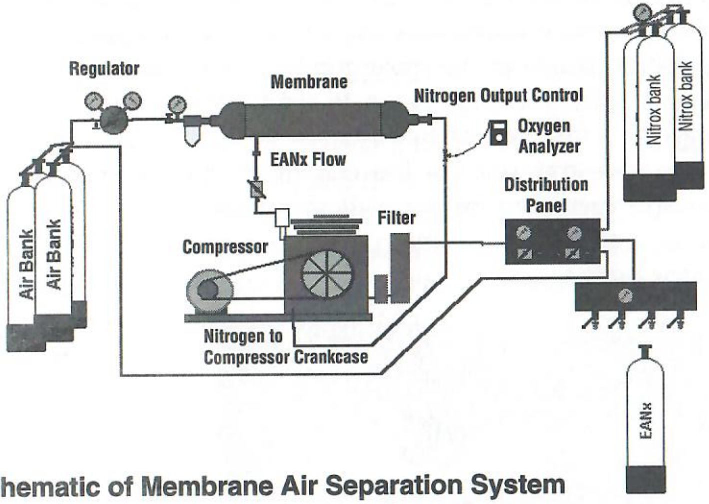
This is a high-volume system. The initial investment is high; operating costs also are high. Almost inevitably, such systems are used in conjunction with nitrox banks, storing the most popular mixes of 32% and 36% oxygen. This is because it is impractical to fill individual scuba tanks as they come in to be filled, particularly if successive fills are of different mixes. Just imagine the situation where we need to fill four different tanks: one with 32% oxygen, another with 36%, another with 28%, and the last with 40% oxygen. For each different mix we have to adjust the pressure regulator until the output from the mixing coils is the mix that we want and is stable. We then have to wait until the compressor, tubing, and the rest of the system is flushed through from the previous mix and, at the output of the compressor, we have the mix we want and it is stable. This process is tedious and time consuming, and thus necessitates the use of nitrox banks.



One Type of Mixing Coil

1.3.5 Permeable Membrane Gas Separation

These systems do not use any oxygen. Instead they remove nitrogen from air to produce nitrox. The heart of these systems is the membranes cartridge, which contains thousands of individual membrane fibers made of a polymer material. Pressurized air is fed into the membrane cartridge, and as it enters each hollow fiber, oxygen is preferentially permeated across the membrane wall. The oxygen-rich air is collected on the shell side of the cartridge, whereas the nitrogen-rich air exits the downstream end of the cartridge. The oxygen percentage in the oxygen-rich air is controlled by the flow at the nitrogen output and, consequently, by the pressure in the membrane cartridge. A schematic of the system follows:



Schematic of Membrane Air Separation System

The major advantage of this method is that it does not require any oxygen, thus avoiding the logistics and cost of the supply of oxygen. This can be very useful on remote locations or live-aboards, where the supply of oxygen can be problematic.

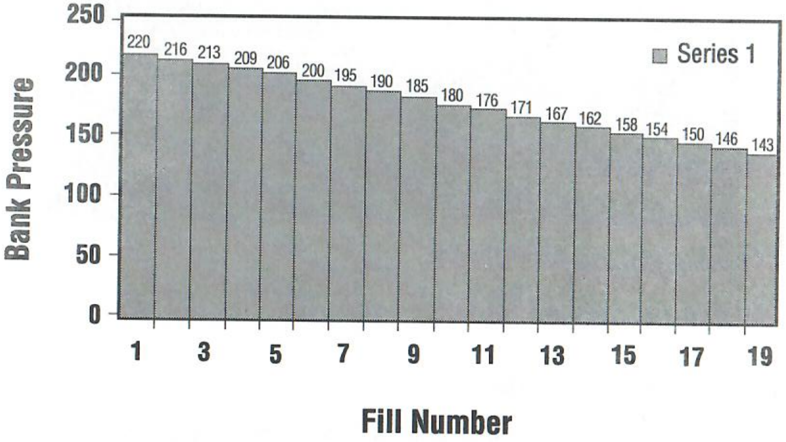
However, the method is limited to a maximum of 40% oxygen in the mix. The cost of initial investment is relatively high, and efficiency is low. For a 40% oxygen in the mix, the efficiency of the system is less than 50% (i.e., for 10 cfm delivery of nitrox, the system must be fed with 20 cfm air at 200 psig).

There are three key points that need to be understood in the operation of such a system:

1. Nitrox is directed from the compressor to nitrox storage banks because it is not practical to fill each scuba tank individually (for exactly the same reasons as explained in Section 1.3.4). Because of a limited size of the nitrox bank, there is a maximum number of nitrox fills that can be completed before the pressure falls too low, and the bank needs to be re-filled. The implication of the above is the time penalty that has to be paid if filling more than a given number of scuba tanks, depending on the nitrox bank size.

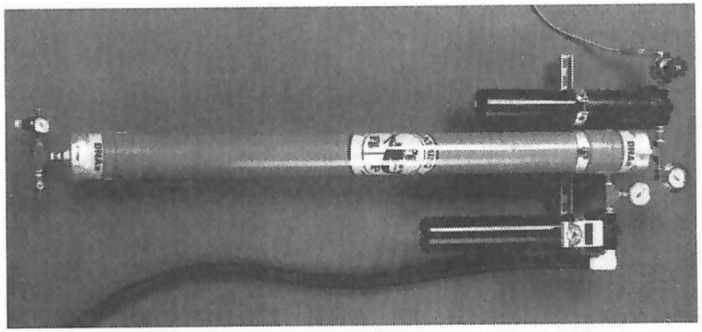
2. If an oil-lubricated compressor is used to compress the nitrox, then this requires some modifications. The oil must be replaced with O_2-compatible oil which must be monitored and changed frequently. It should be noted that most compressor manufacturers will not authorize this, and the warranty may become void. A lot of strain is placed on the compressor and maintenance requirements are usually demanding.

Pressure in Storage Banks After Successive Fills



If pressure is higher than 207 bar (3,000 psi), fill to 207 bar. If the pressure is lower, fill to the maximum.

3. The work load placed on the compressor is at least triple the work load for filling the same scuba tanks with air. To understand this, let's use an example with round numbers: We want to fill an 80 ft^3 scuba tank with nitrox 40. Air has 21%, let's call it 20%. This means that to get our nitrox, we need to process double the amount of air (if no O_2 was wasted at the nitrogen-rich outlet). Now, say the compressor's capacity is such that to fill that 80 ft^3 tank it takes 10 minutes. To fill the same tank with nitrox, our compressor would now need to work 20 minutes for compressing the double volume of air, plus 10 minutes for compressing the nitrox, for a total compression time of 30 minutes! In practice, the compressor works about four times longer. The alternative would be to use a separate low pressure compressor to feed the membrane.



Membrane Cartridge

1.3.6 Using Pre-mix

This involves buying a gas from an industrial supplier. The use of pre-mix is something that appears as an easy solution. Pre-mix, of course means that there is no blending or mixing. However, there are several disadvantages:

1. You are restricted to one or two mixes. Usually, most people will get 32% or 36% nitrox for recreational courses. Technical courses are out of the question, because the whole meaning of technical diving is that the diver is responsible for planning his dive, and the choice of gas (travel gas, bottom gas, or decompression gas) cannot be set or restricted.

2. When using pre-mix, one needs a booster pump, otherwise, after filling a few scuba tanks of nitrox, the pressure would drop below 170 bar (2,500 psi) which would be the minimum acceptable pressure by the diver. This means that pre-mix is, in fact, an expensive option, even as far as the initial investment is concerned, as the booster pump costs over $8,000.

3. As a gas, pre-mix is expensive, so the cost per nitrox tank is much higher than if blending took place.

4. When using pre-mix, any residual gas in the scuba tanks has to be wasted in the atmosphere if nitrox of a different composition is required.

NOTES

Section 2

2. Setting Up a Blending Station

2.1 Safe System Design and Construction

Any high-pressure system requires care in its design, operation, and handling. A well-known example in scuba diving is the necessary inspection and hydro-testing of scuba cylinders (high-pressure vessels).

In gas blending there is an additional reason to apply extra care. Inevitably, at one stage or another of a blending station or, to be absolutely correct, a nitrox production station, there will be an oxygen-rich environment. Nitrox is an oxygen-rich atmosphere! The higher oxygen concentrations increase the susceptibility to ignition and propagation of combustion with the obvious dangers of an "oxygen fire" or generation of carbon monoxide. Ignition initiation mechanisms include: heat of compression; friction; particle impact; static electric discharge; and high-frequency vibration. All of these mechanisms can be eliminated by correct system design, and by using carefully selected components.

The sections in this book on setting up a blending station, generating clean air, tubing valves and fittings, and system cleanliness are aimed at providing accurate and complete information that is necessary for maximum safety.

2.2 An Overview of the Necessary Equipment

GUIDE TO SYMBOLS

☑	Equipment necessary for this type of blending system
◇?	Equipment NOT Necessary, but optional
☒	NOT NEEDED
↔	Alternatives

A blending station can be as sophisticated (and expensive) as you want it to be. The key is that equipment selection must meet your operational needs and bring you closer to your business objectives. Constraints from your environment can be important as well. For example, availability of oxygen, noise level that can be tolerated, temperature and humidity in your area, and any other regulations in place.

To make a wise decision, you must first understand your own requirements. Second, you must understand the capabilities and limits of the equipment. Below, we list some of the equipment that can be used to set up a blending station according to a generic method of gas production.

2.3 Planning the System Layout

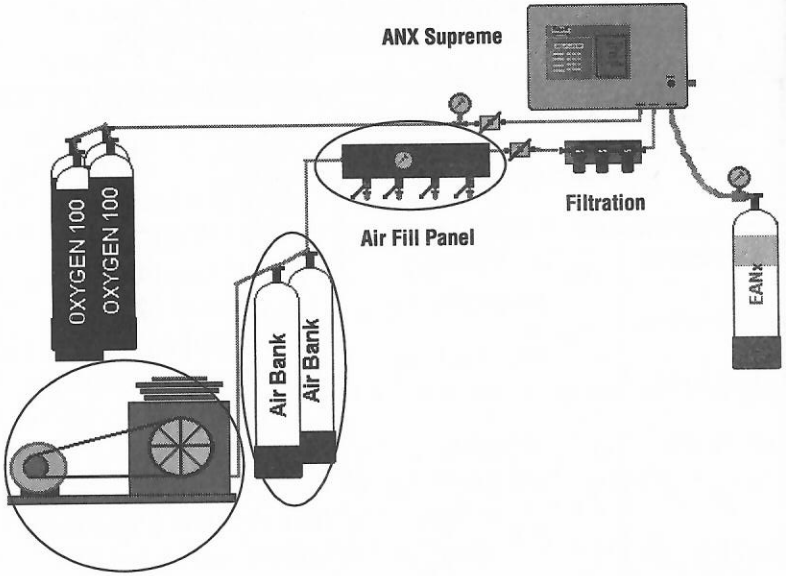
One key to a good system layout is drawing several sketches of the different possibilities so that an evaluation can be made, and then the details of the preferred layout can be worked out.

STEP 1: Start by drawing a schematic of the blending system. On this diagram you should mark the existing equipment. The diagram below is an example of a blending station using an automatic mixing system.

In this sketch the existing equipment is the compressor, the air banks, and the air fill panel.

TABLE OF AVAILABLE EQUIPMENT FOR A COMPLETE BLENDING STATION

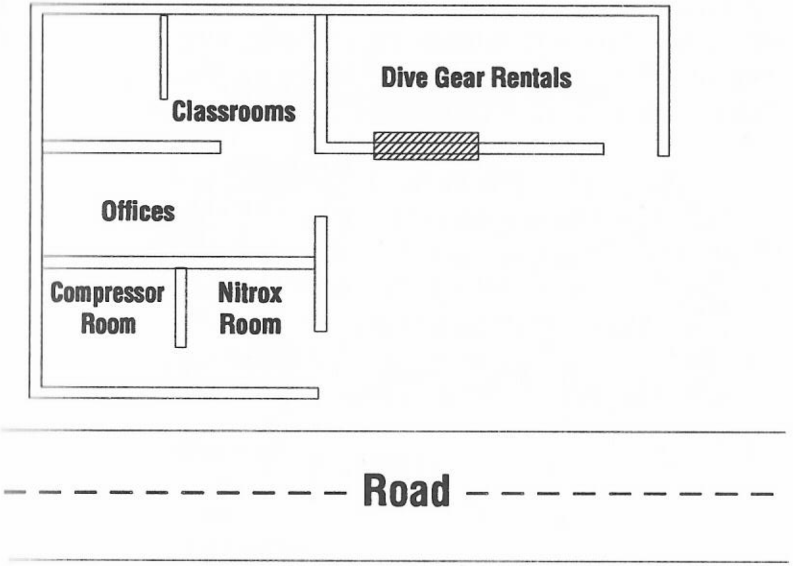
Equipment	Automatic Blending System	Manual Partial Pressure System	Membrane, Denitrogenation System	Continuous Blending System
Compressor	☑	☑	☑	☑
ANX Supreme	☑			
Membrane			☑	
Mixing Coils				☑
Air Bank	☑	☑	☑	◇?
Nitrox Bank	☒	☒	☑	☑
Regulator	☒	◇?	☑	◇?
PP Panel		☑		
Filter System	☑	☑	☑	◇?
Oxygen	☑	☑	☒	☑
HP O_2 Tank	☑ ↔	☑ ↔	☒	☑
PSA and Booster Pump	◇? ↔	◇? ↔	☒	◇? ↔
Valves and Fittings	☑	☑	☑	☑
Hoses	☑ ↔	☑ ↔	☑ ↔	☑ ↔
Tubing	☑ ↔	☑ ↔	☑ ↔	☑ ↔



STEP 2: Ensure that the schematic of the blending station (as drawn above) meets your operational needs. If not, add those components that you think are necessary to meet all your operational needs. In other words "walk your system." Do this by starting at the supply side for oxygen or air. You will be amazed to find that a couple of valves or gauges could make the system much more functional.

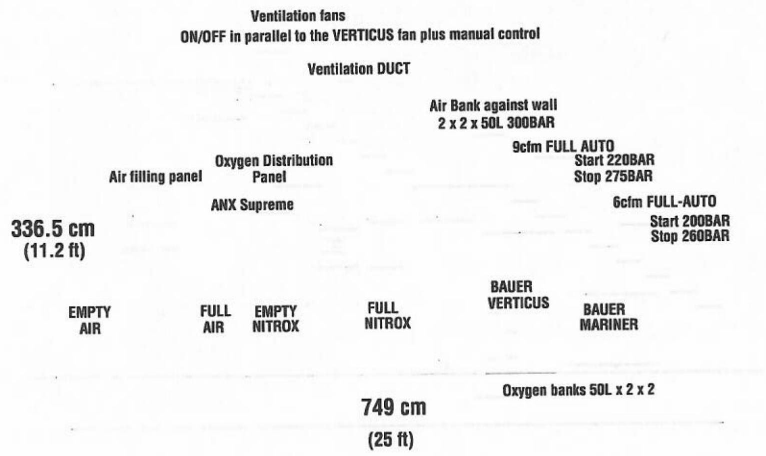
In the diagram above, for example, what is missing is a pressure gauge and an isolation valve immediately before (downstream) the filters. These are necessary in order to know the air bank pressure, and to be able to isolate the system (for maintenance, for changing filter elements, etc.) without disturbing the normal air filling.

STEP 3: Draw a sketch of your facility. This should be one that shows the entire premises. It is important to draw this overall sketch because it can reveal possible problems, such as access to the road in order to bring in oxygen cylinders, etc. In many cases you are restricted in space anyway, but there is always some choice in the layout. Maybe the oxygen should be stored outside the shop, for example.



STEP 4: Draw a sketch of the room where you are thinking of setting up your blending station. If possible, include some dimensions. This will help in estimating the length of tubing or hoses you will need and will, in fact, show whether the equipment will actually fit in the space that is available. Space restrictions can sometimes be a big constraint. You may also have to work around existing equipment that cannot be moved. One thing that is often neglected is the space necessary for the scuba tanks themselves!

FILLING STATION



Make two or three copies of this diagram and, on the drawing, start placing the gas blending equipment. Produce two or three configurations so that you can decide on the best layout. Some of the considerations are:

- ✓ Access to the controls of the blending system
- ✓ Access to oxygen or other source gases
- ✓ Availability of space for the empty scuba tanks waiting to be filled and those which have just been filled
- ✓ Ease of moving oxygen or helium cylinders in and out of their storage place

STEP 5: Check for SAFETY. The most important precaution to be taken is for fire safety. A fire could be generated in your filling station or elsewhere in your premises. Because there is a high concentration of oxygen in your blending station and compressed gas containers are involved, fire precaution is very important. Make sure that suitable fire extinguishers are clearly marked and easily accessible. Make sure that there are escape routes for personnel, and that operators are trained in how to handle possible fires.

Also, provide for safety as far as pressurized gas is concerned. If there is the slightest risk of over-pressurization, insert appropriate pressure relief valves. Provide bleed valves for depressurizing system lines, and ensure that relieved gas is always directed away from personnel. If you are using air banks at high pressure, use reducing regulators to eliminate the possibility of over-pressurizing scuba tanks.

2.3.1 Use of Air Banks

An air bank can perform four main functions:

1. It can provide storage for air so that tanks can be filled without having the compressor running. It also allows the simultaneous filling of four or five scuba tanks in a relatively short amount of time, thus being an important tool in coping with peak demand.

2. It can be a buffer. In this way, the compressor is decoupled from the filling operation. You don't need to have your compressor running to fill tanks and the compressor may be switched on or off independently. It can be completely automated and the compressor can start when the pressure falls below a set level, and stop when the pressure exceeds a certain level. In blending in particular, the function of the bank as a buffer is very important because the charging rate of your compressor and the flow through your blending

system are never exactly the same. Unless the charging rate of your compressor is less than the flow that the blending system allows, you may get a pressure built-up in tubing and hoses, which can force the compressor's pressure-relief valves to open. The compressor may stop altogether if there is an auto-stop function.

3. It helps your compressor and lengthens its operational life. Electrical controls and the motor windings have a limited life in terms of the number of times that they can be switched on/off. Motor manufacturers recommend that motors are not switched on/off more than four to six times in an hour. Also, the first stage piston during the first few strokes, actually hits the head, until pressure builds up which acts as a "spring" or "damper." (This is why you hear the louder noise at the beginning before the compressor becomes more quiet.) The banging of the piston to the head induces sudden impulsive stresses, which accelerate crack growth and reduce the life of the head and piston. An air bank helps you reduce the number of times the compressor is switched on/off.

4. An air bank allows the air from your compressor to cool down further. It also allows any droplets of impurities to condense on the bank walls. This improves the life of your filters significantly. The accuracy of your blends also is increased, as the temperature of the air used in mixing is closer to ambient.

2.3.2 What Size of Air Bank?

This depends on the prime function that the bank will perform. If it is storage, you need a large volume; if it is to be a buffer, the required volume could be small.

Generally, there is a compromise between the size of the air bank and the size of the compressor. For gas blending, 50L would be quite sufficient as a buffer. A larger bank may be preferred to allow the filling of air tanks at the same time that you are mixing nitrox. In peak demand this is important.

If the function of the air bank (or at least one of the air banks) is for storage, it must be remembered that the bank will only help to smooth out peaks in demand. The bank has to refilled anyway, whether it is now or later. If the average demand is high, then the answer is not a larger air bank, but a compressor with a higher charging capacity.

An excellent arrangement is to use an air bank of a relatively small size (e.g., 200L) which is rated at 300 bar or higher, and store the air at a high pressure (290 bar). Air at 220 bar can be supplied for normal air filling or for nitrox mixing via a high-pressure regulator.

Below we present computer simulations showing the pressure in the air bank for the following cases:

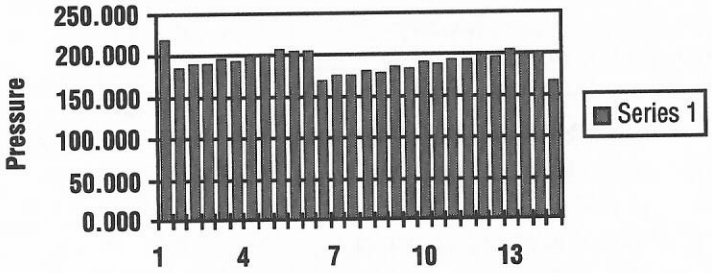
1. 12 cfm compressor 50L air bank.
2. Compressor of 7.5 cfm running at the same time as filling takes place. Air bank size 200L.
3. Compressor of 7.5 cfm running at the same time as filling takes place. Air bank size 100L.
4. Compressor of 7.5 cfm running at the same time as filling pumping to 300 bar. Air bank of 100L.

In all cases, the model obeys the following laws:

- The compressor has an auto start/ auto stop function. The compressor stops when the pressure reaches 300 bar, and starts again when the pressure falls to 220 bar.
- All tanks filled are 12L (80 ft³) filled to 200 bar .
- Filling successively, one tank at a time, it takes five minutes to fill the tank and there is a one-minute waiting time between tank change-overs.

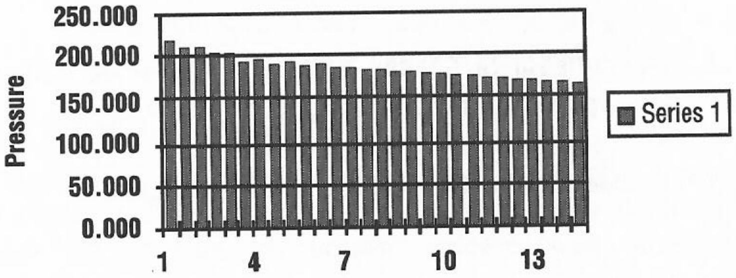
CASE 1: 12 cfm compressor 50L bank

Air Bank Pressure After Successive Fills



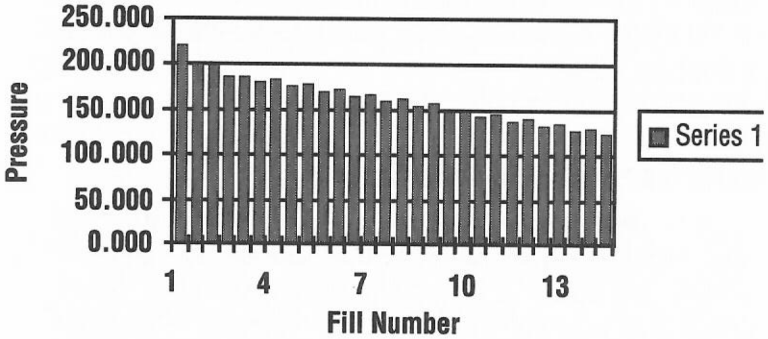
CASE 2: 7.5 cfm compressor, 200L bank

Air Bank Pressure After Successive Fills



CASE 3: 7.5 cfm compressor, 100L bank

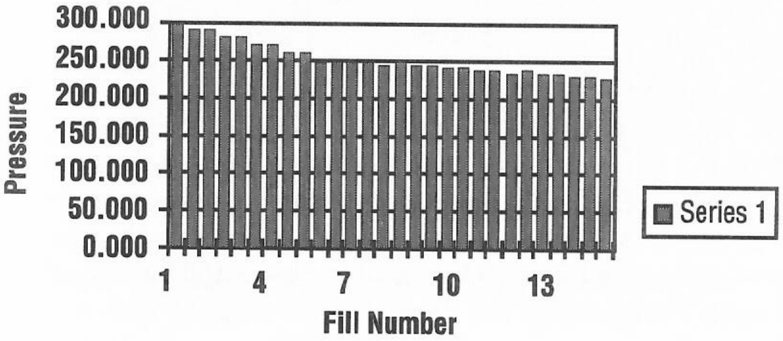
Air Bank Pressure After Successive Fills



CASE 4: 7.5 cfm compressor to 300 bar, 200L air bank

Here the laws obeyed by the model are modified to simulate the condition of using a regulator with outlet pressure 210 bar. The compressor auto start/auto stop function is set at 260 and 300 bar respectively.

Air Bank Pressure After Successive Fills



Here the system is capable of delivering a constant pressure of 210 bar, even after 10 successive fills from the air bank. The compressor essentially runs unattended.

In all the above cases, the filling is assumed to take 5 minutes. When using a bank, the filling time is primarily determined by the valve flow coefficient of your control valves for filling.

2.3.3 Use Nitrox Banks Or Not?

The decision on the use of nitrox bank must be made after careful consideration of the operational need that such a bank will serve. A storage system does cost a significant amount of money: Each storage cylinder is approximately $300 and a booster is about $6,000-$8,000. The tubing, valves, and fittings also cost money. Unfortunately, many such decisions are made on psychological and sentimental reasons rather than logic. A storage system is used primarily to increase your ability to cope with times of great demand. Given that demand in a diving facility comes in peaks, this function can be very useful.

A nitrox bank can increase your total capacity. But the penalty is extra strain on other equipment and a higher cost because, in order to replenish the banks, mixing must be done off normal hours. Why do you need the extra capacity? Is it a rare occasion that demand is high, or do you face same problem every weekend?

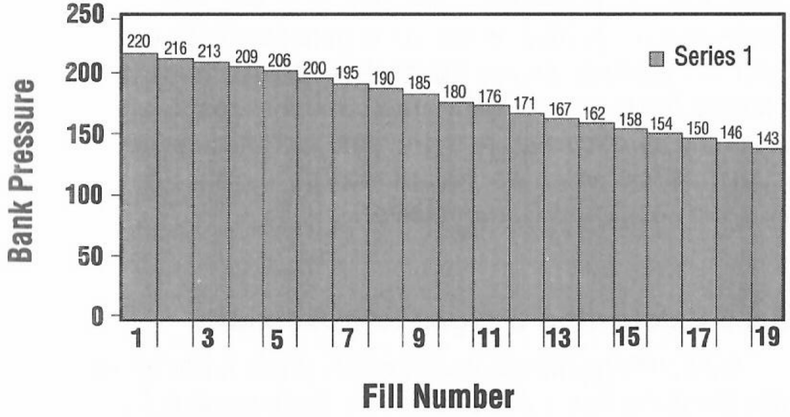
Careful time planning is another way to deal with peaks in demand for mixed gases. From experience, these peaks will be known quite accurately. They occur at 8:30 AM or at 2:00 PM before people go on their dives and they occur during weekends, public holidays, or special events, courses, etc. Tanks of your staff or of the students can be filled during off-peak hours because the oxygen percentage in the mix is known from the previous day.

If the decision is made to use a nitrox bank, its performance must be evaluated in advance. If we assume that the minimum useful pressure is 165 bar (2500 psi) and that the bank is filled up initially to 220 bar (3200 psi), it is not too difficult to calculate what size of bank is needed, and how many scuba tanks can be filled before the bank has to be replenished.

In the graph below, we examine the pressure after successive fills. The bank size in this example is 450L bank (which is about 10 large cylinders similar size to the ones used for oxygen):

With this particular nitrox bank, we can fill 13 tanks before we need to stop and fill our banks again. Consequently, the size of the bank is a function of the number of successive fills that can be completed before the bank needs to be replenished. A similar simulation to the

PRESSURE IN STORAGE BANK AFTER SUCCESSIVE FILLS



If pressure is higher than 207 bar, we fill to 207 bar. If the pressure is lower, we fill until equalization.

above can be done for systems that can be charging the banks at the same time that nitrox is drawn from the bank to fill scuba tanks. In this case, there is a fine balance between the charging rate into the bank, the size of the bank, and the maximum number of successive scuba tanks that can be filled from the bank.

Of course, a nitrox bank has an extremely important operational role to play in membrane air separation, and continuous blending systems. In such systems, a nitrox bank is almost mandatory to make the whole filling operation practical. The critical question concerns the sizing of such a bank. Bigger is not always better for many reasons. The guidelines for sizing a nitrox bank are similar to those for sizing an air bank, and this is best done using software programs.

2.3.4 Supply of Oxygen

By far the simplest and most cost effective way in most cases is to get compressed oxygen cylinders. However, there are more options available. It is also possible to get liquid oxygen in mini tanks, or to generate your own oxygen with a Pressure Swing Adsorption (PSA) machine. These options have hidden dangers or hidden costs, and careful planning is required. A more detailed discussion on PSA systems as well as liquid oxygen can be found in Appendices B and C, respectively.

2.3.5 Calculating Oxygen Requirements

Calculating your oxygen requirements is not an easy job, not because the calculations are too complex (complexity can easily be dealt with by a computer), but because of uncertainty, and variation in the demand. Your use of oxygen

depends on many parameters, all of which will vary. This subject is dealt with in detail in Section 6.

Your layout must be able to cope with the number of oxygen cylinders that may be needed today, and in the future.

NOTES

Section 3

3. Generating Clean Air

3.1 What Is Clean Air?

"Clean air" or "oxygen compatible air" may sound a bit strange. Does it mean that the air from a normal breathing air compressor is not clean? The term "clean" is a relative term. Breathing air quality standards like CGA Grade E, or BS4275, or DIN 3188, have been set with main criteria being the **physiological impact** of contaminants to the diver at elevated pressures. These are tabulated below:

CGA GRADE E

Condensed hydrocarbons	5 mg/m^3
Gaseous hydrocarbons	25 ppm
Carbon dioxide	500 ppm
Carbon monoxide	10 ppm

On the other hand, "oxygen compatibility" of compressed air for nitrox preparation is determined based not only on physiological criteria, but also on **operational criteria** when the air is mixed with pure oxygen or oxygen-rich atmospheres.

There is no one single standard regarding quality of air used for mixing with oxygen in the preparation of nitrox.

In 1992, the technical diving training agencies and various governmental agencies from the U.S. and other countries met in Orlando, Florida, and agreed on a set of standards for oxygen compatible air. These standards represent a consensus (based on the knowledge, experience and technology available at the time) on the compatibility of air and common impurities with oxygen. These are tabulated below: OCA:

Condensed hydrocarbons	0.1 mg/m³
Gaseous hydrocarbons	15 ppm
Carbon dioxide	500 ppm
Carbon monoxide	2 ppm
Water	39 ppm or - 40C dew point

3.1.1 Air Quality Requirements As Set By NS Research

The NS Research philosophy is that air quality itself is not a sufficient requirement. What will usually present a problem in oxygen systems is not the level of contamination itself (given that this is under the standards as specified above), but accumulated hydrocarbons in the system.

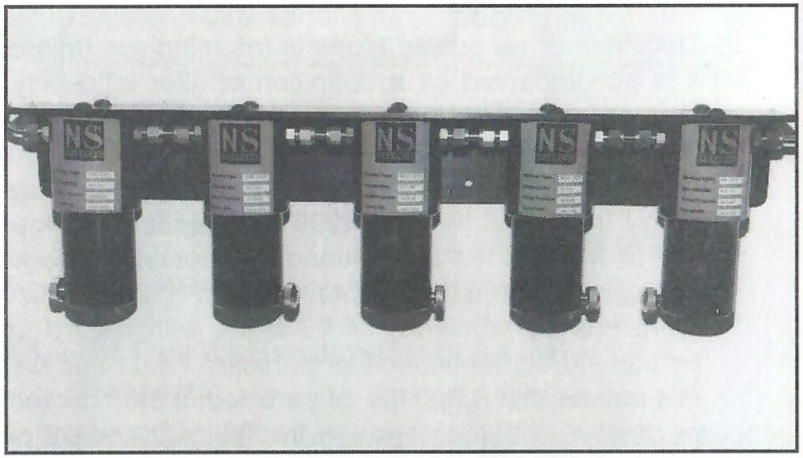
The following two points are fundamental in the requirements for air quality:

1. It is a recommended practice that nitrox facilities disassemble their mixing system, inspect, and re-clean it annually as part of their routine preventative maintenance. Filters should also be changed on a regular basis. Experience shows that although safety conscious users do follow the guidelines, a large proportion of users do not. We believe that air quality must be such that even with late replacement of filters, and no inspection and re-cleaning of the system's internal surfaces, there is still very low risk since accumulation is kept low (even after two, three, five, or even ten years). Contamination in the air must be very low, and filter life high, so that replacement on a yearly basis is sufficient for most users.

2. Definition of air quality alone is meaningless unless it is accompanied by a definition of filter efficiency. In most cases when air quality is defined, one assumes (wrongly) 100% filter efficiency. This can never be the case. Efficiency for a good filter may range from 90% to >99.99999% depending on flow conditions and the contaminant in question. A good example is particulate contamination. If a filter element has an efficiency of 99.999% with regard to particulate contamination of particles >0.01 micron, this means that 0.0001% of particles of 0.01 micron or greater, still goes through the filter. The effect of this becomes apparent when one considers accumulation of contaminants.

Based on the above points, we have set a very strict standard:

Condensed hydrocarbons	0.01 mg/m³
Gaseous hydrocarbons	0.01 ppm
Carbon dioxide	500 ppm
Carbon monoxide	10 ppm
Water	39 ppm or - 40C dew point



Five Stage Filtration System by NS Research

3.2 Why Bother About Hydrocarbons When Mixing Nitrox?

As we have already explained, acceptable hydrocarbon contamination is determined not only from physiological criteria, but also from operational criteria with regard to the contact of contaminants with oxygen-rich atmospheres.

There are two main concerns as far as the contact of contaminants and oxygen is concerned:

1. Production of Carbon Monoxide due to incomplete combustion of contaminants. This goes unnoticed in most cases, but it presents a serious hazard to the diver, especially at elevated pressures.

2. A more dramatic and more commonly known problem is an oxygen fire, for which contaminants on internal surfaces of hoses or tubing and fittings may act as initiators. This is possible because the ignition temperature of contaminants is relatively low, and could therefore burn in an exothermic reaction generating even more localized heating. It could also happen because hydrocarbons can be ionized in a flow of gas, thus storing an electrical charge. If there is a discharge through an arc, then ignition is possible.

The above two risks are closely related to system design. More specifically, it relates to fluid velocity and to the possibility of the generation of pressure shock waves. A shock wave is, by definition, a discontinuity in the properties of the gas. A sudden rise in pressure can result in a sudden rise in temperature. Pressure shock waves can be created by opening a valve quickly, closing a valve suddenly, or by an obstruction in the system, such as a sharp bend or a kink in the tubing or hoses. These can create a local temperature rise. Contaminants have an ignition temperature that is relatively low compared to the material of the internal surfaces of tubing and hoses. Their ignition almost unavoidably will create CO and CO_2 as combustion by-products. It also will create a further local temperature rise due to the heat of combustion, which can be sufficient to cause the ignition of the tubing or hose material. The consequences of this can be catastrophic.

3.3 Generating Oxygen Compatible Air

In the discussion above, regarding air quality requirements for oxygen compatible air, reference was made to filtration. However, filtration is only one way to achieve the required air quality. A second way is to avoid introducing hydrocarbon contamination in the compressed air in the first place. This is possible by using an oil-free compressor.

3.3.1 Oil-free vs. Double Filtration

An oil-free compressor will not introduce any additional condensed hydrocarbons to the air. Yet, it must be understood that there is no such thing as hydrocarbon-free air. Even with an oil-free or non-oil-lubricated compressor, the air drawn in still contains hydrocarbons as well as other contaminants, such as CO, CO_2, nitrous oxides, dust, and dirt particles of all sorts. These are all present in the atmosphere, and find no trouble passing through the intake filter of any compressor. Oil-free compressors use special rings and depend on the tripological properties of the material for low friction. Oil-free compressors are about 30% more expensive than oil-lubricated compressors and for this reason, as well as for their maintenance requirements, they are not popular products. They are also limited in their temperature operating range, as ambient temperatures above 30-35C create many maintenance problems.

Oil-free compressors are mandatory in continuous blending systems because oxygen-rich atmospheres are being compressed. Atmospheres rich in oxygen should avoid contact with oil, especially at the running temperatures of the compressor's pistons.

Three Stage Filtration System by NS Research

3.3.2 Filtration Systems and Considerations

Flow-rate Requirements:

Ideally, filtration systems should be placed after the air bank and before the mixing panel. Good filtration systems should specify a nominal flow. Under no circumstances should air-flow exceed this nominal flow.

For those facilities which wish to use only oxygen compatible air for all their fills, both nitrox and air (thus eliminating the possibility of contamination when their nitrox tanks are filled with air from their air charging panel), it is recommended that the filtration is placed after the compressor and before the air bank. Placing the filtration system after the banks means that nominal flow rate may be exceeded. This could happen when more than two scuba tanks are being filled simultaneously. It is also important to emphasize that the air banks must be free of contaminants.

Reliability of Air Quality:

It is imperative that air quality must be guaranteed at all times within the operating parameters of the filters used and within the conditions likely to be encountered in a breathing air/ enriched air facility. This means that the secondary filtration system must be able to perform to the specified standard, even if the compressor filter fails catastrophically and the compressor itself generates air of very high oil concentration. The maximum acceptable concentration of contaminants entering the filtration system should be checked out with the manufacturers to ensure that safety is maintained under the worst conditions. In general, a good filter should be able to cope with more than 15mg/m^3 of condensed hydrocarbons for short exposure times without any significant drop in efficiency. This would be a typical situation if, for example, the automatic condensate drain of the compressor fails or if the compressor's main filter is saturated with oil.

Modes of Failure:

Any piece of equipment can fail. A filter may be considered as a critical piece of safety equipment, as a significant deterioration in air quality could create safety problems. It is almost impossible to achieve a fail-safe system. However, the design of a good filtration system should be able to achieve a safe-failure mode. Filters that use a single cartridge cannot achieve safe-failure. On the contrary, failure is usually complete and could be catastrophic.

At this point, it is important to identify the possible modes of failure of a filter. What do we actually mean by "failure?"

1. Delivering air with hydrocarbon content higher than specified
2. Delivering air with hydrocarbon content higher than the maximum acceptable safety limit
3. Releasing charcoal particles to the filtered air downstream
4. Releasing molecular sieve "dust" to the filtered air downstream
5. Releasing charcoal particles upstream due to pressure vibrations
6. Developing a high pressure differential
7. Filter breakage due to pressure

Some of these modes of failure can have more potentially dangerous consequences than others. Only the first and the sixth failure mode can be considered to be a "safe failure" mode. All the others could contribute to one of the mechanisms of ignition.

3.4 Air Quality Testing

Due to the requirements for very low levels of hydrocarbons in the air, it is imperative that air quality is tested on a regular basis. It is recommended that this is done quarterly. Air quality testing is the most reliable way of ensuring that the filters are performing to specifications.

There are a number of different analysis procedures, and the laboratories performing the analysis usually provide their own sampling kit with instructions on how to use the kit and how to send the samples to the laboratory. A good test report should include the following:

- ✔ Sampling method
- ✔ Test method and accuracy for each contaminant
- ✔ Level of confidence (usually 95%)
- ✔ Test procedure/standard under which the tests are carried out
- ✔ Standard of compliance for air quality

3.4.1 Interpreting "Accuracy" of Testing

Accuracy of any type of measurement is something that tells you the limitations of your method. Ask a material supplier to the aerospace industry "How many cracks are there in the material you supply?" The answer will most surely be "Get out of here! Our material contains no cracks." Yet, any engineer knows that there are cracks in the material, it's only a matter of size.

If an air quality report indicates "Hydrocarbons: NONE," what it really means is that the level of hydrocarbons present in the sample is less or equal to the accuracy of the test method. So, if the accuracy of a test method is only 0.5 mg/m^3 of condensed hydrocarbons, **we must assume** that there are 0.5 mg/m^3, even if the report indicates "NONE."

Unfortunately, too many reports simply indicate a mere "PASS." These reports are worse than useless. They are dangerous because they offer false confidence and complacence.

A Note on Dräger Tubes:

This method of testing for hydrocarbon levels is not sufficiently accurate for testing oxygen compatible air. Accuracy is 0.5 mg/m^3, which is the physiological limit for hydrocarbons. It is impossible to measure the 0.1 mg/m^3 that is required for oxygen compatible air. What is more, the confidence level for Dräger tubes is low.

3.5 Water Content In Air

The aim of this Section is to explain the effect of water content with regard to the air, the diver's breath, and the air we use for mixing gases. Basic principles of hydrometry and an example on the condensation of water as air is being compressed can be found in Appendix A.

Why Do We Want Dry Air?

Filtration and drying are important for many different reasons. Almost every breathing air compressor has molecular sieve and/or water separators to remove excess water. As far as the breathing air is concerned, it is important that the air is dry enough so that we avoid freezing during the expansion of the air through the first stage and sometimes second stage regulator. Dry air is also good for the scuba cylinders, especially steel cylinders, because corrosion is less likely. Extremely dry air, however, is not desirable for divers due to the dehydration and subsequent physiological effects it can cause.

As far as the filtration process itself is concerned, excess water can damage or reduce the efficiency of other chemicals, such as activated carbon, which removes hydrocarbons, or hopcalite, which removes carbon monoxide.

With regard to gas blending, there is no reason why water content should be kept low, other than avoiding the possibility of freezing of certain types of metering valves.

NOTES

Section 4

4. Tubing, Hoses, Valves, and Fittings

4.1 Tubing vs. Hoses

Essentially, both tubing and hoses perform the same function: They transport the gas. However, each has its own role, and they are not completely interchangeable. In general, tubing is preferred for permanent and long runs.

Tubing	Hose
• Firm once bent and secured in place • About 30% of cost of hose per meter • Wide range of outside diameter, wall thickness, and pressure ratings • Requires small space, provides compact and neat installation • Tube cutting and bending tool required	• Flexible • Expensive compared to tubing • Limited range of ID and pressure ratings • Can be supplied in large rolls, ideal for long runs requiring fewer connections • Large bend radius • No special tools required

4.2 Tubing Selection and Specification

Careful specification, selection, and purchasing of tubing are essential to the safe and problem-free operation of your blending station.

Several general rules apply:

1. Metal tubing must always be softer than the fitting material. For example stainless steel tubing should not be used with brass fittings.
2. In high pressure systems, tubing must be seamless and fully annealed.
3. Wall thickness must be carefully checked.
4. Tubing surface finish is very important to proper sealing. Scratches and other marks may result in leakage. Particularly important to avoid are longitudinal scratches.
5. Oval tubing which will not easily fit into fittings, nuts ferrules, and bodies should never be forced into the fitting.

Material:

For gas blending where tubing may be exposed to high pressure oxygen, the following materials are acceptable: Stainless steel 316 ASTM A632 and Alloy 400 ASTM B165 (a copper-based alloy suitable for oxygen service).

Quality:

Good quality tubing is usually supplied with a test certificate which specifies the standard to which it conforms, the material batch and composition, and the heat treatment batch. Also, the tubing itself, will have the standard of compliance, material, rated pressure, OD, and wall thickness printed directly on it.

It is recommended that a conservative pressure rating is established based on "worst case" conditions with maximum allowable pressure defined as the maximum pressure the system could possibly encounter during its entire service life. A derating factor may also be applied for elevated temperatures.

In selecting wall thickness for tubing, use the table below:

STAINLESS STEEL 316 OR 304
FOR TEMPERATURES 29C TO 37C

	Wall thickness (inches)			
	0.028	0.035	0.049	0.065
Tube OD	**Rated pressure in psig**			
1/8"	8,500	10,900	—	—
3/16"	5,400	7,000	10,200	—
1/4"	4,000	5,100	7,500	—
5/16"	—	4,000	5,800	8,000
3/8"	—	3,300	4,800	6,500
1/2"	—	(2,600)	3,700	5,100

No derating required for temperatures up to 93C.

Calculations are based on minimum wall thickness and OD allowable under ASTM A269. No allowance is made for erosion or corrosion.

ALLOY 400 TUBING FOR TEMPERATURES FROM 29C TO 37C

	Wall thickness (inches)			
	0.028	0.035	0.049	0.065
Tube OD	**Rated pressure in psig**			
1/8"	7,900	10,100	—	—
1/4"	3,700	4,800	7,000	9,500
3/8"	—	3,100	4,400	6,100
1/2"	—	—	3,200	4,400

For temperatures above 37C and up to 93C, use a derating factor of 0.88.

Calculations are based on minimum wall thickness and OD allowable under ASTM B165. No allowance is made for erosion or corrosion.

Recommended Practice:

Use stainless steel 1/4" OD 0.035" wall thickness, or Alloy 400 1/4" OD 0.049" wall thickness. Seamless, fully annealed.

Please Note:

Larger OD may be required when high mass flow rates are involved. This is to keep the gas velocity within acceptable levels and to reduce flow resistance and resulting pressure drop. In practice, OD larger than 1/4" is used for long runs (15m+) or where flow rate can be more than 20 cfm. In all cases, wall thickness guidelines must be observed closely.

4.3 Tube Handling

Built-in quality of carefully specified tubing can be quickly degraded by careless handling. Good handling practices will reduce scratches, bends, and nicks which can interfere with proper sealing.

Good quality tubing is usually supplied in 4 - 6 m lengths inside a protective cardboard tube. Once outside its protective cover, it should never be dragged along hard surfaces. Oval tubing which does not easily enter the nut, ferrule, and body of the fitting should be recut. Forcing out-of-round tubing into the fitting will cause major leakage.

4.4 Planning the Tube Layout

When laying out a blending station, the first step is to draw a schematic of your system. This will illustrate all the equipment you will need to use. For this purpose, software planning tools such as the NS Research Blending Station Planning Tool may be used. Then start by drawing a rough sketch of the room or rooms. This will help you decide where to put (or move) your compressor, air storage, oxygen cylinders, your blending system, and the filters. Put some dimensions on your drawing to help determine the lengths of tubing required and the number of unions, elbows, or tees required.

You can now plan the tube run. The following guidelines should be observed:

1. Tubing must be clear of access doors and equipment must be accessible.
2. When tubing is attached to an item that must be occasionally removed for maintenance, the method of connection must permit easy removal.

3. Equipment that vibrates, such as a compressor, should be connected to tubing via a short hose to allow for movement.

4. Valves should be put in place to allow equipment to be isolated and depressurized for maintenance.

5. Tubing should not be directly connected to oxygen cylinders. These are removed for refilling, and will almost never be reinserted to align perfectly. Use a short hose instead, which then connects to your tube line.

6. Never place the tubing so that it can be used as a foot rest at low runs or as a bus rail at high runs.

7. Long runs of tubing should be supported at maximum intervals of 1.5 m or 5 feet.

8. Where tubing is likely to be hit by scuba tanks placed against a wall, use a protective cover, or mount at a reasonable height so that collision can be avoided.

9. Tube support should be used at both sides of valves and very close to valves, so strain on tubing is minimized. A much better alternative is to use a proper valve support.

10. Avoid straight runs between two fixed fittings. The tubing cannot be bottomed in the fitting at both ends, and large stresses can be exercised due to thermal expansion.

11. Bend tubing skillfully and use correct lengths of tubing to avoid using too many unions or elbows. Every extra fitting adds cost and is a potential source of leakage.

12. If you are not sure about the exact length of tubing required for a particular run, error on having longer tubing. This can easily be corrected by cutting the extra bit. If the tubing is shorter, you may be forced to use an extra union, or use a new piece of tubing altogether.

4.5 Use of Hoses and Their Selection

Hose selection must be approached with the same care as tube selection. We are referring primarily to high-pressure hoses. There are three main types that are of interest. These are:

1. Thermoplastic hose
2. Flexible metal hose
3. Teflon hose

Each will be discussed in more detail. However, it is useful to discuss the evaluation criteria first.

Criteria:

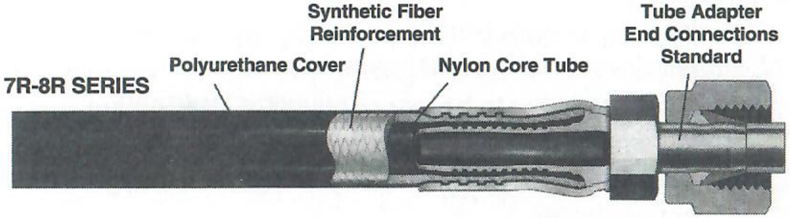
- ✓ **Pressure rating:** The working pressure of the hose should be at least equal to the maximum possible pressure likely to be encountered in the system.
- ✓ **Material compatibility:** This is particularly applicable to hoses that will carry oxygen or oxygen-rich atmospheres.

- ✔ **Abrasion resistance and resistance to UV light, salt water, or other environmental conditions:** This will determine its service life to a large extent.
- ✔ **Non-contaminating internal core:** This is important as it will be carrying breathing gases.
- ✔ **Minimum bend radius, or flexibility:** Note: small bend radius is not always desirable. There are cases where we wish to avoid sharp bends in the system.
- ✔ **Weight:** In same cases especially for long hoses (e.g., surface supply) it is beneficial to use light-weight hoses.
- ✔ **Cost:** An important aspect of any business decision.

All the above also apply to end fittings. These must have the correct pressure rating to be compatible to the gas and to the environment. Always try to avoid carbon steel end fittings. Although the hose may carry only air, and at first oxygen compatibility is not required, imagine what will happen when rust chips get detached and travel at high velocity in the system until they reach a valve!

Thermoplastic Hoses:

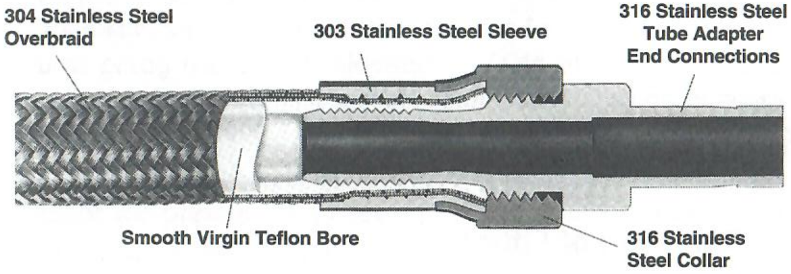
Thermoplastic hoses can reach pressures up to 345 bar (5,000 psi). They usually consist of a polyurethane cover around the synthetic fiber reinforcement (glass or kevlar) which supports the nylon core tube. The core tube (nylon 11) is compatible with oxygen, as well as with most chemicals.



The polyurethane cover does not post-cure in service, has excellent abrasion resistance and offers a long service life. Bend radius is relatively large (not too flexible). Cost is also relatively high.

Teflon Hoses:

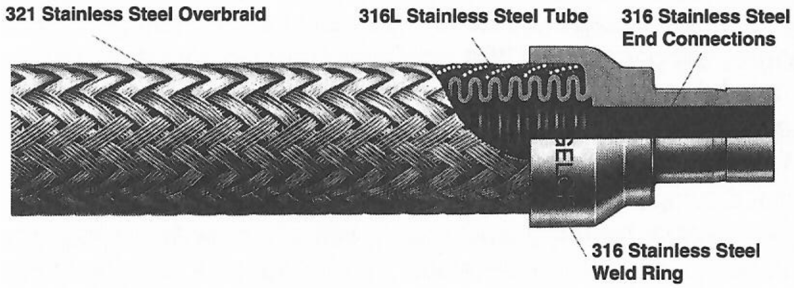
Teflon hoses consist primarily of a smooth virgin Teflon bore, supported in a 304 stainless steel overbraid. Primarily used for high purity systems because Teflon is FDA approved for food, pharmaceuticals, etc. Pressure rating is to a maximum of 207 bar (3,000 psi). Very flexible. Has good temperature range and resistance to aging. Teflon is a permeable material and gases will migrate at a rate that depends on several variables. This hose is NOT suitable for transferring helium. Cost is somewhere between thermoplastic and flexible metal hoses.



Flexible Metal Hoses:

Flexible metal hoses consist primarily of a bellow type 316 stainless steel tube surrounded by a 321 or 304 stainless steel overbraid. Working pressures do not exceed 220 bar (3,200 psi). The material is compatible with oxygen, and these hoses are often found in oxygen systems. They have good abrasion resistance, but can easily be dented and damaged. Bent radius is relatively small (quite flexible). Their cost is lower than good thermoplastic hoses.

They are sensitive to pulsating or shock pressures. Fast-closing valves can cause system pressure surges, shocks, or pulsations. Flexible metal hoses used under these conditions, should not be subjected to pressures exceeding 50% of their stated working pressures.



Note: One very important thing that needs to be emphasized for hoses used in oxygen systems is that usually the swaging process of placing the fitting into the hose uses lubricants that are NOT compatible. If you are going to use hoses in an oxygen system, clearly specify that they need to be oxygen service rated.

4.6 Selection of Fittings

Fittings are essential in the connection of a filling station. Good fittings will ensure leak-proof performance and long service life. We highly recommend the use of compression fittings. Apart from materials compatibility with regard to the fluid wetting the fittings, it is necessary to pay attention to materials compatibility with regard to the tubing used. In particular, the material of the fittings must have a hardness higher than that of the tubing material. If the tubing is stainless steel, the fittings should also be stainless steel; brass fittings may not give a reliable seal.

4.7 Valves Selection

There are many different designs and types of valves. Most of them perform one or more of four main functions:

- ✔ ***Isolation:*** The valve is either closed or open; its function is to turn the flow on or off.
- ✔ ***Regulation*:** The valve can isolate the system (fully closed) or regulate the rate of flow through the system by control of the number of turns that the valve is open.
- ✔ ***Direction:*** The valve allows fluid to flow only in one direction or select the fluid flow through two or more branches.
- ✔ ***Protection:*** The valve protects the system from excessive pressure.

The above functions can be performed by more than one type of valve. Also, one valve may perform more than one function.

Isolation is usually performed by ball and plug valves where a quarter turn of the handle quickly opens or closes the valve. These types of valves are usually found in compressor air panels. They are NOT suitable for oxygen-rich atmospheres, where the function of isolation is best performed by a needle valve.

WARNING:
NOT ALL NEEDLE VALVES ARE THE SAME.
FOR OXYGEN-RICH ATMOSPHERES, IT IS NECESSARY
TO KNOW THE FLOW CHARACTERISTIC OF THE VALVE.

Regulation is best performed by metering valves or regulating needle valves. These valves have a long, finely tapped stem tip, and a fine pitch stem thread. They fully open in five to ten turns.

Direction: Selection valves have three or more connections. They are useful in gas blending in cases where the flow needs to be directed to or from two different storage banks. They are also common in recompression chambers. They MUST NOT be used in oxygen-rich atmospheres at high pressures.

Check valves are also known as one-way or non-return valves. They are very useful in gas blending in preventing the flow of oxygen back to the air channel, the air filters, etc., as well as preventing the flow of air to the oxygen bank. Check valves are held closed by a spring, which opens automatically when inlet pressure exceeds the outlet pressure and the spring force. This is often known as the cracking pressure.

Protection is performed by relief valves. They protect the system from excessive pressure. The valve is held closed by a spring as the system operates at its normal pressure. When the pressure increases beyond a set point, the valves open automatically and remain open until the pressure falls back to a set point. These two pressure points are not necessarily the same.

Criteria for Valve Selection:

1. **Pressure rating:** This must be at least as high as the maximum pressure the valve is likely to encounter during its entire service life.

2. **Materials compatibility:** Most common materials are stainless steel, brass, and carbon steel. Carbon steel is not suitable for oxygen-rich atmospheres, and stainless steel should be grade 316L. Carbon steel, apart from its non-compatibility with oxygen, is prone to rusting which creates aesthetic problems,

improper sealing, and leaks — it should be avoided even when the gas is air. Materials compatibility must also be considered for stem seals and other non-metal parts. Ask for o-rings and valve seat materials that are oxygen compatible.

3. **Flow characteristic:** See Section 4.7.2

4. **Cost:** This is very important for any business decision.

5. **Other criteria include:** End connections, type of stem seals (packing), and temperature range.

4.7.1 The Meaning and Importance of the Flow Coefficient

The flow coefficient of a valve (Cv) is defined as the number of cubic meters of water flowing though the valve per second under a pressure differential of 1 bar. In the imperial system, Cv is defined as the number of US gallons of water flowing through the valve per second under a pressure differential of 1 psi. The imperial system for valve flow characteristics is more widely used throughout the world. The examples shown below are according to the imperial system. Essentially, we are concerned with how much fluid can flow through the valve. In most cases, reference to flow coefficient implies the flow coefficient when the valve is fully open.

This is only important in determining the size of the valve and how much fluid can be delivered through it under a given pressure differential.

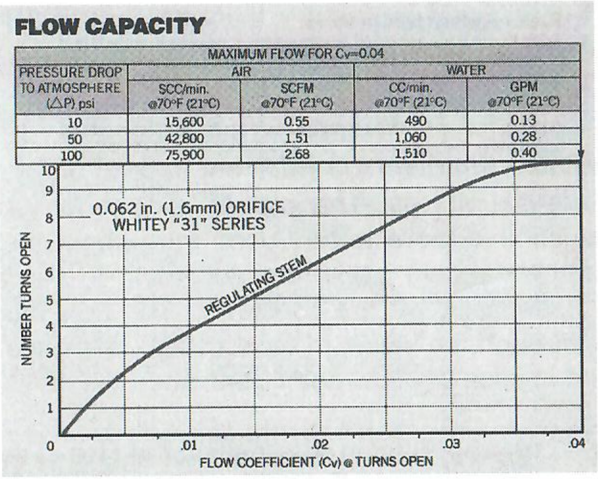
4.7.2 Interpreting the Valve Flow Characteristics

In selecting valves in gas blending, we are interested in the valve flow characteristic, which is a curve that shows how Cv changes with number of turns opening of the valve.

The valve characteristic is extremely important for system safety. Small flow coefficients avoid the possibility of creating pressure shock waves which can result in high temperature rises in the system.

What is more, the temperature of the gas in the scuba tank increases in a manner similar to a step function, where 85% of the temperature rise occurs within the first 10 seconds of filling (see Section 7.2). This is when the valve is being opened or has just been opened and gas flowed through. The valve flow characteristic is critical in determining the magnitude of the temperature step rise.

The graph below is for a Whitey union bonnet valve.



FLOW CAPACITY

PRESSURE DROP TO ATMOSPHERE (△P) psi	MAXIMUM FLOW FOR Cv=0.04			
	AIR		WATER	
	SCC/min. @70°F (21°C)	SCFM @70°F (21°C)	CC/min. @70°F (21°C)	GPM @70°F (21°C)
10	15,600	0.55	490	0.13
50	42,800	1.51	1,060	0.28
100	75,900	2.68	1,510	0.40

4.7.3 The Right Valve for the Right Job

Even for the same type of valve, the stem can make a big difference. Depending on the function that we want the valve to perform, we must have a different characteristic.

One-quarter turn opening ball valves have flow coefficients from 0.9 to 2.4. Usually, no characteristic is provided. Although these valves are used in compressors and in scuba tanks, we strongly discourage their use in gas blending. Alternatively, the function of isolation can be performed by needle valves whose maximum flow coefficient Cv is no greater than 0.2.

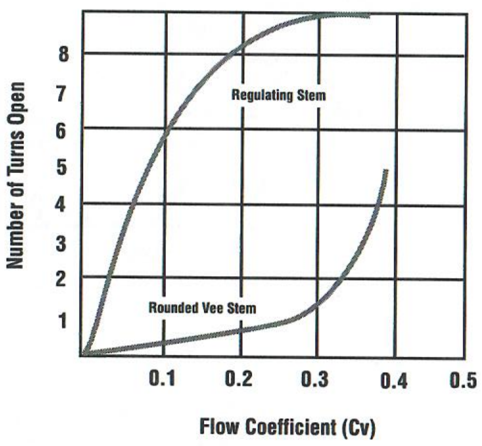
It is recommended that no valves with flow coefficient greater than 0.2 should be used in gas blending. Especially for isolation of oxygen, the characteristic of valves used for isolation must be very steep at the first few turns. This means that many turns are required for a small increase in flow coefficient.

RECOMMENDATION

For isolation of oxygen, use needle valves with an almost linear flow characteristic so that one turn opening Cv is less than 0.05.

A typical valve characteristic is shown below:

Flow Characteristic*

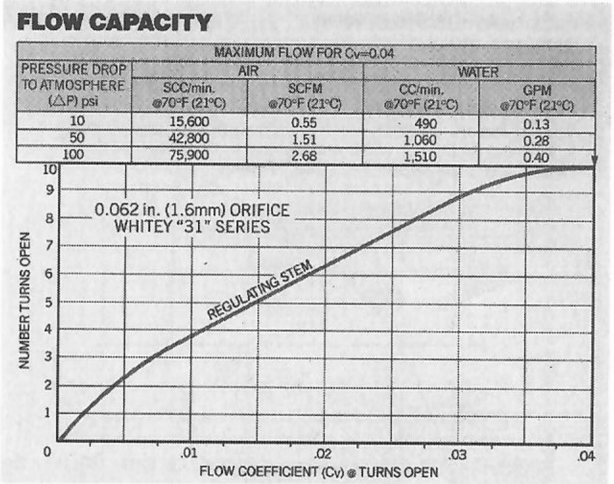


*Whitey® "I" Series valve 0.172" orifice

The two characteristics are very different although it is the same valve. The two different stems make a very big difference. The rounded vee stem is unsuitable because only 1/8th of a turn, which is essentially just cracking the valve, makes a large increase in flow coefficient. With a regulating stem, it would take about three complete turns to get to the same increase in flow coefficient.

If the function of the valve is regulation and control of the flow (such as valves used as the main control for blending), we recommend that metering valves are used with characteristic similar to the one below. Maximum flow coefficient should not exceed 0.05.

Flow Capacity

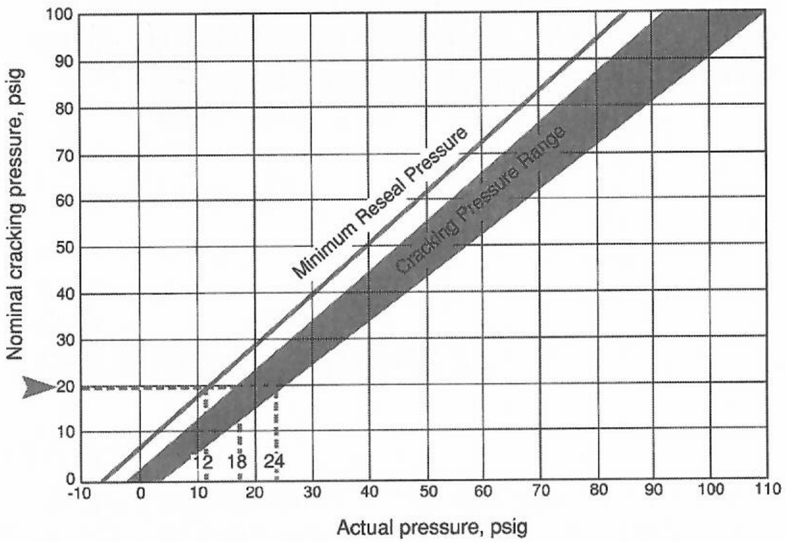


FLOW CAPACITY

PRESSURE DROP TO ATMOSPHERE (△P) psi	MAXIMUM FLOW FOR Cv=0.04			
	AIR		WATER	
	SCC/min. @70°F (21°C)	SCFM @70°F (21°C)	CC/min. @70°F (21°C)	GPM @70°F (21°C)
10	15,600	0.55	490	0.13
50	42,800	1.51	1,060	0.28
100	75,900	2.68	1,510	0.40

4.7.4 Check Valves

Check valves or non-return valves have their own characteristics as well. The valve characteristic mainly determines the cracking pressure and reseal pressure. **Cracking pressure** is the upstream pressure at which the first indication of flow occurs. **Reseal pressure** is the upstream pressure at which the valve closes bubble-tight. Although not as critical as Cv, it still can contribute to the overall safety of the system. One such characteristic is shown above.



When specifying check valves, ask for a low reseal pressure. One-third bar or 5 psi is a suitably low reseal pressure. The reason for such a low reseal pressure is the disassembly of the system. Unless there is a venting outlet upstream from the check valve, gas at the reseal pressure will be trapped in the hose or tubing upstream from the check valve. For safety reasons, this pressure has to be very low.

Another type of valve useful in a blending station is a bleed valve. This is a low-cost valve and can be installed in a tee placed in lines that need bleeding for service and maintenance.

The function of a bleed valve can be integrated in a pressure relief valve with a manual override. This valve will ensure the safety of the system against over pressurization, and with a manual override you can ensure that lines can be depressurized safely for service and maintenance. However, the cost is significantly higher.

Section 5

5. System Cleanliness

5.1 Oxygen Service

Oxygen service refers to the suitability of a system or component for use in an oxygen environment (pure oxygen or oxygen-rich atmosphere). Oxygen service requires the system or the component to be both oxygen clean and oxygen compatible. One condition alone is not sufficient. What is more, for oxygen service to apply, a system must also be free of burrs.

5.2 Oxygen Compatibility

Materials are oxygen compatible if they are not likely to become combustible at the working pressure of the system in the presence of either pure oxygen or oxygen-rich atmospheres. This is primarily based on the ignition temperature of the material, as compared to the maximum theoretical temperature that can be reached in the pressure system. There are other important criteria in the suitability of materials for use in oxygen environment. These include: minimum auto ignition temperature; specific heat capacity; and thermal conductivity. In practical application, geometry is extremely important because it largely determines the ability to conduct heat away.

It should be noted that although ASTM gives guidelines based on auto-ignition temperatures, it is equally important to consider what happens when the material does burn. For example, the entire diving industry had, until recently, been using viton as the prime oxygen compatible material for o-rings. In fact, viton is not the best material. Organizations like Air Liquid and NS Research are no longer using viton o-rings. Nitrile is a much better material although its ignition temperature is lower than viton. When it does burn, viton gives out toxic fumes!

The table below indicates some common oxygen compatible materials which can be used safely in practice:

METALS	NON-METALS
316L Stainless Steel	Nylon 11
Monel Alloy 400	PTFE
Inconel Alloy 600	Viton or Nitrile
Brass	TFE-based plastics

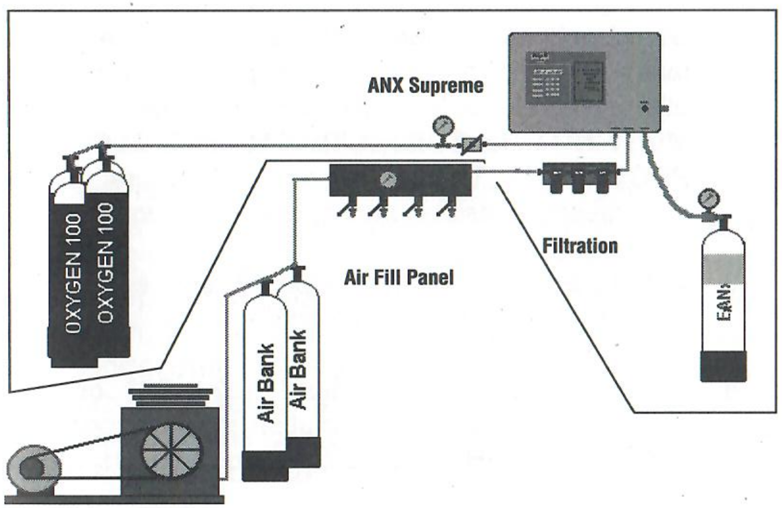
5.3 Oxygen Cleanliness

Oxygen cleanliness refers to the cleanliness of the system or component or, more specifically, to the absence of contaminants which could act as fuel or ignition sources. Oxygen cleaning applies to the components that include wetted surfaces with either oxygen, enriched air, or air after the filtration system.

In the industry, there has been a lot of argument whether cleaning is required if the percentage oxygen is below 40%, below 50%, or below any other percentage that people have proposed from time to time. What we suggest to people is **always clean** your equipment whenever possible, but do not get hysterical. Cleaning is always good. It does not cost a great deal to clean your valves and tanks and involves maybe a couple of days' work every year! If nothing else, a clean system will not have the nasty smell of hydrocarbon contamination, and that alone will definitely give you happier customers.

Oxygen cleaning your regulators, for example, also forces you to service and maintain them! It forces a discipline. In 99% of the cases, there will be no detectable oil but there will be lots of scale and other scary things. Oxygen cleaning forces the discipline to maintain your equipment.

The diagram below indicates the components that need to be oxygen clean.



Individual components that include wetted surfaces must be recleaned and reinspected before assembly or packaging. If there is any period of time until these components are to be assembled to your system, **do not** leave them exposed to dirt, dust, or to the oily hands of somebody curious. Place them in a nylon self-sealing bag, and mark the bag with a permanent marker, "PART #, OXYGEN CLEANED." You may have printed labels on colored paper and you can just write the part number of the item(s) in the bag by hand. Valves and fittings need particular attention in their oxygen cleaning. For this purpose, we provide a detailed oxygen cleaning procedure, which is strongly encouraged to follow.

5.3.1 Oxygen Cleaning Procedures for Valves and Fittings

1. Disassemble the parts to their individual components. Make sure that an assembly diagram is readily available in order to avoid problems later on. If a drawing is not available, make a rough sketch yourself.

2. Select only the components that include wetted surfaces. In particular, when cleaning Swagelok parts, or other compression type fittings, please note that **NUTS MUST NOT BE SUBJECTED TO THE CLEANING PROCEDURE.** This will remove their natural lubrication, causing possible jamming due to sticking.

3. Use a tissue or a cloth to wipe off any heavy layers of grease or dirt from the component.

4. Ultrasonic cleaning: Use Biox®, Tev-a-Oil®, or other chemical or biochemical solution in the appropriate concentration. Heat does help and speeds up the cleaning process. If you are planning to buy an ultrasonic cleaner, you are strongly encouraged to buy one that has a heater incorporated below the tank. If you already have an ultrasonic cleaner that does not have heating, a nice trick is to use hot water to dilute your chemical cleaning solution. Fill the cleaning tank to about 3/4 and immerse the items to be cleaned in the solution for about 15 minutes under sonics. Visually inspect the parts at the end of the cleaning cycle. In particular, check areas where there are threads, grooves, and potential traps of dirt. If necessary, repeat the cleaning cycle or use a small brush.

5. Rinse the parts thoroughly with fresh clean water. (If you are using the tap in your sink, you are strongly encouraged to use a plastic basin. Make sure you put a trap in your drain to avoid accidentally losing small components.)

6. Carefully dry the rinsed components by blowing dry, clean (i.e., pre-filtered) air through them.

5.3.2 How Clean Is "Clean"?

There is no one single standard that determines the cleanliness of a surface. Similar to the considerations for air quality, the maximum acceptable contamination of a surface depends on many parameters specific to the system design. It also depends on the contaminant in question. According to ASTM, 200 mg/m^2 would be acceptable. However, we must strongly emphasize that such specifications can be highly misleading. What matters is localized concentrations of contaminants. To put things in perspective, 1 m^2 of internal area is equivalent to the internal area of 70 m of 1/4" 0.035" wall thickness tubing. On average, one would find about 5 - 6 m of tubing in a typical filling station.

Localized contamination is what must be avoided. One must pay attention to valves, fittings, and entry points of tubing and hoses.

5.3.3 Burrs

A much more serious hazard than hydrocarbon contamination is the presence of burrs in the system. These are created by badly cut tubing and tubing which has not been properly cleaned. Oxygen cleaning will not remove those. A proper de-burring tool has to be used. If such burrs are present, the system is NOT fit for oxygen service, even though the materials are oxygen compatible and hydrocarbons and other contaminants have been removed through the oxygen cleaning process.

There are four main reasons why burrs can be dangerous:

1. Burrs can be detached, flow with the gas at high velocity, and at a narrow pass such as a valve orifice, form an immediate obstruction which creates a pressure shock wave resulting in high temperature rise. This may be the initiation of an oxygen fire.

2. If detached, they can block valves so that proper sealing is impossible.

3. Impact with the tube or hose walls may in itself dissipate enough energy locally to initiate an oxygen fire.

4. Even if the burrs are not detached, their anomalous surface creates a change of the flow pattern, which can create pressure shock waves. Heat dissipation at the burr tip is poor because the area available for heat conduction to the bulk of the metal is small. Therefore, local heating can reach high temperatures more easily, and become the initiator of an "oxygen fire."

NOTES

Section 6

6. Logistics Planning

Logistics planning is very important both from an operational point and from a cost perspective. In logistics planning, we are essentially dealing with the requirements in source gases such as O_2 and helium and consumables such as oxygen-compatible lubricants, o-rings, cleaning chemicals, etc.

6.1 Calculating Your Oxygen Requirements

An accurate calculation of oxygen requirements is vital in expeditions, as well as in cases where the oxygen supplier has a lead time of more than a few days.

An approximate way to calculate the oxygen requirements is to assume a given quantity of oxygen added to each nitrox fill. In most cases for fills 32-40% oxygen at 200 bar (3,000 psi) pressure, 40 bar (600 psi) of oxygen is not far off.

The number of nitrox fills from each oxygen cylinder can be calculated as below:

$$N = \frac{(PO_2 - P) \times VO_2}{(d\ PO_2) \times Vs}$$

Where:
N = Number of nitrox fills per O_2 cylinder
PO_2 = O_2 cylinder pressure
dPO_2 = Added pressure of oxygen (40 bar is a good rough estimate)
P = Pressure that is not useable (e.g., 30 bar)
VO_2 = Volume of O_2 cylinder in liters
Vs = Volume of scuba tank in liters
1 bar = 14.51 psi

6.1.1 Variability and Uncertainty

Variability and uncertainty occur in many forms. In our calculations above, we have assumed 40 bar of oxygen in all fills, same volume scuba tanks, and no residual pressure in the scuba tanks. In reality, we are actually trying to predict a future demand for nitrox fills, as well as predict the compositions, scuba tank sizes, even their residual gas pressures. We cannot be certain of a future situation. Uncertainty can be numerically expressed as a percentage confidence. Say we are 90% sure of the prediction. The uncertainty is then ± 10%. So if we calculate that we need six oxygen cylinders, then ± 10% means either five or seven. Because the cost of running short is much higher than the extra oxygen cylinder, we recommend that uncertainty is always factored into your calculations.

We have to deal with variability in the following:

1. **Number of nitrox fills:** This is very much related to the market, and to our planned activities, e.g., courses, expedition, etc.

2. **Composition of the gas:** This depends on the type of diving. For example, for a recreational center, it may be mostly 32% and 36% and nothing above 40%. For a rebreather expedition, the situation may be totally different with most of the fills at 50% or 60% O_2.

3. **Tank sizes:** This is easy to know if using only your own tanks. For example, you may have 20 10L tanks and 25 12L tanks dedicated for nitrox.

4. **Residual gas in scuba tank:** Most divers come up with 30-50 bar pressure in their tanks. Others may use much more air or even less air. Some cylinders may only be used for decompression.

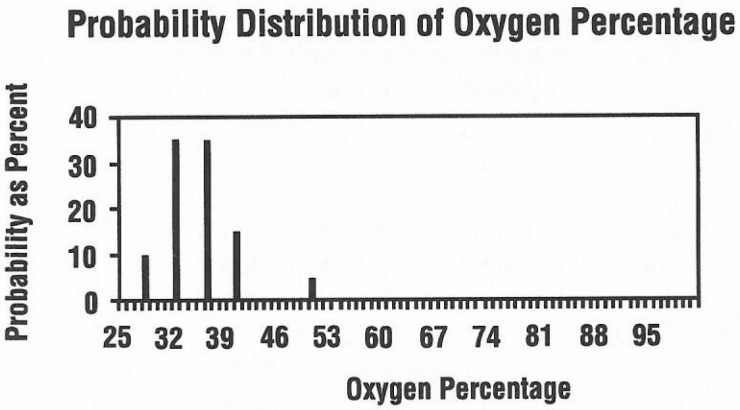
A typical example for such variability, and the probability distributions is shown below:

Situation:

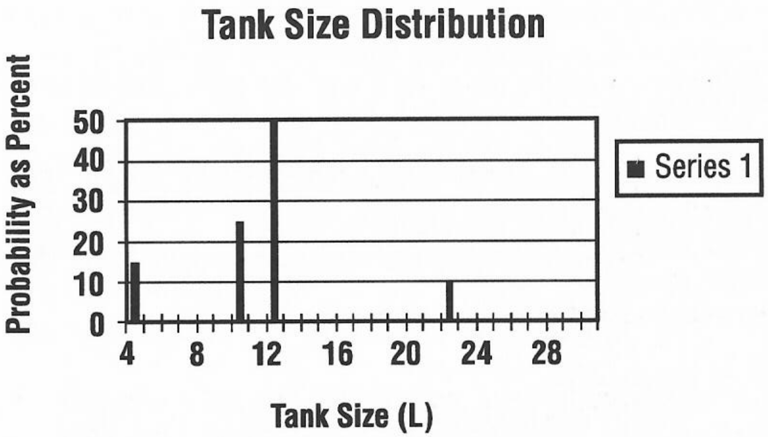
A live-aboard is planning a five-day trip at open sea. Three dives are planned per day, and there are 12 divers on board plus four crew, for a total of 16 divers. Only eight divers are nitrox qualified as well as all of the crew. Two divers are taking a rebreather course.

1. Nitrox fills:
   5 days x 3 dives/day x (8+4) nitrox divers = 180

2. Composition of the mixes:



3. Tank sizes:



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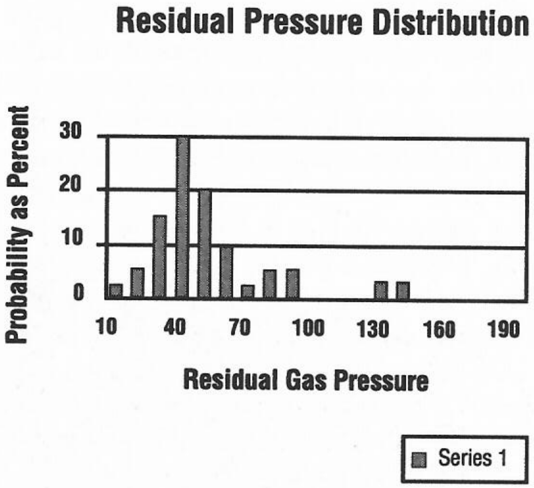
4. Residual gas pressure in scuba tanks:



A more accurate calculation of our oxygen requirements can then be calculated as follows:

$$PO_2 = \frac{FP(TC - 0.21)}{0.79} - \frac{IP\,(1 - IC)}{0.79}$$

$$AVPO_2 = \frac{1}{0.79}\left[\sum_i (FP_i \times Prob_i)\right] \times \left[\sum_j (TC_j \times Prob_j - 0.21)\right] + \frac{1}{0.79} \times \left(\sum_k IP_k \times Prob_k\right) \times \left[1 - \sum_m (IC_m \times Prob_m)\right]$$

Number of nitrox fills per oxygen cylinder, N:

$$N = \frac{(PO_2 - PresO_2)\,VO_2}{AVPO_2 \times \sum_n (vs_n \times Prob_n)}$$

Please note: *The numerical calculations can get a bit too tedious and the above treatment is only provided for better understanding of the issues involved. Such calculations can be done very easily using software tools available from NS Research (see Appendix G).*

The expression above takes into account the distribution probability of the four parameters that can vary in a nitrox fill.

AVP O_2 is the average oxygen pressure added in a scuba tank, based on the above probability distribution.

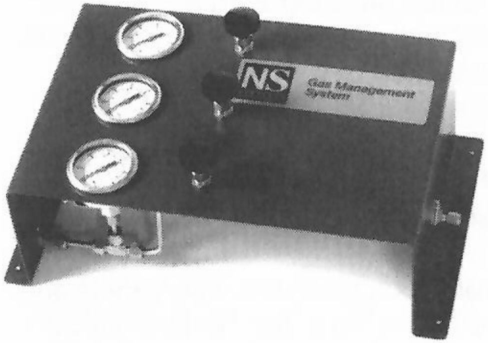
The above expressions clearly define all parameters apart from the residual pressure in the oxygen cylinder (PO_2). Obviously, this is largely dependent on chance. To explain this, we can show that in the above example, if we fill all the empty tanks, and the tanks with a low percentage of oxygen at the beginning, when the oxygen cylinder is full, then when we come do the nitrox fills rich in oxygen, such as the rebreather tanks or decompression tanks, we will not be able to complete the job. This is because the pressure in the oxygen cylinder is reduced, but at the same time we require a high pressure of oxygen.

6.1.2 Best Utilization of Oxygen

There are three main solutions to the above problem:

1. Use a booster pump to boost the pressure of oxygen from say, 30 bar to 100 bar. A booster pump is safe and reliable as long as it is used and maintained properly. However, it is an additional expense and can significantly raise the cost of your blending station. For an average dive center doing 50 nitrox fills per week, the pay back will take more than five years!

2. The alternative is to be more clever in the way you use your oxygen. More than one oxygen cylinder is used. Four or a multiple of four cylinders has been found to work well. The exact number is determined by the economics and your demand for nitrox. If all four oxygen cylinders are open, each having a pressure gauge, together with a switch-over manifold for the four cylinders, you can select from which oxygen cylinder to take oxygen. This depends on its pressure and your mix requirements. This is a simple and effective way that can significantly increase your utilization of oxygen and ensure that you are able to fill the high mixes whenever you need.



Better Utilization of O_2

3. Adjust the order of filling. Fill those scuba tanks that require a high PO_2 first (i.e., when the pressure in the oxygen cylinder is highest). In this way, savings in oxygen are accomplished by both utilizing residual gas and by not wasting oxygen in the oxygen cylinder that is returned to the supplier. Software tools (such as those provided by NS Research) can make this process very simple.

6.2 Time Planning

It is not the purpose of this book to teach you about time management. The aim of this Section is to help you calculate the time requirements for mixing gas. This is very important since time and capacity are very closely related. There are many cases where we have a large number of scuba tanks to be filled in a short period of time. This time factor has led many operators to the wrong decisions resulting in excess capacity and, hence, wasted money.

Calculating Time Requirements:

The time it takes to fill a nitrox tank can be estimated by examining the system set-up. It can also be known by experience. It would normally be anything from 4 - 15 minutes, depending on pressures, scuba tank size, etc. The following points should be remembered:

- ✔ The lower the oxygen cylinder pressure, the longer it takes for a given valve opening.
- ✔ The larger the scuba tank size, the longer it takes to fill it.
- ✔ If filling from an air bank, there is a time benefit only if the bank is at a higher pressure by at least 20 bar than the pressure in the scuba tank. When the scuba tank and the air bank are at approximately the same pressure, it will take much longer for the filling because the volume that the compressor has to fill up to the required pressure is much larger.
- ✔ The total time to fill N scuba tanks is not the same as N times the duration of one fill.

Time for N fills = N x (duration of 1 fill) + N x (analysis time) + N x (logging time) + (N-1) x (changeover time) + waiting time

Waiting time can be a large time constraint. It depends on many factors, some of which are:

- ✔ Oxygen cylinders may need to be replaced.

- ✔ Adjustments may be needed until you get the correct and stable composition for membrane or continuous blending systems.
- ✔ For manual partial pressure systems, the scuba tanks may need to empty their residual gas first.
- ✔ Adjustments may be needed if the produced mix is out in its composition significantly.
- ✔ If air and nitrox banks are needed in membrane or continuous blending systems, those banks need to be refilled to a useful pressure after a certain number of fills (X). This can be calculated according to the size of the bank. For example, for a 200L bank and useful pressure at 150 bar, after seven fills, the bank has to be replenished. Thus, the waiting time is equal to set-up time plus time to fill the bank. If the number of nitrox fills needed (N) is greater than X, then the waiting time has to be added in.

It is important that work is scheduled so that peaks in demand can be smoothed.

For example, peak time may be 8:30AM when everybody is preparing for the morning dive. A practical and easy way to smooth out the peak is to fill the tanks of the staff and students, for which we already know precisely what is required, during the previous evening.

Keeping a few extra scuba tanks prepared for nitrox may be the most effective way to deal with increased demand, rather than using nitrox banks, higher capacity systems, etc. Good time planning can save a lot of money.

6.3 Consumables

In general, consumables include o-rings, oxygen compatible lubricants, oxygen cleaning liquids, stickers, filter replacement elements, etc.

The items that a dive facility would hold in their workshop for their gas blending needs can be distinguished by the following categories:

- ✔ Low cost, short lead time
- ✔ Low cost, long lead time
- ✔ Medium/High cost, short lead time
- ✔ Medium/High cost, long lead time

By lead time, we mean the time between placing an order with your supplier, and receiving the goods in your shop.

Consumables usually fall in the first category, apart from the filter elements. It can be irritating to be unable to fill your nitrox tanks because you cannot replace an oxygen compatible o-ring.

Section 7

7. The Physics of Partial Pressure Mixing

Understanding the physics behind partial pressure mixing is important not as academic knowledge, but because it enables the gas blending technician to make conscious decisions. Doing the job, not simply by following guidelines and procedures, but by understanding the "whys" behind these guidelines and procedures, ensures safety and efficiency.

We aim to give you just enough information for a rounded understanding of the physical process of mixing. It is not the aim of this book to provide detailed scientific information and engineering knowledge.

7.1 Pressure, Volume, and Mass

These properties are the most fundamental, however, since there is a lot of misuse among the diving community, it is useful to define them clearly.

Mass is a physical dimension that determines the quantity of matter. Mass is measured in kg .

Volume is the dimension that determines the physical space taken by a body, a liquid, a gas, etc. Often we refer to the volume of a gas with reference to atmospheric pressure and temperature. This is not a mistake as long as we specify and understand what we mean. So, an 80 ft³ scuba tank, is not really that big!! 80 ft³ is the volume of the gas in the tank at the rated pressure, if it were allowed to expand at a pressure of 1 atmosphere. The importance of this point will be understood later as we discuss how heat is produced and lost to the environment during the filling of a scuba tank and why the physical size of the tank is important.

Temperature is the physical dimension that defines the "degree of hotness or coldness" of a body. There are many different ways of measuring temperature, and a number of scales. Most common in every day life are the Celsius scale, and the Fahrenheit scale in the United States. For scientific purposes, the Kelvin scale is most useful to us.

Pressure is defined as force per unit area. The basic unit of pressure is N/m^2. This is often referred to as Pascal. However, this is a relatively small pressure. When we are referring to compressed gases, the most common units of pressure are bar, and psi (pounds per square inch). To get a feeling of the magnitudes,

$$1 \text{ bar} = 10^5 \text{ N/m}^2$$
$$1 \text{ atm} = 1.01325 \text{ bar}$$ ✓
$$1 \text{ bar} = 14.5083 \text{ psi}$$ ✓

A full Pressure conversion table between metric and imperial units can be found in Appendix E.

7.2 Understanding the Law of Partial Pressures

As the name might imply, Dalton's law of partial pressures is the fundamental principle behind this mixing technique.

The law states that:

"The pressure of the mixture of gases in a container is equal to the sum of the pressures that each gas would exert if it were alone in the container."

As divers, we really are interested in creating a gas which is a mixture with precise proportions of each of the gases of our interest (in most cases oxygen, nitrogen, and helium). We are interested in the volumetric or molar composition of the gases. But how can we measure this as we are doing the mixing? We cannot stop every few seconds and analyze the gas. Pressure is convenient and easy to measure. Pressure gauges can be accurate and inexpensive. They are also small and easy to handle.

But how are pressure and composition related? The composition of the gas is, by definition, the ratio of the quantity or mass of the gas to the total mass of the mixture. So, the composition of nitrox with regard to oxygen is the mass of oxygen divided by the total mass. Putting it differently, the mass of oxygen is equal to the oxygen percentage times the total mass. According to the universal gas law, mass and pressure are proportional. So, the partial pressure of oxygen is equal to the percentage of oxygen times the total pressure.

$$\%O_2 = \frac{MO_2}{M}$$

From the Universal Gas Law $PV = mRT$

$$\therefore\ M = \frac{PV}{RT}$$

$$\text{Hence } \%O_2 = \left(\frac{PO_2V}{RTO_2}\right) \Big/ \left(\frac{PV}{PT}_{FINAL}\right)$$

Ignoring temperature effects:

$$\%O_2 = \frac{PO_2}{P}$$

Expressed differently as:

$$PPO_2 = (\%O_2) \times P$$

NOTE:
We have assumed that the temperature remains constant — we will see later that this is not a correct assumption.

This is where Dalton's law of partial pressures is so useful: We are mixing oxygen and air. We do not know the masses of the gas. What we do know is current pressure, which we can measure on our pressure gauge. What we need to know is what pressure to reach before we stop adding oxygen and start adding air.

7.3 The Universal Gas Law

In a gas, pressure (P), volume (V), mass (m), and temperature (T) are closely related by the universal gas law.

This is expressed as:

$$PV = mRT$$

Where: R = universal gas constant

The above expression is also known as the equation of state.

We can now see that in a scuba tank, where the volume is fixed by the metal container, what we are doing during filling is adding mass. Therefore, the pressure increases.

Temperature also is important. We can see from the universal gas law, that for a given mass of gas, as the temperature increases, so does the pressure at a constant volume.

But, what we really control during filling (for nothing else but ease of measurement) is pressure. We can easily measure pressure using an analogue of digital pressure gauge and we can automatically stop the compressor using pressure switches.

So, if we reverse this argument, we can say that at a given pressure, PO_2, the mass of the gas in a container is less at a high temperature than at a low temperature. The implication, which is something that every diver has probably experienced, can be shown in the following diagram:

Fill air to 200 bar:
Po = 200 bar
T = 40 C
V = 12L

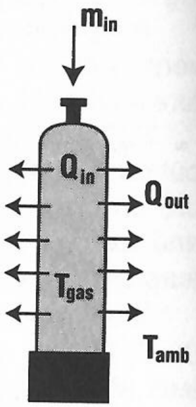
Immediately after filling

P = 192 bar
T = 28 C, ambient
V = 12L

A few hours later

7.4 The Thermodynamic Situation in the Scuba Tank

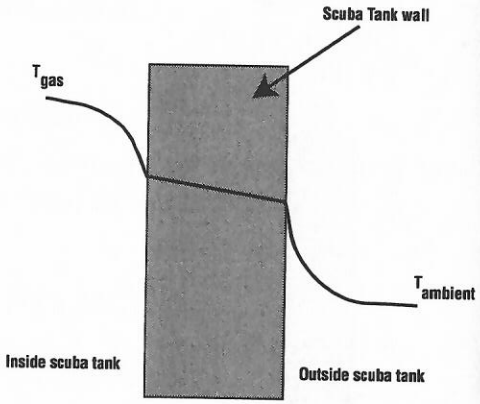
During filling, heat is produced due to compression. At the same time, heat is lost to the surroundings by conduction and convection. Some heat energy is also used to warm up the metal of the scuba tank. As a result, the temperature of the gas inside is not constant but changes continuously with time. Initially, there is a quick rise in temperature. Then it stabilizes. During the end of the filling, the temperature starts falling back to ambient. After a few hours, the gas will be at ambient temperature.



If we want to investigate this further and look at the temperature distribution across the cylinder walls, what we will observe as a snapshot is shown in the diagram to the right.

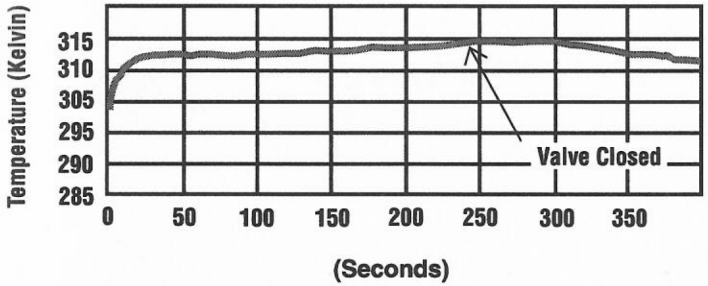
The temperature we often feel on the outside of the scuba tank during or after filling at high pressure, is nowhere near the true temperature of the gas inside. Of course, it must be emphasized that the above is not constant, but continuously changes over time.

Temperature Distribution Between Scuba Tank and the Environment

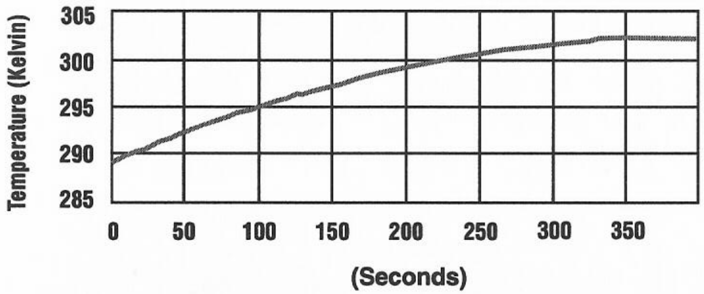


TEMPERATURE VARIATIONS OVER TIME

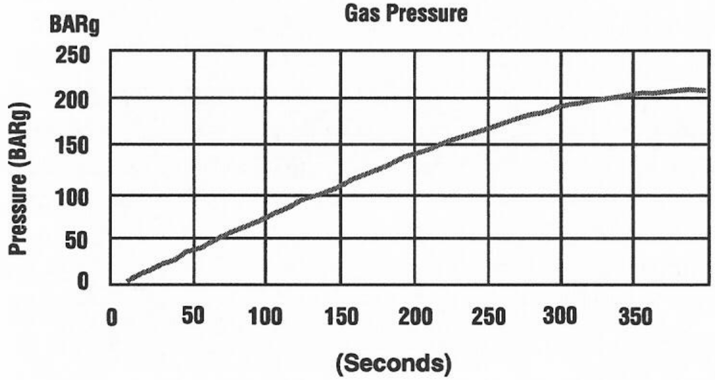
Gas Temperature



Cylinder Outside Surface Temperature



Gas Pressure



The graphs on the previous page show how the temperatures and pressures change over time in a typical fill of a 12L steel tank and a flow coefficient (Cv) of 0.0075.

7.5 Compressibility of Gases

The equation of state of a perfect or ideal gas is:

$$PV = mRT$$

Where:
P = absolute pressure
V = volume
T = absolute temperature
R = an experimental constant called the universal gas constant

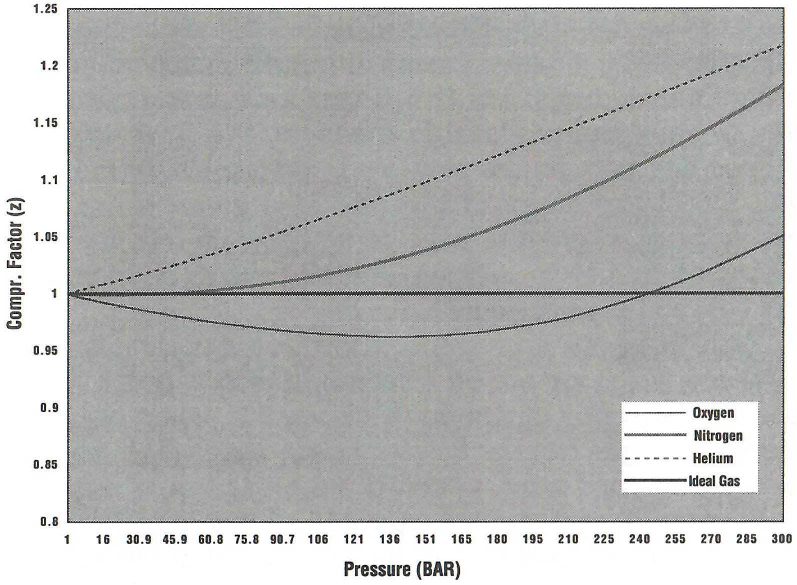
Real gases do not always obey the above equation of state, and a correction factor z is introduced. The equation of state of a real gas is thus written:

$$PV = z\,mRT$$

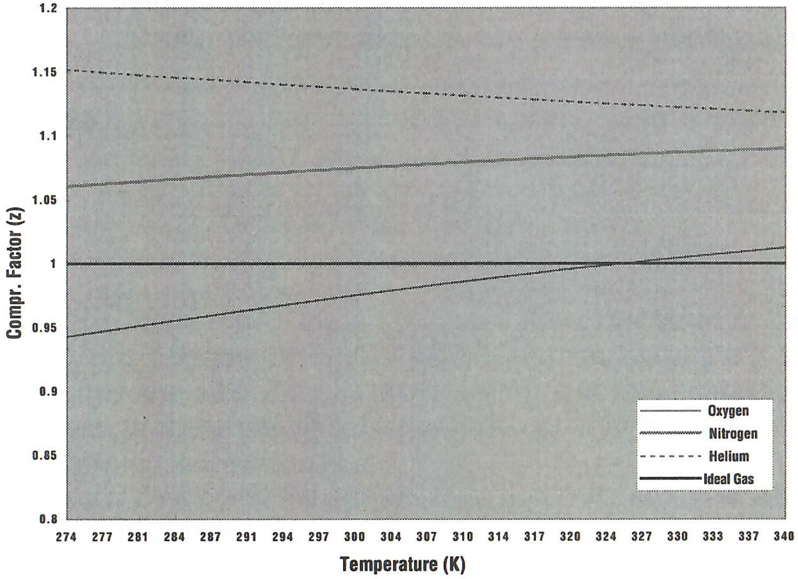
Here, z is called the compressibility factor. It is a complex function of pressure and temperature, and is usually determined empirically. For any one gas, the function of z with pressure and temperature is different. Therefore, in gas blending, z is a function of not only temperature and pressure, but also gas composition, which changes continuously as more oxygen, air, or helium is added in the scuba tank. A graph of compressibility function z for oxygen, nitrogen, and helium is shown on the next page.

Compressibility factor z can vary from 0.962 to 1.10 for nitrox up to 3,000 psi, and 1.16 for trimix, representing an error in calculated pressures of up to 10% for nitrox and up to 16% for trimix.

Compressibility Factors at 300K Temperature



Compressibility Factors at 200 BAR Pressure



7.6 How Does All This Affect the Accuracy of the Mix?

What we are really interested in, in order to get an accurate mix, is the quantity (mass) of oxygen, nitrogen, and/or helium transferred to the tank. Pressure is only a property that is easy and practical to measure. We have already proved that both temperature and compressibility factor z will affect the mass of the gas at a given pressure. Alternatively, in order to achieve an accurate mix, the end pressures for helium, oxygen, and air have to be modified. But how and to what extent?

How to modify these pressure involves very complex calculations which cannot be solved analytically, and it is far beyond the scope of this book. In practice, when blending manually, a gas blender builds enough experience, essentially by trial and error, to adjust the pressures in order to achieve an acceptable accuracy. All of this experience is unique to a particular set-up, a particular set of valves and gauges, and the knowledge resides only within that person.

To what extent? This can easily be shown in the following table. We have calculated the modified pressures to take into account temperature and compressibility effects.

% O_2

GAS MIXING TABLE GIVING AIR PRESSURE FOR 4 LITER CYLINDER

psi

	600	800	1000	1200	1400	1600
AIR	x	x	1032	1244	1456	1669
22	x	x	1033	1244	1456	1670
23	x	x	1033	1244	1457	1670
24	x	x	1033	1245	1457	1671
25	x	x	1033	1245	1457	1671
26	x	x	1033	1245	1458	1672
27	x	x	1034	1246	1458	1672
28	x	x	1034	1246	1459	1673
29	x	x	1034	1246	1459	1674
30	x	x	1035	1247	1460	1674

The table shows the air pressure (final pressure) in the tank. It is between 36 and 77 psi higher than the target (i.e., the pressure after the gas cools down). It is also interesting to note that the adjustment depends not only on pressure, but also on gas composition.

As a final point, the table is for a particular set-up at 27C and for a 4L tank.

$\%O_2$

GAS MIXING TABLE GIVING AIR PRESSURE FOR 10 LITER CYLINDER

→ PSI

	600	800	1000	1200	1400	1600
AIR	607	814	1021	1229	1438	1648
22	607	814	1021	1229	1438	1648
23	607	814	1022	1230	1439	1649
24	607	814	1022	1230	1439	1649
25	607	815	1022	1231	1440	1650
26	607	815	1023	1231	1440	1651
27	608	815	1023	1231	1441	1652
28	608	815	1023	1232	1441	1652
29	608	816	1024	1232	1442	1653
30	608	816	1024	1233	1443	1654

The next table shows the pressures for a 10L tank so that a comparison can be made.

So, even a different tank size can make a significant difference in the pressure adjustment needed.

Errors of this nature can result in a final composition being out by 5% or more.

A full error analysis is shown in the relevant chapter.

7.7 A Theoretical Explanation of the Effect of Temperature on the Accuracy of the Mix

In the previous Sections we explained how the temperature of the gas increases during filling. We also illustrated the practical effect of a temperature increase on the partial pressures of the individual gas with emphasis on nitrox. Here we will give the basic theoretical understanding of the temperature effect on the mix accuracy.

We will take a simple case when we are starting from an "empty" scuba tank.

According to the calculated values, we have PO_2 and P_{final} which are the pressures where we actually close the oxygen and air valve respectively.

As we have proved in Section 7.2:

$$\%O_2 = mo_2 / m \text{ total}$$

Where: m = mass of gas

But from the universal gas law:

$$PV = zmRT$$

Hence,

$$\%O_2 = \left(\frac{PO_2 V}{z_1 RTO_2}\right) / \left(\frac{P_{FINAL} V}{z_2 RT_{FINAL}}\right)$$

This can be re-written as:

$$\%O_2 = \left(\frac{PO_2}{P_{FINAL}}\right) x \left[\left(\frac{T_{FINAL}}{TO_2}\right) x \left(\frac{z_2}{z_1}\right)\right]$$

In most partial pressure mixing calculations, it is assumed that $TO_2 = T_{final} = T_{ambient}$.

As it has been explained in the previous sections, the temperature is often significantly higher than ambient. Consequently, the factor $[(z_1 \times TO_2) / (z_2 \times T_{final})]$ is not a unit, but its actual value determines the accuracy of the mix to a large degree.

Section 8

8. Mixing Procedures and Calculations

8.1 Mixing Procedure

The mixing procedure described here refers to partial pressure mixing and mixing using the automatic mixing system ANX Supreme. Both methods are based on the law of partial pressures.

Mixing using the ANX Supreme:

1. Connect the scuba tank and open the scuba tank valve.

2. Open the venting valve on the ANX and, through the side vent port, analyze the residual gas in the tank.

3. Enter the mix specifications through the keypad: Initial Composition, Target Composition, Target Pressure. Press START for filling to commence.

4. When filling is complete an audio and visual message on the LCD will indicate completion, and prompt you to analyze the gas.

5. Open the vent valve and calibrate the analyzer in air through the side port. Then analyze the mix to confirm its O_2 percentage.

6. Release the pressure in the fill whip and disconnect your scuba tank.

7. Log the fill in your log book.

Mixing using a manual partial pressure mixing panel:

1. Analyze the residual gas in your scuba tank.

2. Do the mixing calculations to find the pressures to close the oxygen valve and open the air valve and write down the numbers.

3. Connect the scuba tank and open the tank valve.

4. Open the oxygen valve and watch the pressure on the mixing gauge until it reaches the calculated pressure.

5. Close the oxygen valve.

6. Allow the gas to cool down for a few minutes.

7. Open the air valve and watch the pressure of air until it reaches the desired final pressure, plus a small adjustment for temperature compensation.

8. Close the air valve.

9. Release the pressure in the fill whip and disconnect the scuba tank.

10. Analyze the gas.

11. Log the fill in your log book.

8.2 Mixing Calculations

Mixing calculations essentially refer to partial pressure mixing systems. All other methods either rely on on-line gas analysis (continuous blending, membrane) or do the mixing automatically (ANX Supreme).

There are two ways one can calculate the pressures required:

- ✓ Use a simple formula
- ✓ Use tables

8.3 Some Definitions

Typically, mixing takes place between oxygen and air. However, there is no reason why we should restrict ourselves to this. Mixing can take place between any two nitrox mixes to produce a third nitrox mix. What one is really concerned with, is the pressures to open and close the control valves.

Below, we define the basic symbols and concepts to be used:

Residual Gas is the gas in the scuba tank that is half full prior to filling

Initial Pressure (IP) is the pressure of the residual gas in the scuba tank

Initial Composition (IC) is the oxygen composition (fraction of oxygen) in the residual gas

Target Composition (TC) is the required fraction of oxygen in the final mix

Target Pressure (TP) is the pressure required of the final mix eg 200 bar.
Source Composition Oxygen (SCO) is the O_2 percentage in the high oxygen source mix. Typically, 100% O_2.
Source Composition Air (SCA) is the O_2 percentage in the source mix low in oxygen. Typically this is air 21%.

8.4 Calculations Using a Simple Formula

Once the scuba tank is connected to the mixing panel and the residual gas has been analyzed, then the oxygen valve will be opened to fill oxygen (if required) until a calculated pressure (PO_2) is reached. Then the valve is closed and the air valve is opened to fill with "air" up to the target pressure. It is PO_2 that we are interested in and this is what the formula below gives.

$$PO_2 = IP + \frac{TP \times (TC - SCA) - IP \times (IC - SCA)}{(SCO - SCA)}$$

WARNING:
IT MUST BE EMPHASIZED THAT THE FORMULA ABOVE DOES NOT TAKE INTO ACCOUNT TEMPERATURE EFFECTS OR COMPRESSIBILITY FACTORS.

If the above formula yields a number that is smaller than IP, then obviously one needs to vent some residual gas, increase the target composition, or increase the target pressure. These conditions are examined later.

8.4.1 Simplifications for Mixing Air and Pure Oxygen

Mixing air and pure oxygen is by far the most common and simplest arrangement. It is also the most economical one. Therefore, all our examples will be based on this case.

The formula for PO_2 can further be simplified to:

$$\boxed{PO_2 = IP + (1 / 0.79) \times [TP \times (TC - 0.21) - IP \times (IC - 0.21)]}$$

Examples:

1. **Residual gas at 40 bar, 30% oxygen. Require 200 bar at 36% oxygen.**

$$PO_2 = 40 + (1 / 0.79) \times [200 \times (0.36 - 0.21) - 40 \times (0.3 - 0.21)]$$
$$PO_2 = 40 + 33.4 = 73.4 \text{ bar}$$

So, we must add oxygen until the pressure in the tank reaches 73.4 bar. Then we close the oxygen valve and open the air valve until we reach 200 bar.

2. **Scuba tank empty. Need 232 bar of 40% oxygen.**

When a scuba tank is empty, the exact value of the initial composition does not really matter, since the effect is only a fraction of a bar in pressure which is "lost." So to simplify the situation, we assume that IC=0.21,

So,

$$PO_2 = (1 / 0.79) \times 232 \times (0.40 - 0.21)$$
$$= 55.8 \text{ bar}$$

3. **Scuba tank with 80% O_2 at 85 bar. Need 232 bar of 40% O_2.**

Using the same simplified formula for mixing air and oxygen, we have:

$$PO_2 = 85 + (1 / 0.79) \times [232 \times (0.4 - 0.21) - 85 \times (0.8 - 0.21)] = 77.3 \text{ bar}$$

Obviously, this is lower than the starting pressure of 85 bar, which clearly indicates that we need to vent some gas or change the mix specifications. Changing the mix specifications may be simpler, provided that we have the freedom to do so.

How much do we need to vent?

From the simplified formula we can see that the need to vent comes about because $IP > PO_2$. Therefore we need to vent until they become at least equal or $IP \leq PO_2$.

The above condition is satisfied when:

$$IP = TP \times (TC - 0.21) / (IC - 0.21)$$

Therefore we need to vent until the residual gas pressure reaches this value.

In Example 3 this would be a pressure of 74.7 bar.

8.5 Calculations Using Mixing Tables

Using tables could be simpler in the field when there might not even be a calculator available. Tables only involve simple additions and subtractions of pressures. What is more, tables could be already adjusted to take into account compensations for temperature and compressibility effects.

8.5.1 How to Use a Mixing Table

The mixing procedure is the same whether using a table or a formula to calculate pressures. A simple way to use a mixing table is described below:

1. Move down the table until you get to the row with the same O_2 percentage as the residual gas in your tank (IC). Move across the row until you reach the column with the same pressure as the initial pressure (IP). Mark the number indicated.

2. IF YOU ARE STARTING WITH AN EMPTY TANK SIMPLY IGNORE STEP 1 AND TAKE THE INITIAL NUMBER AS ZERO.

3. Check the table again for the Target Pressure (TP) and Target Composition (TC) as described in Step 1. Mark this number again.

4. Subtract the number found in Step 1 from the number found in Step 4. The answer is the pressure of oxygen that needs to be added to the residual gas in the scuba tank. So, the pressure to close the oxygen valve and open the air valve is equal to the number found in Step 5 plus the initial pressure.

5. If the answer found above is negative, then you need to vent or change the mix specifications if you can do so.

Example:

We have a 400 psi 32% mix, and we want to fill up to a 3000 psi 36% mix. What is the pressure to close the oxygen valve and start adding air (PO_2)?

We will use the table on page 102.

We want 36% 3000 psi → 558
We have 32% 400 psi → - 60
498

Starting pressure → 400
PO_2 = 898 psi

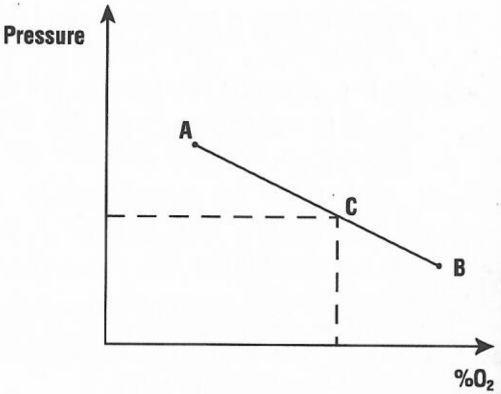
8.5.2 Linear Interpolation

Unfortunately, due to space restrictions in presenting a table on a single letter size paper, most mixing tables are not fully complete. Usually O_2 percentage may be complete only up to 50% and thereafter move at increments of 5% or even 10%. Similarly, pressures usually move at increments of 100 or even 200 psi. So, how can we deal with a pressure of say, 565 psi?

Linear interpolation is an extremely useful mathematical method of approximation assuming a straight line between two points, which is illustrated in the diagram below.

Knowing the values of points A and B, we want to find point C in between.

A typical example for mixing tables is the case when we have an initial pressure of say, 325 psi but the tables jump from 200 psi to 400 psi.



To find point C is easy:

This can be done in more than one stage and each stage uses the results from the previous one.

Value at C = value at A +
(value at B - value at A) x (AC) / (AB)

Example:

We have residual gas of 53% at 330 psi and we want 3000 psi of 42% O_2.

Our table, as shown on the next page, jumps from 40% to 50%, and then to 60%. It also moves on the pressure axis in increments of 200 psi.

Starting with the residual gas, the closest on the table to 53% is 50%, and the next value is 60%. Essentially 50% and 60% are points A and B respectively. 53% is point C that we are interested in. We will do this in two steps.

(Check the values from the table on the next page)

50% at 330 psi gives:

78 + [(156-78) x (330 - 200) / (400 - 200)] = 128.7 = 129 psi

Similarly, 60% at 330 psi gives:

105 + [(209 - 105) x (330 - 200) / (400 - 200)] = 172.6 = 173 psi

But we are interested for 53%, and the correct value is:

129 + [(173 - 129) x (53 - 50) / (60 - 50)] = 142.2 = 142 psi

GAS MIXING TABLE
(COMPENSATED FOR 10 LITER TANK, Cv = 0.007)

	200	400	600	800	1000	2400	2600	2800	3000	3200
AIR	0	0	0	0	0	0	0	0	0	0
22	3	6	9	11	14	31	34	36	38	40
23	6	11	17	22	27	62	67	71	75	79
24	9	17	25	33	41	93	100	106	112	119
25	11	22	33	43	54	124	133	141	150	158
26	14	27	41	54	67	154	165	176	187	197
27	17	33	49	66	81	185	198	211	224	236
28	19	38	57	76	94	215	231	246	260	275
29	22	44	66	86	107	246	264	281	297	314
30	25	49	73	97	121	276	296	316	334	353
31	27	54	81	108	134	307	329	351	372	392
32	30	60	89	118	147	337	362	386	409	432
33	33	65	97	129	161	368	395	421	446	471
34	36	70	105	140	174	399	428	456	483	511
35	38	76	113	150	187	429	461	491	521	550
36	41	81	121	161	200	460	494	527	558	590
37	44	87	129	172	214	491	527	562	596	630
38	46	92	137	182	227	522	560	597	633	670
39	49	97	145	193	240	553	593	633	671	710
40	52	103	153	204	253	584	627	669	709	750
50	78	156	233	310	386	896	963	1028	1091	1156
60	105	209	313	416	520	1213	1304	1392	1478	1568
70	132	263	393	524	654	1533	1647	1756	1854	1891
80	159	316	473	631	790	1845	0	0	0	0
90	185	369	554	740	926	0	0	0	0	0
100	212	423	635	848	1063	0	0	0	0	0

Section 9

9. Gas Analysis

Gas analysis is an essential part of product quality control for the gas. It is also very important from a liability point of view. In most cases, when we refer to analyzing the mix, we normally mean oxygen analysis, even when we are dealing with trimix, and strictly speaking, the nitrogen/helium ratio should also be measured. This is due primarily to the practicalities and cost of gas analysis equipment, as well as the fact that it is an error in the oxygen percentage that can prove critical due to oxygen toxicity. Oxygen toxicity is directly related to the partial pressure of oxygen, and therefore percentage of O_2 in the mix.

$PO_2 = P \times fO_2$ (where fO_2 is the O_2 percentage in the mix)

9.1 Oxygen Analysis Methods

There are a number of methods and equipment available to analyze oxygen. These include:

- ✔ Galvanic cell
- ✔ Paramagnetic sensor
- ✔ Infra red / mass spectroscopy

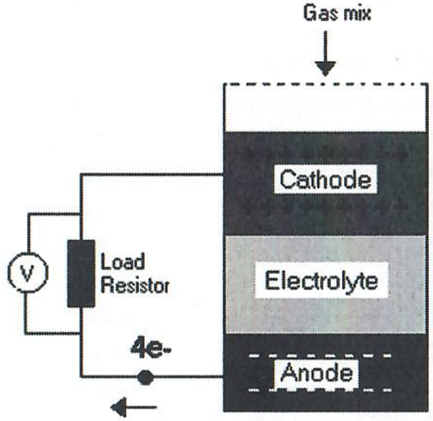
By far the most common method for oxygen analysis is through the use of a galvanic cell.

Paramagnetic and mass or infra-red spectrometers are very accurate but are used only in a laboratory environment due to the size and sensitivity of the equipment. Also, they are prohibitively expensive for most dive facilities. Details for these methods can be found in Appendix D.

9.2 Operation of Galvanic Cell Oxygen Analyzer

9.2.1 The Principle of Operation

In its simplest form, an electrochemical sensor has two electrodes — a sensing and a counter — separated by a thin layer of electrolyte. Gas diffuses into the sensor to be reduced at the sensing electrode. So, at the cathode, oxygen is reduced to hydroxyl ions according to the equation:



$$O_2 + H_2O + 4e^- \rightarrow 4OH^-$$

At the anode, the hydroxyl ions in turn oxidize the metal anode as follows:

$$2Pb + 4OH^- \rightarrow 2PbO + 2H_2O + 4e^-$$

Overall, the cell reaction may be represented as:

$$2Pb + O_2 = 2PbO$$

The resulting exchange of electrons causes the potential of the sensing electrode to change with respect to the counter. The output is measured by connecting a resistor across the output terminals to produce a voltage signal, proportional to the partial pressure of oxygen.

The sensor current or signal is determined by the rate of diffusion of oxygen being measured across the diffusion barrier. Usually a plastic film (membrane) is used as the diffusion barrier and diffusion is controlled by the number of gas molecules colliding with the solid pore walls of the membrane. If the pressure of the gas is increased, the rate of diffusion of the molecules increases until equilibrium is reached between the outside and inside pressure across the diffusion barrier. This results in an output that is directly proportional to the partial pressure of oxygen and will (in principle) result in a linear response over all concentrations.

9.2.2 Output Reading vs. Pressure

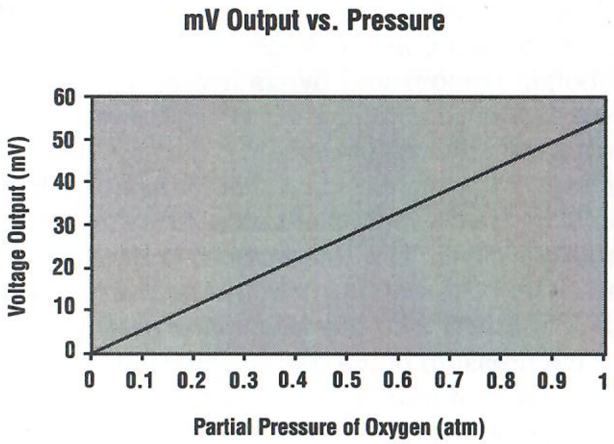
The sensor gives a linear output which is directly proportional to the oxygen partial pressure, as shown in the graph below.

The reading will follow the partial pressure of the oxygen in the mix. If the pressure of the gas analyzed doubles, so does the instrument's reading, thus giving a wrong indication of the oxygen percentage in the mix. Ideally, the pressure at the sensor should be 1 atm. Therefore, any back pressure at the sensor must be avoided.

Let's examine how a pressure may develop:

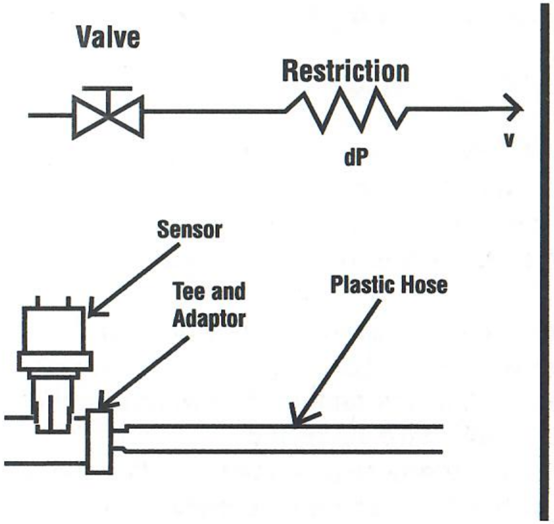
When we are analyzing the mix, our sample is at a high pressure in the scuba tank (or elsewhere) and is being vented to the atmosphere via a valve.

Inevitably, there is a restriction after the sensor. This may be in the form of a tee, a plastic hose, a reduction in



cross section, etc. The pressure that is developed across these restrictions depends to a large extent on the velocity of the gas. Therefore, the flow rate must be kept at low levels. In general, 2 - 4 L/min is a good guide.

A mathematical treatment that shows the error developed through increased flow is illustrated below.



The pressure differential developed across the restriction is given by:

$$dP = \frac{Q \times 8 \times \mu \times L}{\pi \times a^4}$$

Where: dP = Pressure developed across sensor
Q = Volumetric flow rate in m³/min
L = Length of hose
a = Internal radius of hose
μ = Coefficient of viscosity

For a typical case,

$$dP = Q \times (8 \times 0.0185 \times 10^{-3} \times 0.2) / (3.14 \times 0.0024) =$$
$$= 589172 \times Q$$

So, for Q = 4 L/min, then dP = 0.024 bar

Thus, for a flow rate of 4 L/min, the pressure developed across the sensor is approximately equal to 1.024 bar.

If the true volumetric composition of the mix is 34%, then the instrument would show 34 x 1.024 = 34.8%. It is, therefore, important that the flow does not exceed 4 L/min.

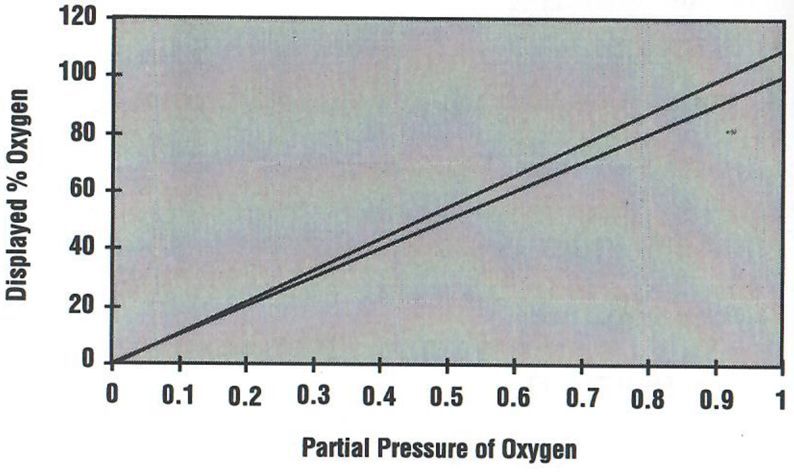
9.2.3 Correct Calibration Matters

As we have seen in the previous Section, the sensor's output is a linear function of the partial pressure of oxygen. One point is a true point, and that is the zero. This means that when there is zero partial pressure of oxygen, the output is also zero.

When we are calibrating the oxygen analyzer, we are essentially defining the slope of the straight line by fixing a second point on the line, the point 0.21, 21.

It is interesting to note the effects of an error in the calibration. From the graph above, we can see that the error

Effect of Incorrect Calibration

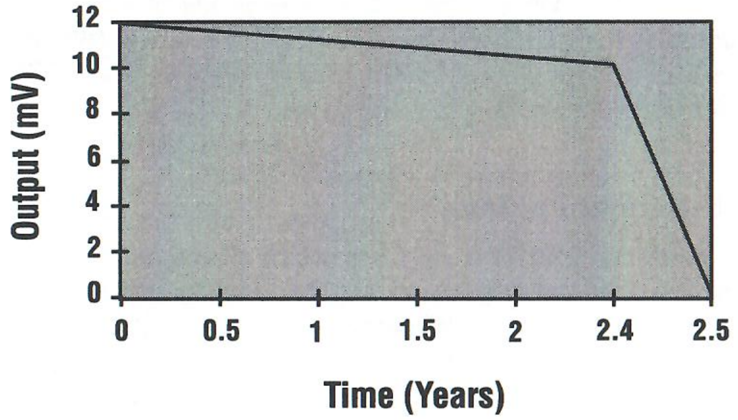


gap widens as the oxygen content increases. It is now obvious that a small error of 0.5 in calibration (that is, at 0.21 partial pressure of oxygen), can result in a much larger error at higher partial pressures of oxygen. So, at 40% oxygen or partial pressure of 0.4, the reading would be 41%, thus giving an error of 1%.

9.2.4 Operating Life

The stability of output over a sensor's operational life differs from manufacturer to manufacturer, but most sensors are highly stable over this period of time. Sensors are manufactured to operate from 1 - 4 years in air at around 20C. This depends on the different manufacturer. A good sensor should only begin to show significant output loss at the very end of its life. Typical sensor drift rates are normally less than 5% per year. Towards the end of the sensor's life, the signal will fall to almost zero in just a few days.

Typical Output Characteristic Over Time



Sensor life is governed by the mass of lead available to react with the oxygen and its rate of consumption. High oxygen partial pressures and high temperatures will increase the sensor output, thus shortening the operating life. At the end of the operating life, the sensor signal will quickly collapse to around 0mV in air.

9.2.5 Temperature Effects

Almost all sensor manufacturers incorporate a built-in temperature compensation circuit consisting of a thermistor network mounted close to the sensor's electrodes. This results in a sensor output that is relatively unaffected by the temperature fluctuations. However, it is not perfect!

Calibration of the analyzer is done at ambient temperature, which is around 30C in the summer. We are interested in the sensor's output at temperatures close to 0C because this is the temperature of the gas as it exits the scuba tank. (The gas temperature drops as the gas expands through the valve restriction).

The sensor output at zero is, in most cases, lower than the output at 20C or 30C, because the speed of the reaction is slower. Typically sensor output at 0C is 98% of the signal at 20C. For example, if the oxygen partial pressure is 0.4 and the analyzer is reading 40% oxygen at 20C, at zero it would be reading 39.2% oxygen.

9.2.6 Response Time

Response time is a very important characteristic of the sensor. It is primarily governed by the density and thickness of the membrane of the diffusion barrier.

Different manufacturers may give different definitions of the response time of their sensors. Unfortunately, this can be very misleading. A sensor that has a response time of 10 seconds for 90% of reading, is not necessarily better than a sensor that has a response time of 30 seconds for 99.5% oxygen.

Another important point is that response time depends on the change in concentration. It will obviously take a longer time for the sensor to respond to a change in concentration from 21% to 60%, than from 21% to 36% oxygen.

A true and useful definition of response time is one that specifies the $T_{99.5}$ for a change in concentration from 0.1% to 20.9% oxygen.

9.3 Oxygen Analysis Procedures

Oxygen analysis procedures may vary slightly, depending on the model of the particular analyzer and the situation at hand. Different manufacturers may describe different techniques for the analysis. Whatever technique is used, the general procedure is the same:

1. Calibrate the analyzer at 21% or 100% O_2.

2. Allow the sensor to come in contact with the gas for half a minute or so or until the reading stabilizes.
3. Read the analysis result and compare with expected value. If there is a significant deviation, re-calibrate and repeat the procedure. For high mixes calibrate at 100% O_2 as well.
4. Mark the tank's label.
5. Log the cylinder and analysis result in your logbook.

Different Techniques:

Depending on the situation and the tools available, different techniques may be used:

- ✔ Use a flow adapter connected to the LP hose that feeds your BCD.
- ✔ Use a flow adapter and measure directly from the tank pillar valve. In this case make sure that the flow is 2-4 L/min (a slight hiss).
- ✔ Use the vent valve of your mixing system, calibrate at air, and then measure the gas through the same vent port.
- ✔ Use the bag method. This is important to know when out in the field there are no adapters or flowmeter devices. A bag with small holes can be used with the sensor inside and after it is flashed a couple of times with the mix, analysis can be done.

NOTES

Section 10

10. Trimix Blending

10.1 What Is Trimix?

Trimix, as the name implies, is a mixture of three gases. The term is used more specifically to describe a mix that contains oxygen, helium, and nitrogen. Trimix is used for dives beyond 50 m (220 ft) because the use of helium dilutes the nitrogen as the inert gas in the mix, thus reducing both the narcotic effect of nitrogen, the decompression time, and the potentially lethal danger of oxygen toxicity. Trimix is not a gas for all divers, as considerable training and experience are required for its use.

For the gas blender, this means that the amount of trimix fills are only a small percentage of his regular nitrox fills. Also, trimix blending is a more difficult task. There are three main reasons for the increased difficulty:

1. There are two inert gases present in the mix (nitrogen and helium) creating problems in the analysis.
2. Helium is a gas with properties significantly different from either nitrogen or oxygen, creating problems in accuracy of simple calculations.

3. Even higher accuracy is required because of the use of the gas at deep dives, where small errors could result in serious injury or even death.

10.2 Characteristics of Helium

Helium is special in that its properties are significantly different from either oxygen or nitrogen. It is a "noble" or inert gas. It is a monatomic gas with very small molecules and an atomic weight of 4. The table below shows a comparison of some important properties of the gases used in the diving industry:

Gas	**Molar Mass** (kg/Kmole)	**Gas Constant** (KJ/kgK)	**Specific Heat Capacity** (KJ/kgK)		**Gamma** (C_p / C_v)
			C_p	C_v	
Air	29.0	0.287	1.01	0.72	1.40
N_2	28	0.297	1.04	0.74	1.40
Atmospheric Nitrogen	28.15	0.295	1.03	0.74	1.40
O_2	32	0.260	0.92	0.66	1.40
Helium	4	2.08	5.19	3.11	1.67

From the compressibility graphs in Section 7.5, we can also see that the behavior of helium with regards to compressibility factors is also different.

10.3 Demands on Equipment

Apart from the above properties, which are very important as far as the physics of gas blending are concerned, Helium is also very small as a molecule. The implication is that it "creeps" out easily. Helium leakage is far more serious than leakage of air or oxygen. It is not surprising to find an empty tank that used to be a full helium tank just a few days ago, just because a valve was not sealing properly or the fittings had small scratches. Therefore, care must be applied when preparing equipment for trimix blending. A property of helium that was not mentioned above is **cost**. Helium gas is much more expensive than oxygen. Leakage costs a lot of money!

Proper labeling of equipment is very important for trimix. Scuba tanks should be labeled separately from air and nitrox. A "TRIMIX" or "CUSTOM MIX" band must be placed on the tank, and there must always be a contents label. This is extremely important because tanks may contain hypoxic mixes. Even if the mix is analyzed, and the oxygen percentage is not hypoxic (say 18%), the analysis tells you nothing on the nitrogen to helium ratio.

10.4 Mixing Calculations and Procedure

As with nitrox, in mixing trimix, calculations are simple. We use simple mathematical formulas to calculate the partial pressures of each gas. The difficulty with Trimix is that the deviation from the ideal gas behavior is greater, and the blender needs more experience and slower fills in order to achieve a correct mix. In the filling, we recommend that the flow coefficient is 0.005 as opposed to 0.007 for nitrox mixing.

10.4.1 Calculations Using a Simple Formula

The symbols used here are the same for nitrox mixing:

ICO_2: Initial composition oxygen
ICHe: Initial composition helium
ICN: Initial composition of nitrogen
IP: Initial pressure of residual gas in scuba tank
TCO_2: Target composition oxygen
TCHe: Target composition helium
TCN: Target composition of nitrogen
TP: Target pressure for the mix

1. Calculate the pressures of each gas that needs to be added.

$$\Delta P_{He} = TP \times TC_{He} - IP \times IC_{He}$$

$$\Delta P_{Air} = \frac{TP \times TC_{N_2} - IP \times IC_{N_2}}{0.79}$$

$$\Delta PO_2 = TP\left(TCO_2 - \frac{0.21}{0.79} \times TC_{N_2}\right) - IP\left(ICO_2 - \frac{0.21}{0.79} \times IC_{N_2}\right)$$

for verification: $\Delta PO_2 = TP - IP - \Delta P_{He} - \Delta P_{Air}$

2. Calculate IP + pressure of He to add + pressure of air to add.
3. If the above is smaller than the target pressure, the balance is oxygen. If it is equal to the target pressure, no oxygen needs to be added.

4. Calculate the composition of the mix after you add helium or oxygen:

   After adding helium:
   O_2% = (Initial partial pressure O_2) / intermediate pressure

   After adding oxygen:
   O_2 percentage = (Initial partial pressure of oxygen + pressure of oxygen added) / new intermediate pressure

10.4.2 Mixing Procedure

After calculating pressures as above, you can start mixing. Because of the greater deviation of trimix from ideal gas behavior, we recommend that smaller flow coefficients are used if the mixing is not done automatically. Flow coefficient (Cv) should not exceed 0.005.

1. After calculating the pressures as above, check against the pressure of your source gases helium and oxygen.
2. Ensure that there is enough pressure for the fill.
3. Whichever is the lowest pressure, use that first and fill to a pressure equal to the initial pressure + pressure of that gas that needs to be added.
4. Where possible, prefer to fill helium first because it is a more expensive gas and better utilization of helium pays off. !

5. Before adding the second gas, analyze the gas for its oxygen content and see if it agrees with your calculations.
6. Add the second and third gas if needed.
7. Disconnect the fill whip and analyze the gas for its oxygen content.

10.5 Inherent Accuracy and How It Affects Dive Planning

The oxygen percentage in the mix can be easily measured using an oxygen analyzer. The inherent accuracy of the galvanic cell analyzer is ± 1%. We must therefore assume that we are 1% off in our mix. This may not be the case, but we cannot prove it because the analyzer is only accurate to 1%.

The He/N_2 is something that cannot be measured easily with a low cost and portable analyzer with existing technologies. Based on the usual method of mixing trimix, we can calculate, however, what could be the error in the He/N_2 ratio given a potential error of 1% in the oxygen content.

The calculations are quite involved and depend on the following factors:

1. Trimix composition (required)
2. Error in final pressure
3. Target pressure

The error in He/N_2 could be up to 3.7 the error in O_2 percentage. At the same time, correct O_2 percentage does not guarantee correct He/N_2 ratio. In diving physiology, 3.7% error in N_2/He does not have any significant effect, and in most cases, it is not mentioned at all.

Section 11

11. Error Analysis

This chapter is provided to give a good understanding of the various sources of error and their impact on the final composition, so that the accuracy of your mixes can be improved by avoiding these errors.

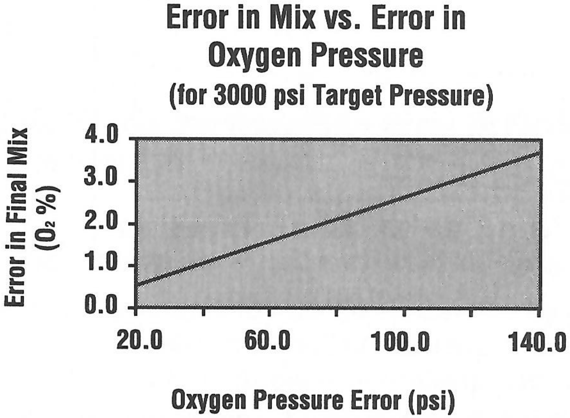
11.1 Sources of Error

Error can come about from four main reasons:

1. Temperature and compressibility effects.
2. Skipping the right pressure either by incorrect gauge or by lack of care.
3. Incorrect calculations of the closing pressures.
4. Incorrect analysis of the residual gas in the scuba tank.

As far as the first reason is concerned, there is not much that can be done when the mixing is done manually, other than accumulating enough experience by trial and error in order to understand how to make small adjustments for

$$\text{Error in final mix (\%)} = \frac{\text{(79\%) error in pressure}}{\text{Final pressure}}$$



Error in air pressure:

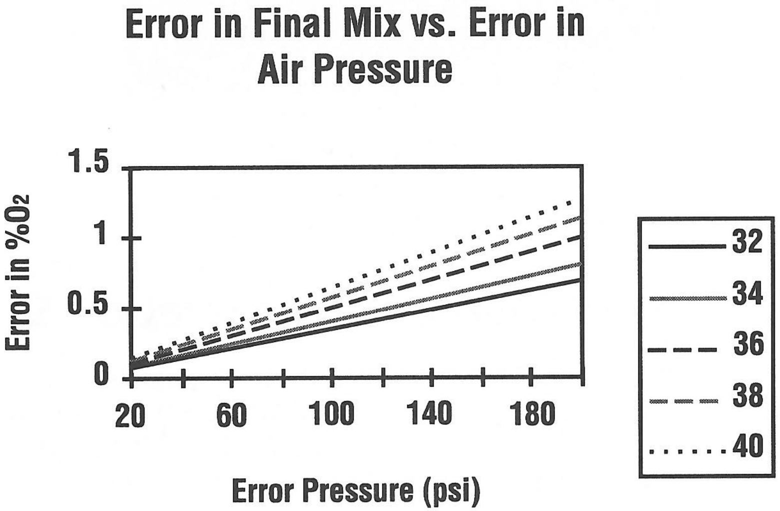
Similar to the above situation, it is possible to have an error in the final pressure, (i.e., the pressure when the air valve is closed). The impact that this has on the accuracy of the final mix is a bit more complex as it also depends on the target composition.

$$\varepsilon = \text{Errp}\left(\frac{\text{TC} - 0.21}{\text{TP} + \text{ErrP}}\right)$$

Where:

ErrP = error in air pressure
TP = Target pressure
TC = Target composition
ε = error in final mix

The result is shown graphically below:



NOTES

Section 12

12. Business Considerations

In this chapter we will discuss the business aspects of selecting the right equipment for a blending station and how to lay out a blending station.

The basic starting point in any business decision should be the market demand. However difficult as it may be, to predict the future demand for mixed gases, it is important to make a wise estimate. It is also important to determine the nature of the demand. Is it going to be mostly recreational, or is there going to be a demand to some technical diving and possibly rebreathers? If the latter is the case, then high mixes will be needed and the blending station should be able to deliver.

12.1 Financial Considerations

12.1.1 Calculating the Cost of Nitrox Fills

The cost of filling one nitrox tank is made up of many factors, the most important of which is labor cost. The cost items are listed below:

1. Labor cost

2. Cost of oxygen

3. Cost of helium (trimix only)
4. Cost of compressed air
5. Apportionment for maintenance
6. Apportionment for interest on initial investment
7. Cost of venting residual gas (negative if save gas)

These depend on several factors:

- ✔ Average fills per week
- ✔ Type of blending system affecting both the time per fill, the apportionment for interest on investment, maintenance cost, and utilization of residual gas
- ✔ Salary of gas blender
- ✔ Cost of oxygen cylinder and oxygen utilization
- ✔ Interest rate

So how do we calculate each of these elements?

Labor cost = Salary per month x (time of one fill in min) / 9,120 mins

Cost of oxygen = Cost of oxygen cylinder / average number of nitrox fills from one cylinder

Cost of compressed air = ($0.20 is a good rough estimate). Note: For membrane systems multiply this by 3 since about double the amount of air has to be processed to give nitrox, plus the compressor has to work to compress the nitrox.

Apportionment for maintenance = Cost of filter element x time that air flows through filter / life of filter element + $0.06 (for annual maintenance)

Apportionment for interest on initial investment = Initial investment x interest rate / estimated number of fills in one year

Cost of venting residual gas = (Average pressure of residual gas) x cost as estimated with the factors above / final pressure. Note: If your system allows utilization of residual gas, then this number must be subtracted from the calculated cost.

Example:

Estimated number of fills per month = 100

Salary of blender = $1,000

Interest rate = 6%

50L 200 bar oxygen cylinder costs: $15

System used: ANX Supreme and NS Clean Air 3-stage filters

Labor cost = $1,000 x 2 min / 9120 = $0.22

Cost of oxygen = $15 / 20 = $0.75

Cost of compressed air = $0.20

Apportionment for maintenance =
$210 x 3 min / 24,000 + 0.06 = $0.08

Apportionment for interest on initial investment =
6% x $5,500 / 12 x 100 = $0.28

Cost of venting residual gas = (0.22 + 0.75 + 0.2 + 0.08 + 0.28) x 40 bar / 200 bar = $0.3

TOTAL cost of one nitrox fill =
0.22 + 0.75 + 0.2 + 0.08 + 0.28 - 0.3 = $1.23

12.1.2 Investment Appraisal for a Blending Station

A blending station is a serious investment. As such, different alternatives should be evaluated.

Two measures are extremely useful in evaluating an investment: pay back period and return on investment.

Pay back period is the period of time (in months) that is necessary in order to make back the money paid for the initial investment.

Return on investment is a number expressed as a percentage that shows how profitable your investment in a particular option for a blending station will be.

Pay back period =
Initial investment / [(selling price - cost of nitrox fill) x number of fills per month]

Return on investment in one year =
[(selling price - cost of nitrox fill) x number of fills per month x 12 - initial investment] / initial investment

In the example used on the previous page, with a selling price of $8.00 per nitrox fill:

Pay back = $5,500 / [($8 - $1.23) x 100] = 8 months
ROI = [($8 - $1.23) x 100 x 12 - $5,500] / $5,500
= 47.7%

The above calculations and a complete evaluation for different options can be done very easily using software tools available from NS Research.

12.2 Other Considerations

Being able to provide the required gas to your customers is a critical point for a dive business. Other than strict finances, the following points are also important for the business:

- ✔ **Flexibility:** The ability to produce the gas without depending on any one individual to do the filling and without tying down any specific employee for filling can be extremely important. People can be sick, need to take holidays, or can be essential for some other urgent job. This has to be taken into consideration when planning the blending station, either by training more than one blender or by using an automatic blending system.
- ✔ **Accuracy and consistency:** Customers become more and more demanding, and a 36% nitrox needs to be 36% or at least very close (irrespective of whether that matters for the dive or not). A blending system has to ensure that accuracy and be consistent. This contributes to the image that the dive business sends out to its customers and can therefore bring in more business.
- ✔ **Maintenance requirements:** This is especially important for busy dive resorts. Downtime at high season can be very expensive, apart from the fact

that it may require parts and service technicians to do the job. A low-maintenance system always provides an advantage, but care should be taken to ensure that one piece of equipment does not impose heavy maintenance requirements on another piece of equipment.

✔ **Installation:** The cost and technical requirements for the installation of a particular setup can be very important. Make sure that installation is straightforward and that the owners and operators of the blending station are familiar with installation requirements.

Section 13

13. Failure Mode and Effect Analysis (FMEA)

13.1 What is a FMEA?

Failure mode and effect analysis is a methodology for identifying and eliminating potential failures on a priority basis. This methodology is used a lot by successful companies in both manufacturing and in engineering design. As a methodology, it is powerful, general, and can be applied to every system, product, or service.

It can be applied very successfully to gas blending as well as in planning your technical and most demanding dives.

In gas blending, a FMEA can be used to ensure that a solid working system is set up as far as the production and dispensing of the gas is concerned. This can significantly help your business in the long run because you will have thought of potential problems and taken action to prevent them before they occur.

Any system (not just equipment, but the overall way we achieve a result — in gas blending the overall way that we deliver accurate mixes to the customer in a timely manner) can fail, we must identify the ways of failure and eliminate them. A FMEA is an excellent tool in prioritizing our corrective action.

13.2 What Does a FMEA Involve?

1. Define what the product or the process is and what is expected of it (e.g., for a torch you expect to get continuous bright light).
2. Identify potential failure modes (e.g., a torch might flood).
3. Identify potential effects of failure (e.g., you have no light, which may lead to disorientation if you are in a cave, which may lead to getting lost, which may lead to running out of air, which may lead to...).
4. Identify potential causes of failure (e.g., the o-ring might rupture).
5. Identify current controls to prevent the bad effects (e.g., check o-ring, have spare lights, etc.).
6. Assess occurrence, severity, and detection. How frequently can each type of failure occur, how severe will it be and how likely is it that the potential failure will be detected before it actually occurs, or before the bad effects occur?
7. Prioritize, then identify and implement preventative action. To prioritize problems and actions, a useful tool is to use the Risk Priority Number (RPN).

13.2.1 Calculating the Risk Priority Number

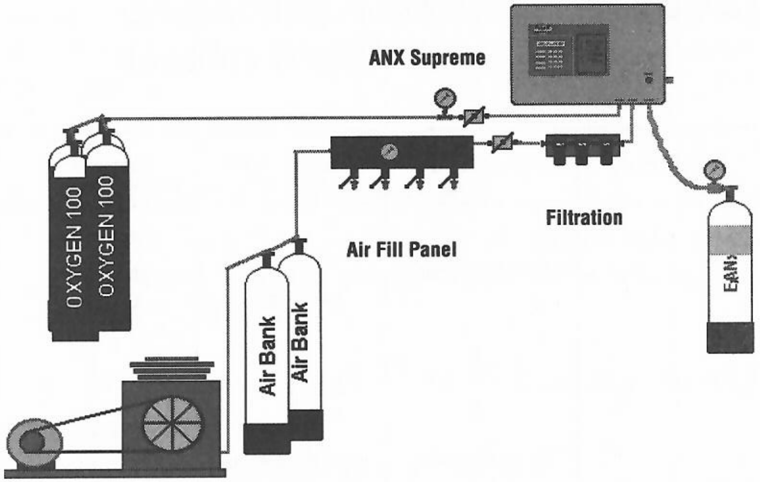
RPN = Occurrence x Severity x Detection

Rating	Occurrence	Severity	Detection
1	Almost never	Hardly noticeable	Absolutely obvious
↓	↓	↓	↓
	Occasionally	Dissatisfaction	Could go unnoticed
	↓	↓	↓
10	Often	Serious effects	Undetectable

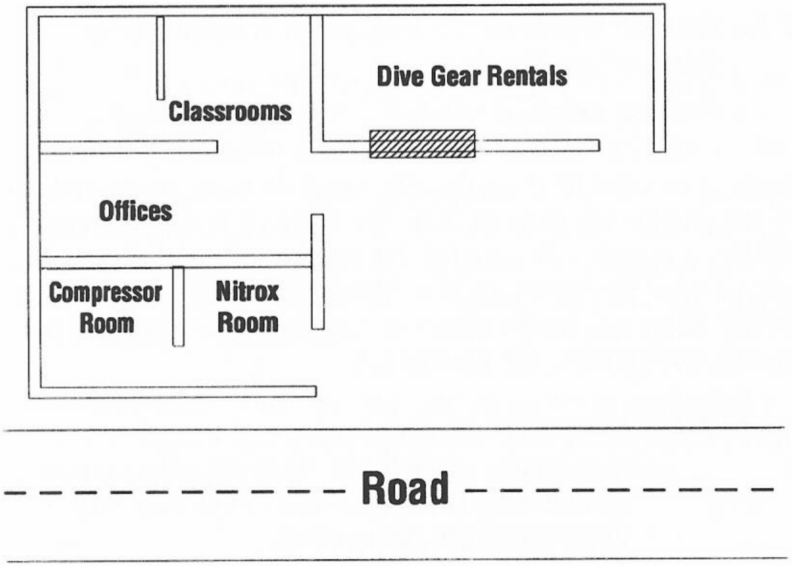
13.3 How to Construct a FMEA for a Mixed Gas Production System

It must be emphasized that a mixed gas production system is not just the hardware or the set of equipment used in producing the gas. It is the hardware as well as the procedures. Some aspects include the ways of ordering oxygen, mixing the gas, maintaining the equipment, and selling the gas to your customer. It also should be noted that the customer need not be an external customer. You may be producing the gas for your own needs.

STEP 1: Draw a schematic of your hardware. If you are considering more than one configuration, you should draw them all. A FMEA will help you in deciding on the best option.



STEP 2: Draw another diagram of your facility and the positioning of the hardware.



Take a big sheet of paper and draw big diagrams on which you can add or modify things as you go on. It doesn't have to look nice. It is your working document.

STEP 3: Walk your diagrams. Start with the first diagram and using the table in the next page below, try to fill all the entries in the first 9 columns. Consider the physical equipment and the physical processes that take place, as well as the movement of people and materials.

Many of the failure causes can be either due to equipment or due to the way you operate. All equipment can fail. But by correct rating and proper selection, you can reduce the occurrence significantly to give you a low RPN. Also, it is important to realize that the effects, and hence the RPN, depend on your own type of operation. If, for example, you are on a live-aboard, failure of your blending system can be extremely detrimental. In that case, corrective action may be to carry spare parts and have somebody trained for maintenance.

FMEA EXAMPLE

Process/ Product	Potential Failure Mode	Potential Effects of Failure	Severity	Potential Causes of Failure	Occurrence	Current Controls/ Method	Detection	RPN
Oxygen Supply	Late in getting oxygen from supplier	Unable to produce nitrox. Hold up customers.	5	Late in ordering	4	Order when run low	7	140
				Not calculate needs correctly				
Nitrox/ trimix	Get %O_2 in mix wrong	Oxygen toxicity or DCS for diver. Diver may have serious physiological problem.	10	Calculate pressures wrong	8	Analyze the gas and write on tag on bottle	1	80
				Operator distracted	8			
				Inaccurate gauge	5			

Section 14

14. Popular Misconceptions

This chapter clarifies some common misconceptions about gas blending. Many of these misconceptions have been around for many years and, although they have absolutely no scientific foundation, they have been based on the word of certain "gurus" in the industry. We face these misconceptions from a scientific point of view, for most of them can be disqualified easily with simple mathematics and fluid mechanics. Readers interested in such mathematical treatment can contact the author via fax or e-mail.

1. **After filling (especially trimix) the scuba tank must be rolled and tumbled to get the mix homogeneous.**

   FALSE. The diffusion coefficient at high pressure and temperature inside the scuba tank is so high that for the geometry of a common tank, the mixture becomes homogeneous in a few seconds. Non-homogeneous mixes are only possible in the very long run and very thin cylinders of pressure of 300 bar that are often used in bells.

2. **Oxygen should never be filled faster than 60 psi / min and air should be filled at 600 - 700 psi / min.**

   FALSE. Such a guide is not the correct way to prevent hazards during filling. Also, it is practically impossible to measure and adjust such rate of increase of pressure in a short time. The temperature in the scuba tank rises in a step function, then remains approximately constant, and then slowly drops (see "Physics of Gas Blending"). The important factor is the initial flow of oxygen or air. Subsequent flow conditions are not as critical. The most important guideline is the type of valve used and its flow characteristic. This is also important as a good valve design will cause the gas to cool down to temperatures from 0C to -10C, significantly reducing the risk of fire, as well as keeping the gas temperatures in the scuba tank significantly lower. Also interesting is that the temperature drop depends on the flow; higher flows result in lower temperatures. This is a nice safety feature. Finally, the guide given is not flow rate, but rate of pressure increase. How can such a guide be given if the corresponding flow rate is obviously different for different tank sizes?

3. **For mixes up to 40%, no oxygen cleaning is required.**

   NOT SUBSTANTIATED. The 40% figure is totally arbitrary and there is absolutely no scientific evidence to support that myth. There can be no such study because generalizations such as this are not just misleading, but dangerous. The percentage of oxygen where a certain amount of contamination may be allowed depends on many factors specific to the system design as well as the contaminants in question.

Such factors include the velocities of the flows, valve characteristics, the materials used in the system and the roughness of their internal surface, the shapes of tubing, etc. Pressure shock waves are the biggest concern in any system and the temperatures reached depend on the severity of these shock waves. What is more, even if we accept a certain amount of contamination present in the system, no oxygen cleaning means that in a period of a few years of system use their concentration could well exceed the set acceptable levels. It is more a matter of attitude than anything else.

4. **Partial pressure method is the "cheapest way out" but the most hazardous one as well.**

   FALSE. Partial pressure method (either manual or automatic) may be the most economical method, but with correct system design it is a safe method. In fact, it can be much safer than other mixing alternatives.

5. **Molecular weight is a very accurate but uncommon way of producing mixed gas.**

   FALSE. Measuring mass is a more direct way than measuring pressure as far as the molar compositions of gases are concerned, but it is by no means more accurate. There are practical problems involved, such as the weight of fill whips and the torque (and consequently force) that they exert on the scale.

6. **The use of nitrox banks is an efficient way to produce nitrox using 50% and diluting it.**

   FALSE. As explained in the relevant section about nitrox banks, they can only serve to cover peaks in the demand. Certainly efficiency drops because those banks have to be replenished, and this process takes significantly longer. Essentially, there is duplication of effort. Also, in order to replenish such a nitrox bank, a booster pump is necessary, thus significantly increasing the initial investment required.

Appendices

Appendix A:
A Note on Hydrometry

How Is Water Content Measured and Expressed?

There are many different ways to express the water content in air: ppm, % RH, dew point, absolute humidity, etc. Unfortunately, this can be very confusing. What is more, humidity is a relatively difficult quantity to measure in practice and the accuracy achievable is not as good as other types of measurement. Humidity can commonly be measured to only about three parts in 100 (i.e., with an uncertainty in the result of ± 3%). As a comparison, pressure can easily be measured to ± 0.25%.

Water vapor is in gaseous form and can be thought of much like any other gas. In the same way that water gives off steam, so water at lower temperatures (including ice) also gives off water vapor. This is due to evaporation, the extend of which depends on a number of factors, the most important being pressure and temperature. Air is said to be saturated when it contains its full capacity of water vapor at a given temperature and pressure.

Definitions:

Dew Point: The temperature at which dew or condensation forms when cooling a gas. This is, in effect, the temperature at which the gas becomes saturated in equilibrium with water.

Absolute Humidity: The mass of water present per unit volume of moist air at a given temperature and pressure. It is expressed as grams per cubic meter (g/m^3).

Parts per million by volume: Volume of water vapor per total volume of gas, for an ideal gas. Sometimes expressed relative to the total volume of moist gas or the volume of dry gas. It is measured as ppmV, ppm(V).

Parts per million by weight: The mass of water relative to the total dry gas or sometimes to the moist gas. It is measured as ppmW or ppm(W).

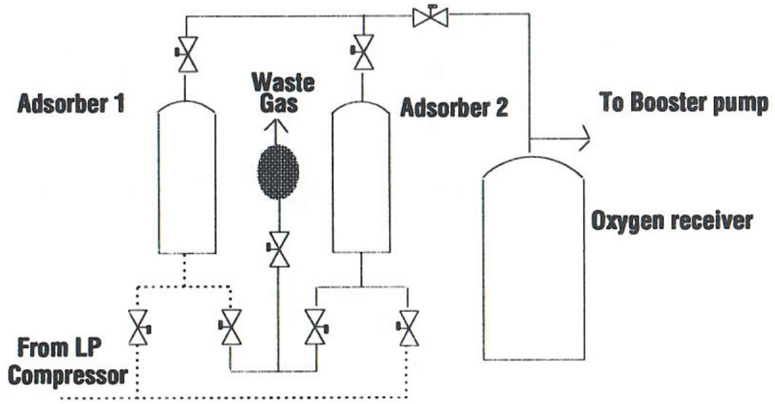
Appendix B:
PSA Systems

The initials PSA stand for Pressure Swing Adsorption. It is a method for on-site production of oxygen and can be a viable alternative to the supply of high pressure oxygen cylinders.

How It Works

The PSA unit separates oxygen from compressed air through the process of adsorption, using a molecular sieve made of synthetic zeolite. The sieve attracts nitrogen, which makes up about 79% of air. When the pressure is reduced, the sieve releases the nitrogen, leaving oxygen and argon behind.

PSA Schematic



As shown in the diagram on the previous page, dry air is supplied at a pressure ranging from 6 - 10 bar (90 - 150 psig) to a series of filters and then to switching valves which direct the air to one of two molecular sieve beds containing synthetic zeolite. The zeolite adsorbs (i.e., attracts on the surface) nitrogen and lets only oxygen and trace gases pass through. Ninety-five percent pure oxygen flows out of the bed into the oxygen storage vessel. This continues until the bed is saturated with nitrogen. The air flow is then diverted to the second bed and the first bed is then regenerated by reducing the pressure and venting the nitrogen to the atmosphere.

A Note on Argon

Air contains about 0.93% argon (A) and other trace gases which, together with nitrogen, are called atmospheric nitrogen. The zeolite sieve adsorbs the nitrogen but not the argon. As a result, purity ranges from 90% to 99% pure oxygen, the remaining gas being argon.

The most common PSA systems offer a 95% oxygen purity, which is acceptable oxygen purity for medical use and approved by the FDA in the United States. Other high purity PSA systems are available that offer up to 99% purity, but there is a significant cost premium for this purity.

It must be noted that the relative narcotic potency of argon is 0.43. This means that argon is 2.32 times more narcotic than atmospheric nitrogen.

The percentage of argon in the breathing gas in the scuba tank is given by:

$$f_A = (1/FP) \times 5 \times (1 / 0.79) \times [FP \times (TC - 0.21) + IP \times (1 - IC)] + 0.93 \times (1 - TC)$$

Where:
f_A = percentage of argon
FP = final pressure in scuba tank
IP = initial pressure
IC = initial composition
TC = target composition

So, for a 200 bar 32% mix, starting with an empty scuba tank, the f_A is 1.354%.

This is equivalent to 2.32 x F_A % nitrogen with regard to narcosis. So in the above case, a 32% mix would be equivalent to a 28.8% mix as far as narcosis is concerned. As far as decompression stops are concerned, things are a bit more complex because the argon molecule is much larger than the nitrogen molecule. Thus, the effect is not so apparent for relatively short exposures. It can become important for long exposures, decompression diving, or repetitive diving. There is not enough data available to the author to substantiate a case study on the above effect.

High Purity and Other PSA Systems

High purity PSA systems can deliver up to 99% pure oxygen. In these systems the 95% pure oxygen is passed through an additional purification stage using carbon molecular sieve, which works in a similar way as the zeolite, but adsorbs the oxygen.

Vacuum Pressure Swing Adsorption (VPSA) is another version of PSA systems, which employs a vacuum to depressurize the sieves and drive off the nitrogen. This improves the life of the sieves.

NOTES

Appendix C:
Liquid Oxygen

The option of using liquid oxygen seems appealing to operators who do not wish to deal with the logistics of high-pressure oxygen cylinders because of the large usage, restrictions in space, etc. The idea also sounds exotic!

Oxygen has a molecular weight of 32. The density of the gas at 1 atmosphere, and 20C is 1.33 kg/m^3. The boiling point at 1 atm is -183C, and the liquid density at the boiling point is 1140 kg/m^3. Typical approximate dimensions of a mini-tank are 1.6 m high and 0.5 m in diameter. The weight of its contents is about 150 kg. So, it holds approximately 115 m^3 of oxygen at 1 atm. This is equivalent to 10 - 16 normal pressurized oxygen cylinders. We can immediately see the benefit in space savings.

The following points must be considered:

1. **Maximum continuous flow rate from the mini-tank:** 10 m^3/hr, or 5.88 cfm, with peak flow rate (5 minutes) 28 m^3/hr or 16.48 cfm.

2. **Working pressure:** 0-21 bar G.

3. **Normal leak rate (when not in use):** 2.09 m^3/day. This would be equivalent of losing 40 bar of oxygen out of a 50L normal oxygen tank, per day (if not in use).

To explain this last point, we must consider that oxygen has a boiling point of -183C. At this temperature it vaporizes from liquid to gas. The mini-tank is essentially a glorified "thermos flask," whose job is to maintain the low temperature. However, some heat from the environment does flow in. This heat energy causes some of the liquid to vaporize. As more and more liquid vaporizes in gaseous oxygen, the pressure of the gas increases. Since the working pressure of the mini-tank is no more than 21 bar, some gas has to be vented, or otherwise we will end up with a catastrophic explosion. For this purpose, the mini-tank contains a pressure relief vent valve, which will open at 20 bar to vent the vaporized oxygen to the atmosphere. **THIS MUST NOT BE PREVENTED UNDER ANY CIRCUMSTANCES.**

Liquid oxygen is a real option for continuous blending systems where the mixing is done at low pressure and then the mixture is compressed through an oil-free compressor. In order to have a useable system, a buffer is required to collect the gaseous oxygen. For any other blending method, and partial pressure blending in particular, a booster pump is required to boost the gas to high useful pressure as well as a second high pressure buffer. Such a system becomes too complex and expensive.

Finally, the mini-tank can be fragile. It is a bit like a glorified "thermos flask" inside, so one needs to be careful in handling. Where there are likely to be vibrations (such as on board a ship), it is strongly advised that use of liquid oxygen is avoided.

Appendix D:
Gas Analysis Using Paramagnetic Technology

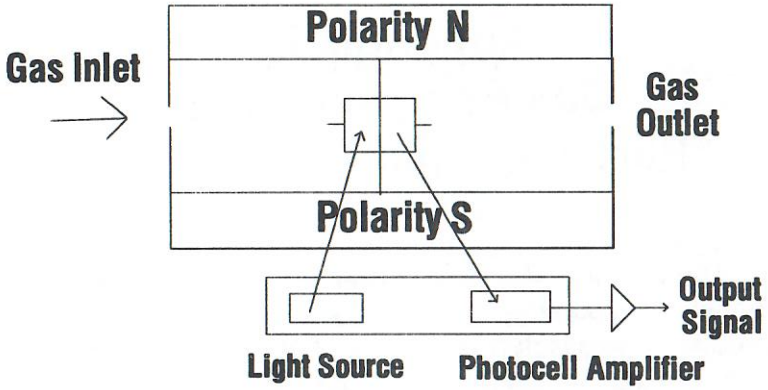
These types of oxygen analyzers are based on paramagnetic measurement technology. They are usually built to be quite sophisticated machines offering a variety of software features for user-friendly operation and analysis for more than one gas.

Principle of Operation

The paramagnetic susceptibility of oxygen is significantly greater than that of nitrogen or helium, in that oxygen molecules are attracted by a much stronger force in a magnetic field than the molecules of other gases. This susceptibility is determined by measuring the force developed by a magnetic field on a test body which is suspended in the gas to be analyzed. In one particular sensor, the ADC7000, the test body consists of two nitrogen-filled quartz spheres arranged in the form of a dumb-bell.

Paramagnetic Cell

When a sample gas containing oxygen surrounds the dump-bell, the oxygen molecules are attracted to the strongest part of the magnetic field and, as a result, tend to displace the dumb-bell. This movement is detected by a light beam and measured by a pair of photo-cells. The signal is fed to an amplifier, the output of which is proportional to the O_2 percentage, and this voltage output is used as feedback control to bring the dumb-bell back to balance.



Typical Performance Data:

Analysis range:	0 - 100% O_2
Resolution:	0.1% (display)
Linearity:	< 0.1%
Noise:	< 0.05%
Repeatability:	± 0.05%'
Total combined error:	0.2%
Response time:	T90 in 3.5 seconds

Appendix E: Units of Pressure Conversion Table

Given unit	Bar	Atmospheres	PSIG	kg/cm2
1 bar	1	0.98692	14.504	1.01944
1 Standard Physical Atmosphere	1.0133	1	14.696	1.03322
1 Pounds/ square inch (psi)	0.06895	0.06895	1	0.07031
1 kg/cm2	1.01944	0.98692	14.504	1
1 Kilopascal	0.01 ✓	0.009869	0.14504	0.010194
1 Torracelli (torr)	0.001332	0.001316	0.01934	0.0013046

1 Cubic foot = 28.316 liters

USN Rev. 7 P153:

33 feet of sea water = 10.~~05~~84 meters

10.3163 msw @ 15°C

Pressure equivalent of 33 feet of sea water = 1.0256 kg/cm$_2$
= 14.685 psig

the guys name is Torricelli !

NOTES

Appendix F:
Nitrox Mixing Tables

These tables give the oxygen pressures for nitrox partial pressure mixing. Instructions for their use can be found on Page 99.

The tables are not compensated for temperature or compressibility effects because these are specific to the particular filling situation. It is therefore up to the user to know how to suitably adjust pressures to obtain accurate mixes.

The tables are generated based on the mixing formula given on Page 97.

NITROX MIXING TABLE GIVING OXYGEN PRESSURE (UNCOMPENSATED) -Metric

Gas Pressure (BAR)

Percentage of Oxygen

	10	20	30	40	50	60	70	80	90	100
21	0	0	0	0	0	0	0	0	0	0
22	0	0	0	1	1	1	1	1	1	1
23	0	1	1	1	1	2	2	2	2	3
24	0	1	1	2	2	2	3	3	3	4
25	1	1	2	2	3	3	4	4	5	5
26	1	1	2	3	3	4	4	5	6	6
27	1	2	2	3	4	5	5	6	7	8
28	1	2	3	4	4	5	6	7	8	9
29	1	2	3	4	5	6	7	8	9	10
30	1	2	3	5	6	7	8	9	10	11
31	1	3	4	5	6	8	9	10	11	13
32	1	3	4	6	7	8	10	11	13	14
33	2	3	5	6	8	9	11	12	14	15
34	2	3	5	7	8	10	12	13	15	16
35	2	4	5	7	9	11	12	14	16	18
36	2	4	6	8	9	11	13	15	17	19
37	2	4	6	8	10	12	14	16	18	20
38	2	4	6	9	11	13	15	17	19	22
39	2	5	7	9	11	14	16	18	21	23
40	2	5	7	10	12	14	17	19	22	24
41	3	5	8	10	13	15	18	20	23	25
42	3	5	8	11	13	16	19	21	24	27
43	3	6	8	11	14	17	19	22	25	28
44	3	6	9	12	15	17	20	23	26	29
45	3	6	9	12	15	18	21	24	27	30
46	3	6	9	13	16	19	22	25	28	32
47	3	7	10	13	16	20	23	26	30	33
48	3	7	10	14	17	21	24	27	31	34
49	4	7	11	14	18	21	25	28	32	35
50	4	7	11	15	18	22	26	29	33	37
52	4	8	12	16	20	24	27	31	35	39
54	4	8	13	17	21	25	29	33	38	42
56	4	9	13	18	22	27	31	35	40	44
58	5	9	14	19	23	28	33	37	42	47
60	5	10	15	20	25	30	35	39	44	49
70	6	12	19	25	31	37	43	50	56	62
80	7	15	22	30	37	45	52	60	67	75
90	9	17	26	35	44	52	61	70	79	87
100	10	20	30	40	50	60	70	80	90	100

NITROX MIXING TABLE GIVING OXYGEN PRESSURE (UNCOMPENSATED) -Metric

Gas Pressure (BAR)

Percentage of Oxygen

	120	140	160	180	200	210	220	230	240	250
21	0	0	0	0	0	0	0	0	0	0
22	2	2	2	2	3	3	3	3	3	3
23	3	4	4	5	5	5	6	6	6	6
24	5	5	6	7	8	8	8	9	9	9
25	6	7	8	9	10	11	11	12	12	13
26	8	9	10	11	13	13	14	15	15	16
27	9	11	12	14	15	16	17	17	18	19
28	11	12	14	16	18	19	19	20	21	22
29	12	14	16	18	20	21	22	23	24	25
30	14	16	18	21	23	24	25	26	27	28
31	15	18	20	23	25	27	28	29	30	32
32	17	19	22	25	28	29	31	32	33	35
33	18	21	24	27	30	32	33	35	36	38
34	20	23	26	30	33	35	36	38	39	41
35	21	25	28	32	35	37	39	41	43	44
36	23	27	30	34	38	40	42	44	46	47
37	24	28	32	36	41	43	45	47	49	51
38	26	30	34	39	43	45	47	49	52	54
39	27	32	36	41	46	48	50	52	55	57
40	29	34	38	43	48	51	53	55	58	60
41	30	35	41	46	51	53	56	58	61	63
42	32	37	43	48	53	56	58	61	64	66
43	33	39	45	50	56	58	61	64	67	70
44	35	41	47	52	58	61	64	67	70	73
45	36	43	49	55	61	64	67	70	73	76
46	38	44	51	57	63	66	70	73	76	79
47	39	46	53	59	66	69	72	76	79	82
48	41	48	55	62	68	72	75	79	82	85
49	43	50	57	64	71	74	78	82	85	89
50	44	51	59	66	73	77	81	84	88	92
52	47	55	63	71	78	82	86	90	94	98
54	50	58	67	75	84	88	92	96	100	104
56	53	62	71	80	89	93	97	102	106	111
58	56	66	75	84	94	98	103	108	112	117
60	59	69	79	89	99	104	109	114	118	123
70	74	87	99	112	124	130	136	143	149	155
80	90	105	119	134	149	157	164	172	179	187
90	105	122	140	157	175	183	192	201	210	218
100	120	140	160	180	200	210	220	230	240	250

NITROX MIXING TABLE GIVING OXYGEN PRESSURE (UNCOMPENSATED) -Imperial

Gas Pressure (psi)

Percentage of Oxygen	200	400	600	800	1000	1200	1400	1600
21	0	0	0	0	0	0	0	0
22	3	5	8	10	13	15	18	20
23	5	10	15	20	25	30	35	41
24	8	15	23	30	38	46	53	61
25	10	20	30	41	51	61	71	81
26	13	25	38	51	63	76	89	101
27	15	30	46	61	76	91	106	122
28	18	35	53	71	89	106	124	142
29	20	41	61	81	101	122	142	162
30	23	46	68	91	114	137	159	182
31	25	51	76	101	127	152	177	203
32	28	56	84	111	139	167	195	223
33	30	61	91	122	152	182	213	243
34	33	66	99	132	165	197	230	263
35	35	71	106	142	177	213	248	284
36	38	76	114	152	190	228	266	304
37	41	81	122	162	203	243	284	324
38	43	86	129	172	215	258	301	344
39	46	91	137	182	228	273	319	365
40	48	96	144	192	241	289	337	385
41	51	101	152	203	253	304	354	405
42	53	106	159	213	266	319	372	425
43	56	111	167	223	278	334	390	446
44	58	116	175	233	291	349	408	466
45	61	122	182	243	304	365	425	486
46	63	127	190	253	316	380	443	506
47	66	132	197	263	329	395	461	527
48	68	137	205	273	342	410	478	547
49	71	142	213	284	354	425	496	567
50	73	147	220	294	367	441	514	587
52	78	157	235	314	392	471	549	628
54	84	167	251	334	418	501	585	668
56	89	177	266	354	443	532	620	709
58	94	187	281	375	468	562	656	749
60	99	197	296	395	494	592	691	790
70	124	248	372	496	620	744	868	992
80	149	299	448	597	747	896	1046	1195
90	175	349	524	699	873	1048	1223	1397
100	200	400	600	800	1000	1200	1400	1600

NITROX MIXING TABLE GIVING OXYGEN PRESSURE (UNCOMPENSATED) -Imperial

Gas Pressure (psi)

Percentage of Oxygen	1800	2000	2200	2400	2600	2800	3000	3200
21	0	0	0	0	0	0	0	0
22	23	25	28	30	33	35	38	41
23	46	51	56	61	66	71	76	81
24	68	76	84	91	99	106	114	122
25	91	101	111	122	132	142	152	162
26	114	127	139	152	165	177	190	203
27	137	152	167	182	197	213	228	243
28	159	177	195	213	230	248	266	284
29	182	203	223	243	263	284	304	324
30	205	228	251	273	296	319	342	365
31	228	253	278	304	329	354	380	405
32	251	278	306	334	362	390	418	446
33	273	304	334	365	395	425	456	486
34	296	329	362	395	428	461	494	527
35	319	354	390	425	461	496	532	567
36	342	380	418	456	494	532	570	608
37	365	405	446	486	527	567	608	648
38	387	430	473	516	559	603	646	689
39	410	456	501	547	592	638	684	729
40	433	481	529	577	625	673	722	770
41	456	506	557	608	658	709	759	810
42	478	532	585	638	691	744	797	851
43	501	557	613	668	724	780	835	891
44	524	582	641	699	757	815	873	932
45	547	608	668	729	790	851	911	972
46	570	633	696	759	823	886	949	1013
47	592	658	724	790	856	922	987	1053
48	615	684	752	820	889	957	1025	1094
49	638	709	780	851	922	992	1063	1134
50	661	734	808	881	954	1028	1101	1175
52	706	785	863	942	1020	1099	1177	1256
54	752	835	919	1003	1086	1170	1253	1337
56	797	886	975	1063	1152	1241	1329	1418
58	843	937	1030	1124	1218	1311	1405	1499
60	889	987	1086	1185	1284	1382	1481	1580
70	1116	1241	1365	1489	1613	1737	1861	1985
80	1344	1494	1643	1792	1942	2091	2241	2390
90	1572	1747	1922	2096	2271	2446	2620	2795
100	1800	2000	2200	2400	2600	2800	3000	3200

NOTES

Appendix G: Software Tools for Gas Blending

The best way to plan a blending station can is through the use of software tools. NS Research has developed a suite of such tools which are particularly useful for everyone that is involved in training on this topic.

Software Programs

The software suite includes the following:

1. **Sizing of air banks:** Extremely valuable program. Air banks are very important in planning the layout of your blending station. But what size of air bank? This is something that often is done arbitrarily. The software application looks at the operational requirements of the dive facility, and gives the best options for air bank size and compressor size. The program is graphical and also allows the user to see the bank pressure after successive fills, as well as to see when the compressor is turning on or off if it is in full auto mode.

2. **Calculating oxygen requirements and best utilization of oxygen:** Imagine the situation where we are going on an expedition on a live-aboard, taking 12 divers out for five diving days, three dives per day on nitrox. How many O_2 cylinders should we take on board? With this software tool, the question can be answered in seconds, and at the same time enable the user to visualize how oxygen is being consumed. Best utilization suggestions are also made.

3. **Schematic layout of blending station and business evaluation:** This software tool allows the user to plan the layout of a blending station with any gas production method he wishes, and presents a complete business evaluation giving cost of filling a nitrox cylinder with a complete breakdown of all cost elements. Payback period and return on investment also is calculated based on the user inputs.

4. **Simple blending calculator:** This software utility simply asks the initial mix and calculates the fill pressures. The beauty of this program is its simplicity.

5. **Compressibility factors calculation:** This is a highly scientific program that uses our thermodynamic models to predict compressibility factors of gases. Compressibility factors are complex functions of both temperature and pressure, and are different for each gas. The program gives values with an error of less than 0.000001 compared to experimental values. Extremely useful to engineers and technically minded users.

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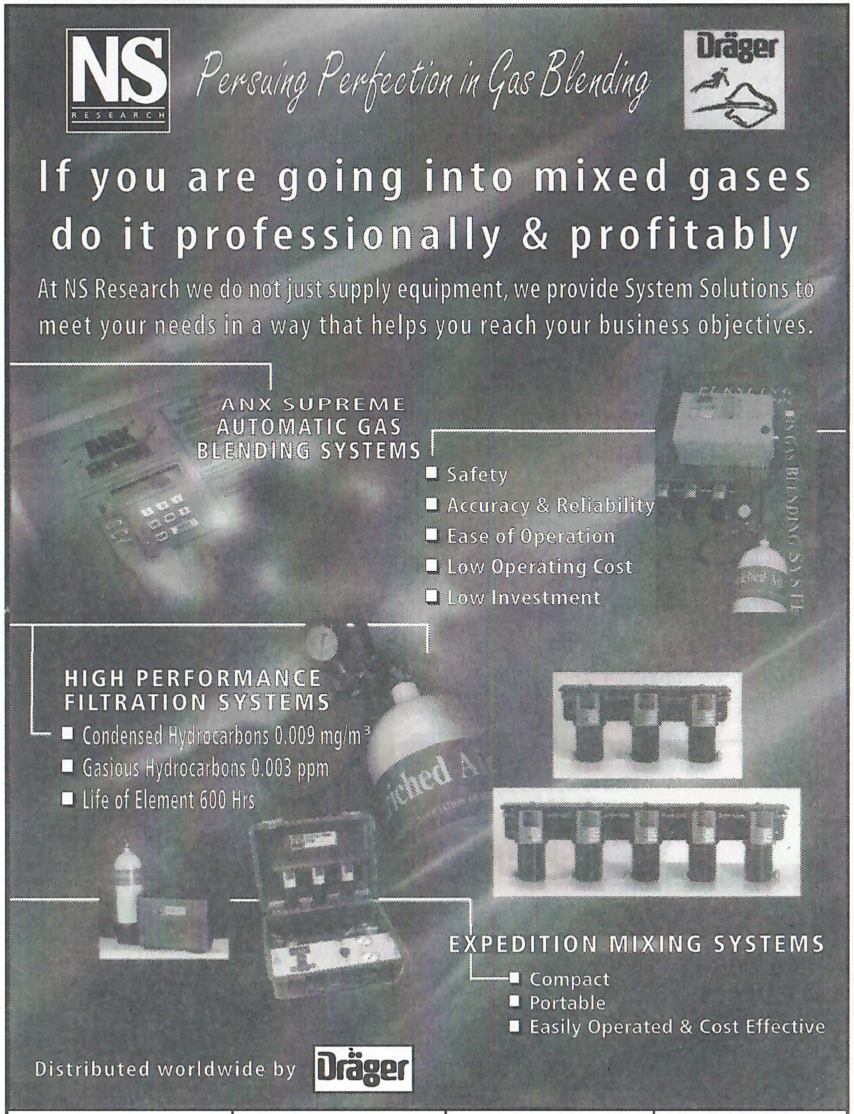

The Technical Guide to Gas Blending is an authoritative, insightful text that explores and explains all aspects of gas blending in a logical, business-oriented way. Several training agencies today offer gas blending courses; however, most of them have a narrow focus on the mechanics of partial pressure mixing. This book covers an important gap in the subject. The author, a pioneer in gas blending technologies and a manufacturing engineer by profession, acknowledges the fact that the selection, organization, planning, and operation of your mixed gas station can have a significant impact on your business. This book will help you :

- Evaluate and select the most appropriate blending method for your operation
- Plan and execute the layout of your blending station
- Prepare the equipment and understand all issues of equipment interaction
- Do logistics planning
- Produce and dispense mixed gas safely

The author takes a scientific approach in every topic, explaining the subject matter from the first principles. Long-standing, erroneous assumptions are challenged and critical thinking is encouraged throughout the text.

"Every instructor worth his salt should get hold of this book — and read it!" – Kevin Denlay, Australia

"For someone who has been mixing gas for so many years, it is hard to believe that one can learn so much from a book on gas blending. Readers will be amazed!" – Michael Lim, Director TDI Asia

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