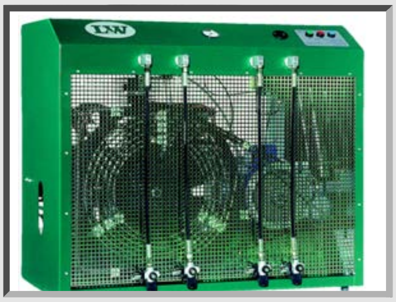
Compressors & Nitrox Installations



Compressors

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Compressors & Nitrox Installations
Scuba Publications – Daniela Goldstein
Jan Oldenhuizing

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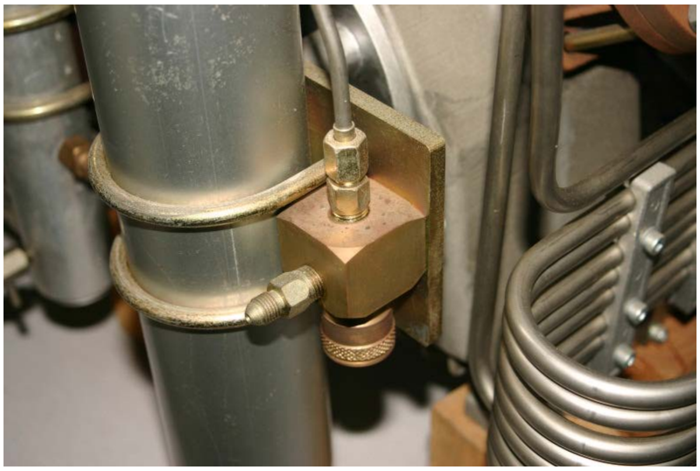
Introduction

Compressor Handling and Nitrox Installations covers a subject that is considered required knowledge for divers at higher certification levels. However, the subject is hardly documented in publications available to those divers. This books intent is to make important concepts and principles available to all who want or need to know more about this subject. Compressors (and the attached Nitrox Installation) can be considered the heart of any diving operation. If the compressor does not work, no more dives can be made.



If you do not operate a compressor yourself, then knowledge about the subject will allow you to improve the safety of diving activities. Pure air and correct Nitrox mixtures are important for the safety of every dive. Knowledge of the equipment that is used to fill diving cylinders provides the understanding that is needed to identify signs that indicate possible problems during the filling process. In addition to safety considerations, the subject is simply interesting.

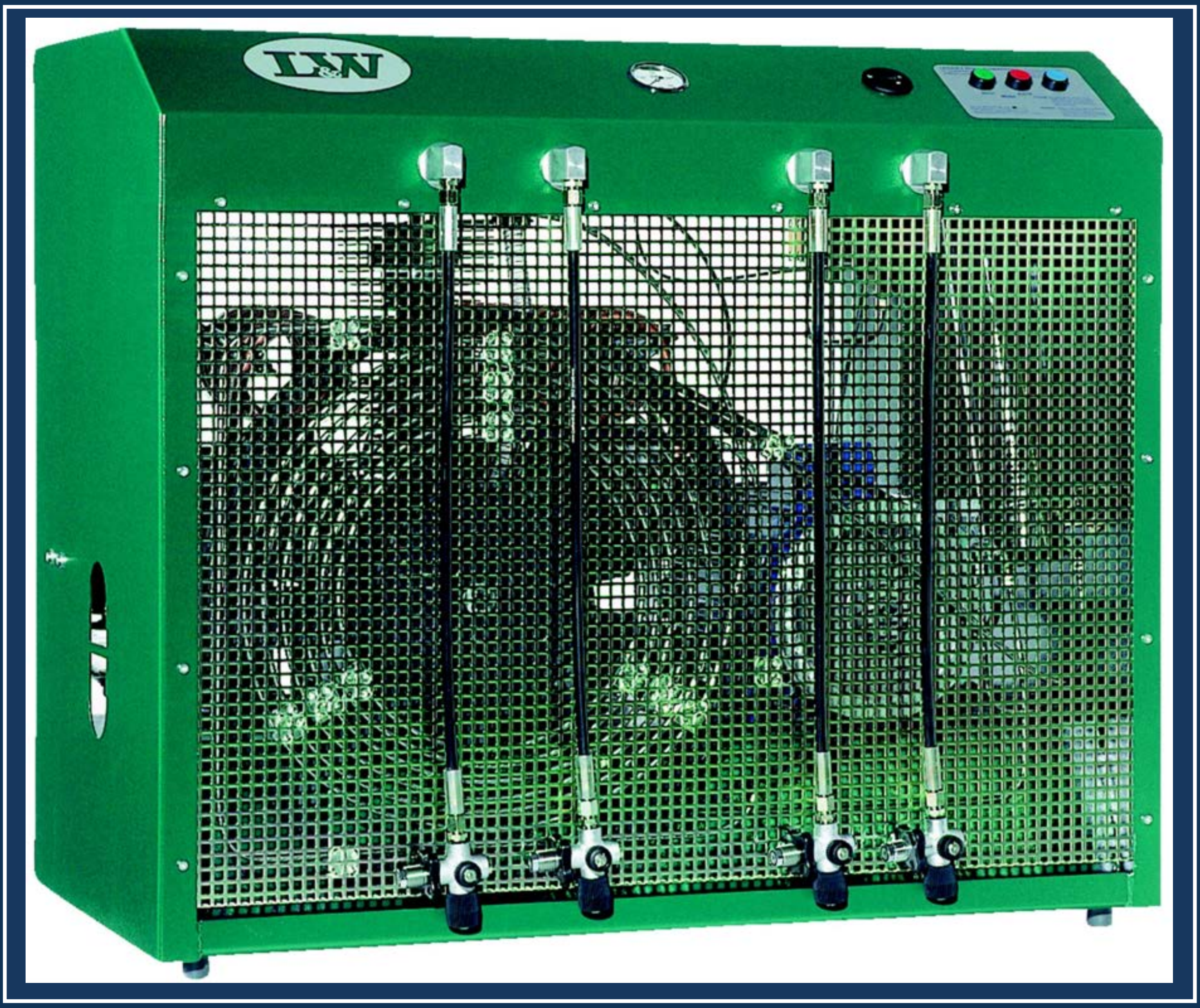
To aid the understanding of the working principles, certain repair and adjustment procedures for compressors are explained throughout this book. This is NOT done with the intent to train you for maintenance and repair of compressors. All after sales service and repairs to compressors, as well as nitrox installations, must be done by a factory trained repair technician. Only these people have the proper tools and spare parts available, are aware of recent spare part changes and recalls and have the handbooks and protocols available for the individual components of the system. Unauthorized manipulations to compressors and nitrox installations can result in a loss of warranty and can transfer the factory liability to the person who manipulated the equipment.

Simply reading a book will not allow you to develop a complete understanding of the subject. This book was written to be used in combination with a compressor handling course taught by a diving instructor. The instructor will help you to understand all aspects covered in this book and will show you practical examples of the items discussed.

Compressors

Compressors are part of a filling installation. This chapter covers the compressor and the directly related parts. The engine, filling ramp, air banks and other parts are the subject of the next chapter.

First the most common types of compressors are introduced. For each of them the key characteristics are explained. The chapter then continues with the individual parts of the compressor and their function. It will soon become clear that a desire to fill big quantities of air at a pressure of 200 or 300 bars is not possible without consequences for the temperature and humidity of the air. Many of the parts of a compressor are not meant to increase pressure, but to solve problems with temperature and humidity.



Rotation vs. Axial Movement

In a combustion engine, timed “explosions” force a piston (the grey part in the drawing) up and down in a cylinder. The resulting axial movement is transferred via the connection rod (the blue part in the drawing) to the crankshaft (the green part in the drawing). The connection rod is connected in such a way (away from the centre of rotation) that the axial movement from the piston becomes a rotation. This rotating movement is then transferred via different mechanisms to make the wheels of a car turn.

A compressor has the same parts, but works the other way around. Rotation is provided by a combustion or electrical engine. This rotation is transferred to the crankshaft. Via the connection rod, the movement forces a piston up and down, altering repeatedly the volume in a cylinder. When the piston is pushed up, the volume in the cylinder is reduced and pressure increases. Valves allow the compressed air to flow out of the cylinder and allow new air to flow in for a next compression cycle.

Divers want their cylinders filled at pressures ranging from 200 to 300 bars. If that pressure is to be achieved by a single cylinder, a piston would have to move between its lowest and highest position to reduce the volume in the cylinder by a factor 200 or 300. Although that would theoretically be possible, it normally does not work that way. Most compressors in dive operations have either 3 or 4 cylinders. These cylinders are also referred to as stages.

Air enters the compressor at the first stage, where it is compressed to an intermediate pressure. The already compressed air is then compressed again in the second stage to a higher intermediate pressure. Only at the last stage of the compressor, the final pressure of 200 or 300 bars is reached. This might give the impression that the air is compressed in steps. That air is only passed on from one cylinder to the next after it is compressed to a new intermediate value. This is not the case. You should imagine it as a continues process. One valve allows air to enter a cylinder while the piston is moving downward and closes when the piston starts moving up. At that moment another valve opens allowing the air to move toward the next location as soon as the pressure is higher than the pressure there. That valve closes again when the piston starts its downward movement.

T, W or X

Most compressors used in recreational diving are from the T, W or X type. There are other models, but they are more seldom. Once you understand the functioning of the most common models, it is easy to apply what you have learned to other types.

The T, W and X refer to the position of the cylinders. In a T-compressor, the first stage is positioned on top of the compressor and the second and third stage horizontally at the sides. A W-compressor also

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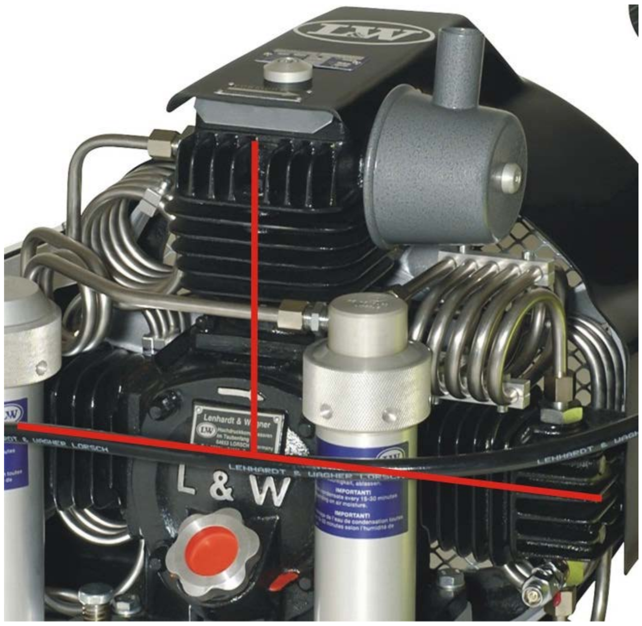
TWX

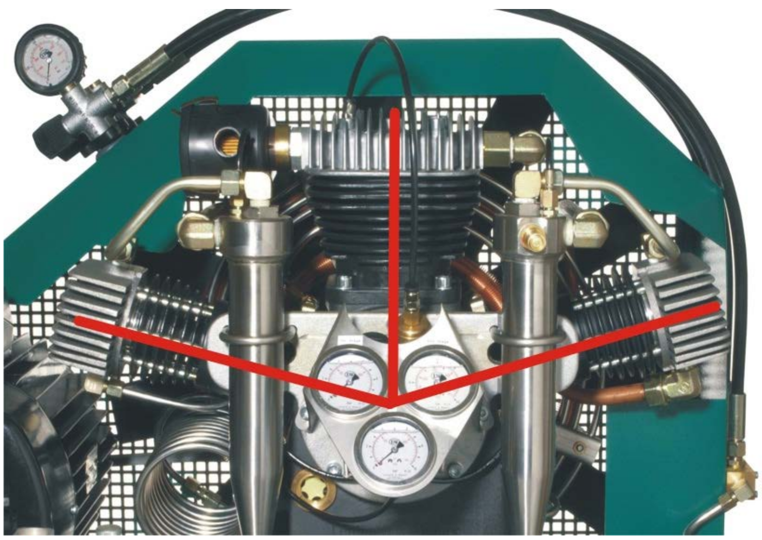
has 3 cylinders. The difference is that the second and the third stage are placed under a slightly upward angle. W-compressors are bigger than T-models. X-compressors have four cylinders, which are mounted in the shape of an X.



T-shaped compressors have a 90° angle between the first stage on the top and the two horizontally mounted cylinders on the sides. T-shaped compressors are meant for personal use. They are small and filling a single cylinder can take as long as 20 minutes. Divers who travel to remote areas use this type of compressor to fill their own cylinders.

The main problem with these compressors is the lubrication. The compressor does not have an oil-pump or another efficient mechanism to distribute the oil while filling. It has a sort of spoon mounted on the crankshaft. Oil is spooned from the oil bin and drops are thrown toward cylinders and connection rods in order to lubricate them.

In order for this primitive lubrication mechanism to work, the crankshaft must turn at high speed. It is common that these models run at 2,500 rotations per minute. At this speed the compressor heats up fast. That problem, combined with poor lubrication leads to the advice to stop the compressor every half hour or so, to let it cool down before filling a next cylinder.



W-compressors also have 3 cylinders, but are equipped with a more reliable mechanisms for lubrication. They turn at about half the speed of T-type compressors. Lubrication can be achieve by either an oil-pump, or mechanisms that make use of piston movement to distribute the oil in such a way that it gets in contact with all the moving parts.

Most W-compressors can fill an entire day without any pause for cooling. This makes them suitable for commercial use. An average compressor of this type needs about 8 to 10 minutes for filling a cylinder. T-compressors are mostly portable with a weight of less than 50kg. W-compressors mostly weigh more than 100kg.

X-type compressors have four cylinders mounted in the shape of an X. They can compress more air in less time and are used by bigger dive centres. Ambient air enters the compressor at the first stage

which can be identified by the air-filter that is mounted on, or to it. The size of the air filter gives an impression of the filling speed of that specific compressor, The bigger the air filter, the faster the compressor fills a cylinder. The second stage is found opposite of the first stage. The third stage points downward on the other side of the compressor and the fourth (and final) stage is mounted opposite the third stage.

Having four cylinders gives some advantages. The compression (from ambient pressure up to 200 or 300 bars) now goes in four steps, rather than three. In a three stage compressor, typical compression steps are:

1 bar à 7 bars à 48 bars à 220/330 bars

In a four stage compressor, this could be:

1 bar à 3.5 bars à 17 bars à 67 bars à 220/330 bars

The pressure ratio between two subsequent cylinders is thus reduced to about half of what it is in a three stage compressor. This leads to a substantial reduction in noise and reduces wear on the valves and other moving parts. Another important aspect of a lower pressure ratio between subsequent cylinders is that the increase in the temperature of the air will be less. Keeping the temperature of the air in the compressor low is important for several issues related to compressing air, which will be discussed later.

The final filling pressure is not defined by the compressor. Virtually all compressors can be used to fill either 200 bars or 300 bars cylinders. As a matter of fact, a compressor can compress air to far higher pressures and must be equipped with a (final pressure) safety valve to prevent the compressor from "damaging" itself. The "final pressure safety valve" defines the pressure to which diving cylinders can be filled.

Because of the important function of this safety valve, it is sealed by the manufacturer. If the valve malfunctions, it is not repaired on-site, but replaced with another sealed valve. In most cases the damaged safety valve can be returned to the manufacturer for repair and sealing.

A compressor can thus be used for either 200 or 300 bars. This is not the case for all equipment following after the compressor. The filter housing, conduits, filling ramp, air banks and filling hoses must all be rated for the pressure at which a compressor is used. The fact that the compressor itself can handle a higher pressure, does not automatically imply that other items that were delivered with that compressor allow you to replace the final pressure safety valve for another rated for a higher pressure. Consult with the manufacturer.

Temperature and Humidity

You cannot increase the pressure of a gas without increasing the temperature as well. As we have seen before, this problem is bigger in a three stage compressor than in a four stage compressor. However, it is a fact that increasing temperature is a major concern for all compressors. Other concerns will be addressed later, but before starting on how compressors work and explaining the function of the individual parts, we have to be aware of the effect of temperature on humidity.

100% humidity at sea level	
Degrees Celsius	Grams of water per kilogram of air for 100% humidity
50°	88.12 grams
40°	49.81 grams
30°	27.69 grams
20°	14.85 grams
10°	7.76 grams
0°	3.84 grams

The amount of water in the air is expressed as humidity in a percentage. 100% humidity indicates that the amount of water in the air is at its maximum. Any water in excess of 100% will condensate and become liquid water. Liquid water is non-compressible. If moisture condensates in a cylinder of the compressor, the compressor is at risk. If piston (upward) movement is blocked by liquid water in the cylinder, the piston itself can be damaged, the cylinder head can be pushed off, or the connection rod and crankshaft will be damaged.

It is thus important to keep the humidity of the air within the compressor below 100%. Humidity hardly depends on the density of the air. It does depend on temperature. That is – the amount of water in the air that corresponds to 100% humidity does not vary much when the density of the air is changed, but changes substantially with a change in temperature (see the table).

You should already be familiar with this. If you place a cold drink on the table on a warm summer day, water from the air starts to condensate against the outside of the glass. The air close to the glass is cooled by the drink. At a lower temperature the same amount of moisture in the air now exceeds 100% humidity. The same principle applies to regulators. Many divers opt for a metal or carbon second stage because warm exhaled air is cooled against the colder inside wall of the second stage. Contact with the colder wall condensates part of the moisture. That moisture is inhaled with the next breath. Divers with metal or carbon (good heat conductors) second stages are thus less affected by a dry mouth during a dive.

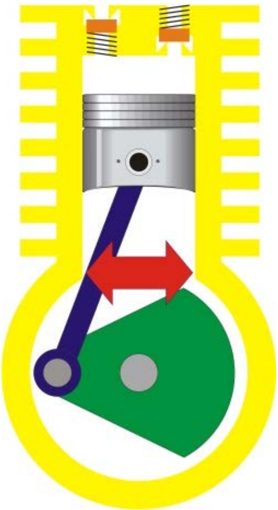
In a compressor, two events take place, which counteract each other. The air is compressed, resulting in the same amount of water now occupying a smaller volume. This increases the humidity. At the same time the temperature rises, which decreases the humidity. As a consequence, there are no humidity problems to be expected in the first and second stage of the compressor. Let's assume that we have a three stage compressor and that we fill cylinders at an ambient temperature of 10° Celsius with a humidity of 50%. As explained before, the first stage in such a compressor reduces the volume by a factor 7. This would increase the humidity to 350%, which would result in condensation.

At the same time the temperature increases. Air of 10° Celsius at 50% humidity would hold 3.88 gram of water per kg of dry air (7.76 divided by 2). If the temperature of the air would rise to 50° Celsius, 3.88 gram of water would (at the same pressure) reduce the humidity to less than 5% (see the table on humidity). Thanks to an increase in temperature, the humidity thus actually decreases (air of less than 5% humidity compressed by a factor 7 would bring the humidity to a value below 35%. This is lower than the humidity of the ambient air in this example). In reality, the increase in temperature is even higher. The calculations given here are simplifications to make you aware of the problem. The values and calculations are not suitable to work out "real" problems.

As the air progresses through the next stages of compression, the reduction in volume continues. The rise in temperature is limited. The benefit of increasing temperature to counteract the reduction of volume is an "advantage" that only applies to the first and second stage of the compressor. Before passing the air from the second stage to the next stages, water must be removed from the air. If this would not be done, the compressor could be damaged beyond repair. Starting from the next page, the different parts of a compressor are explained and discussed. Temperature, safety, but especially humidity, are the reason why a compressor has more parts than would be needed to increase the pressure of the ambient air.

Decreasing Volume and the Shape of Pistons

In a car engine, all cylinders and pistons have the same size and shape. By now it should have become clear that this cannot be the case in a compressor. As air passes from one stage to the next, the space that is available for the air has to decrease. If the next cylinder would have the same size as the previous one, the air that has just been compressed would expand and fall to ambient pressure. The maximum volume of a next cylinder (piston in the down position) should be more or less the same size as the minimum volume (piston in the up position) of the cylinder from which it receives the air that is compressed to an intermediate pressure.

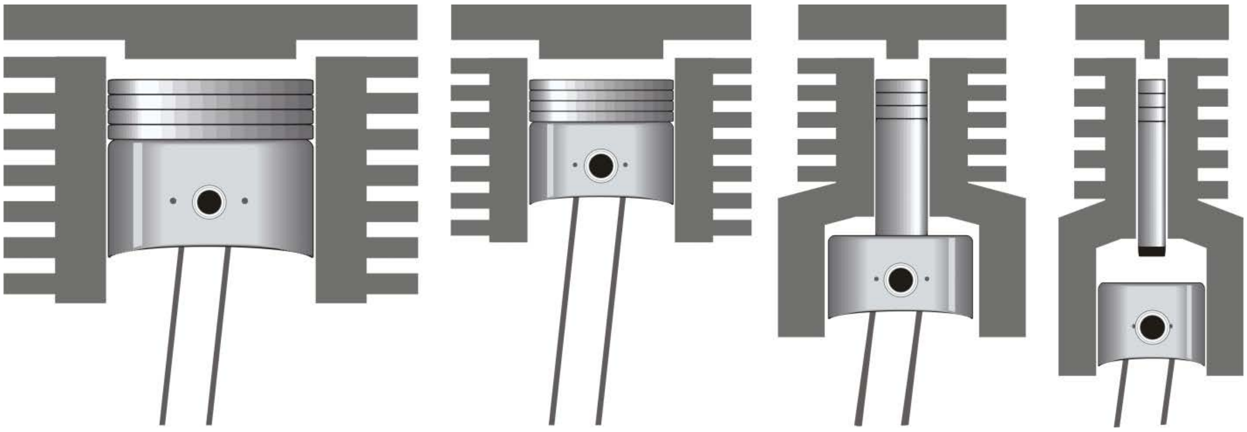


The size of the cylinders varies substantially. The piston in the fourth stage (on the left) is just the bright part in the middle. Compare that diameter with the first stage on the right.

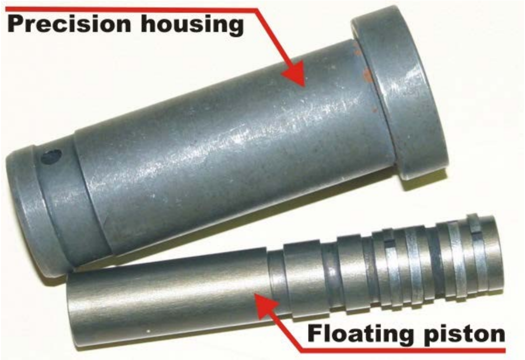
The decreasing volume of subsequent cylinders requires a smaller diameter. This leads to a problem for the construction of a compressor. The rotation of the crankshaft results in a left to right swinging movement for the connection rod while it transfers the up and down (axial) movement to the piston. The diameter of the cylinder must allow for this “swing” of the connection rod. This requires the diameter to be sufficiently large.

With decreasing diameter of the piston, it gets harder to provide the space needed for the “swing” of the connection rod. To solve this problem, compressors are equipped with different shapes of pistons. Some of these pistons are unique for compressors. They are not found in engines. Initially, the diameter of the piston allows for a normal piston. That is the same model as found in cars and other engines. Depending on the size of the compressor, the second piston diameter might still allow enough space for a normal piston. In T or W-compressors this is not often the case.

A first option to overcome a problem with the diameter is a “stage piston”. This is a piston that has a smaller diameter on top than for the lower part of the piston. This solution will work only up to a certain diameter. The upper part of the piston can hardly make any sideward movement. The piston has to “seal” with the cylinder walls to prevent compressed air from seeping to the oil bin of the compressor. The lower part however is affected by the swing of the connection rod. Swing causes strain on the metal at the location where the diameter changes. Imagine bending metal wire repeatedly. At some point it will break. If the diameter of the smaller part of the piston gets so thin that the forces in the compressor can cause bending, the piston will break.



A floating piston is an elegant solution for this problem. You could imagine a floating piston to be a stage piston that is broken on purpose during manufacturing. The floating piston is pushed upward by a guiding piston. The pressure in the cylinder, above the piston, will than push it back down when the guiding piston moves down. Although the guiding piston and the floating piston are not attached to each other, they stay in contact during all upward and downward movement. Permanent contact is possible under the condition that the pressure in the cylinder is high enough to push the piston down.



The pressure needed to push the guiding piston down is absent when the compressor is just started. The air entering the first stage will need some cycles before it arrives (at high pressure) in the last stage of the compressor. The cylinder with the floating piston. This results in the typical sound of a compressor when being started – tak-a-tak-a-tak-a-tak-rrrrrrrrrrrrrrrrrrrrrrrrrrrrr. Before the compressor starts running smooth, there is a period in which the guiding piston is tapping on the floating piston when moving up, but the floating piston does not move down with the guiding piston. The moment the sound of the compressor changes indicates when there is enough pressure above the floating piston to bring it in permanent contact with the guiding piston.

The seal between a piston and its cylinder is achieved with piston rings. Three or more rings around the piston trap an oil film between them. The combination of the rings and the oil film prevents the high pressure air from escaping from the cylinder. Small quantities of air seep through (maybe 5 to 10%), but the bulk of the air stays in the circuit where it is supposed to be and passes from one cylinder to the next.

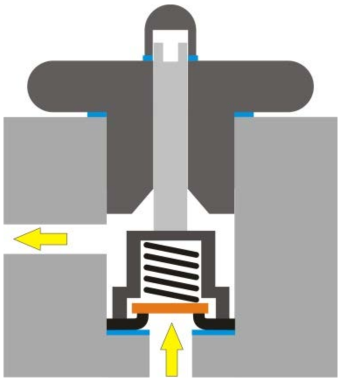
Not all floating pistons are equipped with piston rings (normal pistons and stage pistons are). If a floating piston is not equipped with piston rings, there needs to be another system in place to prevent the oil from being pushed toward the oil bin. The solution for that problem is an oil-injector. Such an injector receives oil from the oil pump, but holds it back until the pressure of the oil is around 60 bars. That pressure is high enough to push a spring aside, which opens a passage to the side of the floating piston (the mechanism resembles a first stage of a piston diving regulator). The injected oil thus has a pressure which is between the highest pressure in the last stage of the compressor (200 or 300 bars) and the pressure at which the air enters that cylinder. This makes the injected oil move up and down several times before being replaced with new oil.

Inlet Valves and Outlet Valves

The valves that allow the air to flow in and out of the cylinder are located in the cylinder head. In many cases, the inlet valve is mounted on the inside and the outlet valve on the outside. **In**let/**in**side and **out**let/**out**side. The size of the valves varies, depending if it is a first stage of the compressor, or a later (and smaller) stage.

A small and weak spring holds a metal valve against a metal seat. Even slight piston movement is enough to overcome the force of the spring. When the piston starts to move downward, the inlet valve opens practically at the same moment. The same goes for the outlet valve that opens the moment the piston starts moving up. When one valve is in the open position, the other is closed, depending if the piston moves up or down.

In the drawing, the same parts are shown as in the picture. A spring pushes the valve (orange part) against the seat. All other parts have a role for the air integrity of the valve. The seat is pushed against a cupper washer (the blue part) by the four arms of the spring holder. The spring holder is kept in place by the main nut, which in turn is sealed in the cylinder head by its own washer. A screw through the top of the main nut allows extra tension on the spring holder in order to push the seat firmly against its washer. Once the tension is maximized, the screw is sealed with a nut that has its own washer to assure air integrity. When the piston moves upward, the increase in pressure pushes the valve away from the seat and air can escape to the left. From there it flows to the next cylinder.



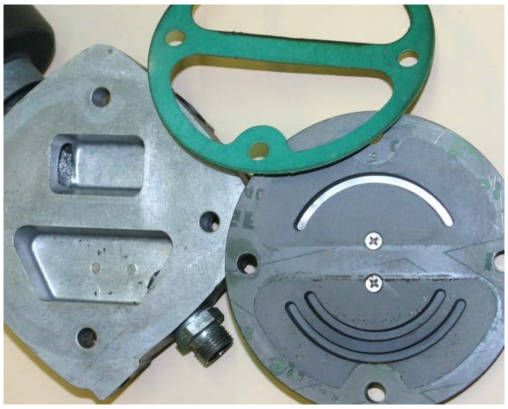
If an outlet valve is malfunctioning, in most cases that is because the seat has cut through the valve (as shown on the picture). In that case the valve and washer (the two parts at the right) must be replaced.

Not all brands have outlet valves that can be disassembled in individual parts. In some, the outlet valve is a single piece in which all the individual parts are assembled. The assembly is then sealed. If the outlet valve can be disassembled, only replacing the small valve and the cupper washer would repair the compressor. If the outlet valve is a single piece, the entire valve must be replaced.

The cost of an entire valve to be replaced is compensated by ease with which it is done. You have seen that the cylinders of a compressor (and thus the cylinder heads) are mounted at an angle. In order to assemble an outlet valve, the cylinder head must be in a horizontal position. This will require the cylinder head to be removed from the cylinder and to be replaced once the valve is repaired. If the valve is a single piece, it can be replaced at any angle, which makes the procedure faster and easier. For most compressors, the small inlet and outlet valves of the last stage (the cylinder with the floating piston) are a single piece.

The construction of the inlet valve is simpler. The reason for that is its position inside the cylinder head. The pressure in the cylinder assists in pushing the seat against its cupper washer. A complex mechanism to increase tension is thus less necessary. The parts of a second stage inlet valve, including the special tool needed for assembly and disassembly, are shown in the picture.

The washer is put in place first, followed by the seat, with the sharp edge in the direction of the valve which follows next. The spring is placed in the housing and then screwed in position in the cylinder head to keep all parts in place. If the housing is not level with the cylinder head, this indicates that the valve has moved out of position and that the procedure must be repeated. The size of the different cylinders, and thus the cylinder head, varies substantially. The available space for the valves is thus also different.



The first stage has bigger valves. In older compressors, this would simply be an upsized version of the valves shown in the previous pictures. Newer compressors are equipped with a different solution. A laminated plate holds both the passage for the air flowing into the cylinder and for flowing out. The valves are identical, but are mounted in the opposite direction. The laminated plate with valves is simply mounted between the cylinder and the cylinder head. In the picture you see a laminated plate (right) which holds both the inlet and the outlet valve for the first stage of modern compressors. Air integrity is assured by adding sealing material (top).

Older compressors have an outlet valve on the last stage that is screwed into the cylinder head. This solution has been a cause of problems. The pressure passing through this valve is very high and there have been incidents with this type of valve. Today most compressors have a double cylinder head for the last stage. The first holds the valves and the second (with the same diameter) is placed on top to hold the outlet valve in place. A screw through the second cylinder head allows extra tension on the valve to assure air integrity. It has the same function as was seen with a similar screw for the second stage outlet valve. You can see that the lower cylinder head is functional, as it has the entry and exit for air fitted to it. The second cylinder head has no functional parts, other than the screw to increase tension on the outlet valve.

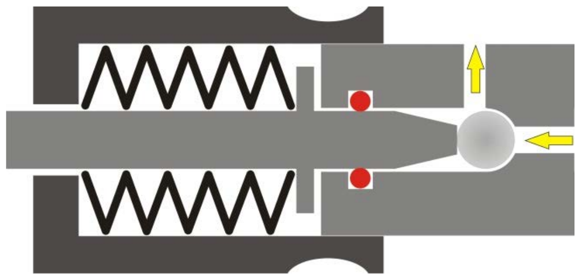
The Pressure Hold Valve

The pressure hold valve is essential for a correct functioning of a compressor. As discussed before, the floating piston depends on the pressure in the last stage of the compressor to stay in contact with its guiding piston. It was also discussed that the outlet valve opens the moment the piston starts moving up. If an empty cylinder were connected to the compressor, the last stage could not build-up the pressure needed to push the piston back down, as all air would immediately escape to the empty diving

cylinder. The compressor would not stop the tapping on the floating piston after starting (it would continue to make the typical tak-a-tak-a-tak-a-tak sound).

The pressure hold valve prevents this from happening. A spring loaded valve requires the pressure to increase to a value that can overcome the force of the spring. Only then the air can flow away from the compressor to the cylinder to be filled. A value for the spring load could be 120 bars.

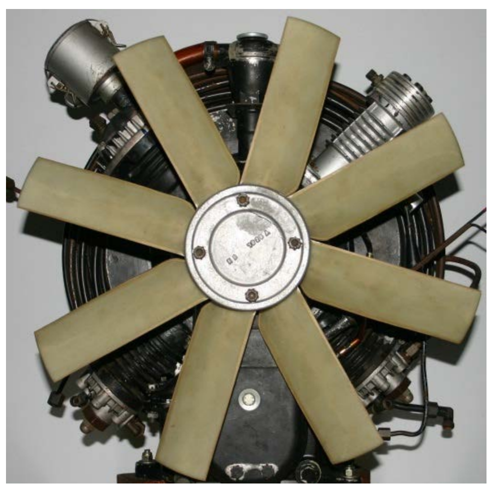
The pressure hold valve also performs three other desirable functions. After use it maintains the pressure in the compressor. This prevents moist air from entering the compressor. Moist air could cause corrosion. Some users "drain" the compressor after use, but that is not recommended. A compressor under pressure is sealed from the outside air.



The placement of the pressure hold valve results in another important function. The valve does not follow immediately after the last stage, but is placed after the chemical filter. When removing a diving cylinder from the filling hose, the hose needs to be purged. Purging lets the pressure return to ambient pressure and the purged volume becomes part of the workload for the next filling cycle. By placing the pressure hold valve after the chemical filter, it is prevented that the chemical filter is purged along with the hoses. This reduces the volume that must be pressurized again in the next filling cycle. The above does not apply if the filling hose is equipped with a purge that allows partial purging of only the part of the hose that is connected to the cylinder (for bigger compressors this is virtually always the case).

Also in that case, it is important that the pressure hold valve is placed after the filter. It ensures that the volume of air passing through the filter is small (air at 100 bars only occupies 1/100 of the space occupied by air at one bar). The smaller volume passes slower through the filter, which results in a longer and better contact between the filtering material and the air (and thus in better filtering).

Inter-Stage Cooling and Moisture Separation



The rotation of the compressor is used to blow air at ambient temperature over the compressor. Even in the warmest climates, the ambient air is a lot cooler than the temperature of the compressor. For a compressor, air at ambient temperature is "cool", even if for you it is hot. Compressors do have a maximum operating temperature, which could be something like 40°C. The air flow aids in convection cooling of the metal parts. Convection means that air in contact with warmer parts makes place for cooler air once it is heated up. Convection happens "naturally", because warmer air is lighter than cooler air, but is accelerated when air is blown over the compressor. Cooling is necessary to prevent the temperature in the compressor from getting too high while it passes from one compression step to the next. It is also necessary to assure adequate separation of the moisture in the air being compressed.

When the air flows from one cylinder to the next, it is passed through a cooling spiral to reduce the temperature of the air before the next compression step. The diameter of the conduits is big between the first and second stage, but is smaller between the later stages. As the air is more compressed it occupies less volume. The needed length of the cooling circuit is established when the machine is designed. It should be long enough to bring the temperature below 100°C in order to assure proper functioning of the separators (discussed below). In the separators, the moisture in the air must condensate to a liquid, but water at temperatures higher than 100°C will remain in a gaseous form (steam).

There is no separator between the first and the second stage of the compressor. The reason for that was explained in the chapter on “temperature and humidity”. A three stage compressor has two separators. The first is located between the second and the third stage, and then one after the third stage. A four stage compressor has three separators. Separators follow after the cooling spiral. The temperature of the air must first be reduced to approach 100°C.

There are three types of separators. The first type is called spray or nipple separator. Air enters a rod in the separator and is sprayed against the wall. Vapor condenses against the wall and drops down, while the dryer air is passed on to the next stage of the compressor via a rod that takes the air from high up in the separator. In order for the separator to work, the wall must be cooler than the air blown against it. A hole in the bottom of the separator is equipped with a valve that can be opened periodically to drain the collected moisture from the separator. The water is pushed through the hole at the bottom, much like clearing a diving mask. A disadvantage of this type of separator is that the air is always blown against the same spot. Although metal is a good heat conductor, there is some delay is equally distributing the heat.

The second type of separator is called a vortex separator. Essentially the function is the same as the nipple separator, but the air is sprayed around, rather than always being sprayed at the same spot. This aids in maintaining a cooler temperature of the separator wall. In some cases, cooling of the wall of the separator cannot keep up with the heating inside. In that case a solution must be found that is independent of the effectiveness of the cooling of the outside (the wall) of the separator.

If an increase in pressure results in an increase in temperature, then the opposite holds true as well. Provoking a drop in pressure can create a cooling effect and thus separation of water vapor. This is done with the use of a sintered filter that delays the passage of air. The air has to force its way through the filter, which leads to an increase in pressure. Once the air reaches the outer surface of the filter, the pressure drops. With the pressure also the temperature drops and separation of moisture takes place.

The moisture accumulates in the lower part of the separator and must be drained periodically. The manual for the compressor will indicate the exact intervals, which could be something like every half hour. If purging is forgotten and the separator fills up completely, the accumulated water will be sucked toward the next cylinder where it can damage the compressor beyond repair. The same type of damage would result if the end of the hose that leads the ambient air to the compressor inlet would fall in the water while the compressor is running.

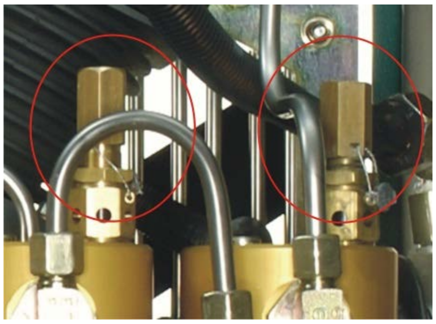
Water is non-compressible and when a liquid enters the cylinder, the piston cannot move all the way up. The connection rod will either force the crankshaft down, or the cylinder head will be forced up. In both cases, the damage to the compressor is substantial. For this reason most compressors are equipped with an installation to purge the separators automatically. The automatic purge for the separators works with an electronic magnetic valve. A timer opens the valve at set intervals. In some cases each separator has its own dedicated timer. In others the draining of subsequent separators is initiated by a pressure drop in the previous separator.

When the first separator purge is opened by the electronic timer that opens a magnetic valve, the liquid is removed via the bottom of the separator. During that action the pressure in the separator drops. The mechanical solution males use of that pressure drop (if not all separators have their own dedicated magnetic valve). A small piston closes the drain as long as the pressure is high enough to keep it in the down position.

The pressure of the first separator is lead to the piston that closes the drain of the second separator. When the pressure drops, the piston moves up, opening the way for draining the second separator. If there is a third separator (as would be the case in a four stage compressor), the pressure drop in the second separator is used in the same way to initiate the draining of the third separator.

There is no need to drain the filter periodically (it does not accumulate moisture in the bottom). The valve on the filter is meant to drain it of pressure when changing the filtering material. Pay attention though. In some cases a separator and the filter are combined in the same housing.

Safety Valves



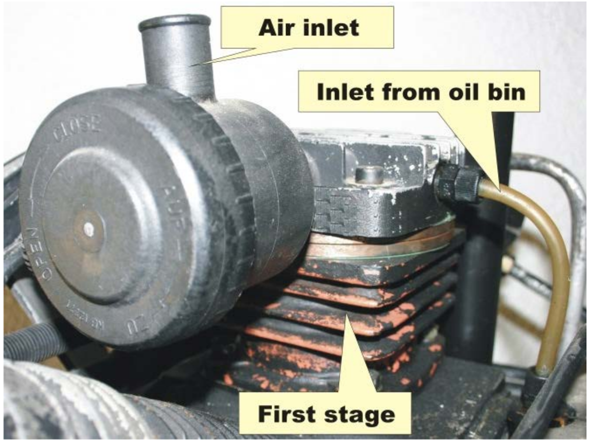
A compressor is equipped with safety valves for every step in which the pressure is increased. These valves not only increase safety, but are also an important diagnostic tool for a compressor technician. For example: after the first stage of a three stage compressor, a safety valve is mounted that is set to be activated (to open) at a pressure of 8 bars. The first stage increases ambient air pressure to a pressure of 7 bars, which is not enough to activate the safety valve. This makes it probable that air from the second compression step is flowing back in the direction of the first stage. The technician would then (as a first step) verify the air integrity of the inlet valve of the second stage when this safety valve is activated.

Although there is no rule that requires it, the placement of the safety valves is rather consistent along a wide range of makes and models. The safety valve for the pressure created by the first stage is often found on the cylinder head of the second stage (on the side where the air coming from the first stage enters the second stage). The safety valve for the second stage is located on the separator between the second and third stage. In a four stage compressor the same applies to the safety valve of the third stage (on the separator between the third and the fourth stage). The final pressure safety valve has no standard location, but is often combined with the final separator.

Optically, safety valves can look very different (compare the model to the right with the final pressure safety valve shown in the beginning of this book). The most probable location as described above can help you to identify the parts of a compressor.

Lubrication

The oil bin (the part in which the crankshaft is turning) is partly filled with oil. This oil has to be distributed to the moving parts of the compressor to reduce friction and to aid in cooling. There are different ways in which this can be done. Very small compressors (T-shaped) make use of a small spoon mounted on the crankshaft. It was already indicated that this solution requires an adequate rotation speed of the crankshaft. This results in a compressor that can only be used for shorter periods of time. Other solutions must both permit a slower speed and a more reliable distribution of the oil to the essential parts of the compressor.

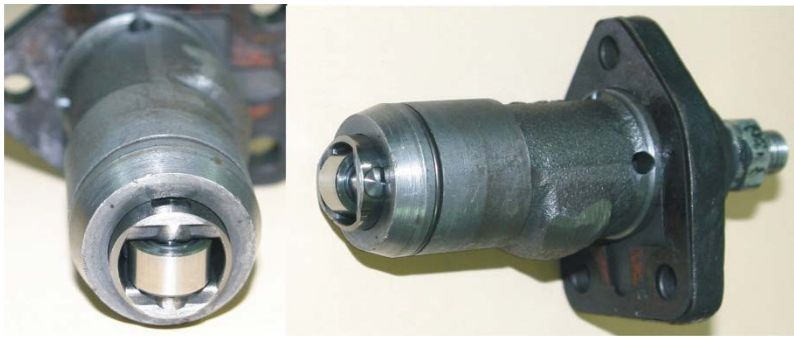


The first stage of a compressor is lubricated by purposely contaminating the air that enters the first stage with some air from its own oil bin. That air is contaminated with oil vapour. A liquid such as oil can only travel from high pressure to low pressure. Since the pressure in the cylinders is higher than the pressure in the oil bin, you cannot expect the oil to creep up between the cylinder and the piston. It has to enter from the top or it has to be injected at a pressure that is higher than the pressure in the cylinder when the piston is in the down position.

Lubrication from the top is easiest. I does bring the inconvenience that assuring breathing quality of the air requires full removal of oil residue once the air is pressurized (filtering will be discussed later). Two stroke engines use a similar technique. Oil is added to the fuel of the engine to lubricate the piston from the top. It was mentioned earlier that there is some loss of pressure because of air leaking past the piston rings toward the oil bin. This would increase the pressure in the oil bin and would cause air with oil to be pushed out of the bin. This could cause the outside of the compressor to become completely greasy. The intake from the oil bin directs air that seeped to the oil bin to enter the first stage. Lubrication and keeping the outside of the compressor clean thus go hand in hand.

As indicated before, there is no separator between the first and the second stage. Part of the oil vapour will travel unhindered to the second stage, which is thus also lubricated from the top in the same way as the first stage. The separator that follows after the second stage will remove some of the oil from the air passing through the compressor. The traces of oil in the water that is drained from separators give it its milky white colour. The white coloration of the water is an indication that the compressor is working correctly. Brown coloration of the water would indicate that the compressor is using too much oil, while clear water could be an indication that the compressor is running dry (without lubrication). Note that the coloration of the drained water changes with time. Verification should only take place while draining the separators.

Separation of humidity and oil vapour is only partial. Separators are not meant to achieve completely dry and oil-free air. This means that there is some transfer of oil-vapour to the third stage as well. For some models the amount could be sufficient to assure proper lubrication. Often it is not. This requires an alternate way to lubricate the later stages of the compressor. In some cases the movement of the piston is used to transport oil through a hose connecting the oil bin with the cylinder. This would not result in lubrication from the top. The oil could not be transported against the high pressure in the cylinder. The maximum that could be done is to bring the oil high enough in the cylinder to allow it to be picked up by the piston rings. The main purpose of this type of lubrication is thus not the friction between the piston and cylinder, but the moving parts below the piston.



Some compressors make use of an oil pump. The oil is pumped to the last stage of the compressor, where it is delivered to an oil regulator. Such a regulator resembles the first stage of a diving regulator. The passage of the oil into the cylinder is blocked by a piston that is held in that position by a (strong) spring. The oil pump continues pumping oil to the regulator, which increases the pressure. Only when the pressure is high enough to compress the spring in the regulator, the piston moves up allowing the oil to be injected between the (floating) piston and the cylinder. If the pressure of the oil has a value between the maximum (piston in up-position) and minimum (piston in down position) of the pressure in the last stage, most of the oil will be kept in place for effective lubrication of the last stage of the compressor. The regulator is set for such a value.

The oil pump is activated by the crankshaft. In a three stage compressor, this could be a rounded part sticking out on one side of the crankshaft. The oil pump is equipped with a small wheel that is pushed down every time the part of the crankshaft roles over it. Since the oil pump is mounted under oil level, this results in oil being pumped toward the oil regulator. A one-way valve prevents the oil from flowing back to the oil bin when the spring in the oil pump pushes the small wheel back out to be ready for the next pumping action.

The construction of an X-compressor requires that the movement of the crankshaft is used indirectly. The oil pump must be positioned under oil level. In many cases a chain transfers the rotation of the crankshaft to a second crankshaft, which is just meant for activating the oil pump. The floating piston on compressors with an oil-pump and oil-regulator in most cases has no piston rings. The piston is precision crafted and allows minimal space for the high pressure oil to creep slowly up and down.

The most important aspect of the lubrication of a compressor that you should remember is that the air is contaminated on purpose in order to allow for lubrication from the top. Since the separators only achieve partial removal of moisture and water vapour, the air must be filtered before it can fulfil the standards set for breathing quality of air. It also means that compressors must be cooled effectively. In some countries, there are requirements that the construction of a compressor must assure that the air in the cylinders does not get warmer than 160° Celsius. If the air (with oil vapour) would get too hot, the mixture could auto-ignite, resulting in the creation of carbon monoxide and carbon dioxide. This would not only pose a problem for meeting the standard for breathing quality of air, but could also be a risk for divers as carbon monoxide is a toxic gas.

Air Quality Standards

For air to be considered breathing quality, it must meet strict standards. The standards can vary from country to country, but normally address a minimum oxygen content and maximum level for oil (hydro carbons), carbon monoxide, carbon dioxide, and moisture. The requirements for the water content result in the dry mouth divers experience during their dives, but are necessary to prevent corrosion in diving cylinders. Countries where steel cylinders are common typically require lower moisture levels than countries where aluminium cylinders are used. There are also some variations in the oil (hydro carbon) content of the air. For air to be considered breathing quality, the oil content may be relatively high. If the air is mixed with pure oxygen, the higher levels may pose a risk for auto-ignition (and thus the creation of carbon-monoxide). These concerns have (in some countries) resulted in different requirements for breathing air and oxygen compatible air.

Standard	% O_2	CO_2 ml/m^3	CO ml/m^3	H_2O mg/m^3	Oil mg/m^3
DIN 3188	20.0 % - 21.0 %	800	30	25	0.3
EN 12021	21% - +/- 2%	500	15	25	0.5
CGA E-Grade	20.0 % - 22.0 %	500	10	67 Depending on use	5
Modified CGA E-Grade Tec 93	20.0 % - 22.0 %	500	2	67 Depending on use	0.1

For European compressors, the DIN (German Industrial Norm) 3188 used to be the norm of reference. In the manual of older compressors, you might find this norm to be mentioned as the standard to which the frequency for filter change is measured. Many other European countries did not have their own standards for breathing quality air and simply took reference to the German norm. This changed with the introduction of the European standard for air – the EN12021.

Leading European manufacturers consider the air meeting the EN12021 to be oxygen compatible. This means that there is only one norm for both filling cylinders with air and for Nitrox installations. In the United States, the situation is different. The standard for breathing quality air allows a rather high oil content (10 times higher than the European standard). This has brought concerns about the use of air of this quality to fill Nitrox. Those concerns where addressed during a Tec conference in 1993. Participating organizations agreed that a modified standard was needed for air being used in Nitrox installations. The result of this consensus was the “modified E-grade” (E-grade is the Compressed Gas Association designation for breathing quality air).

Analyses of the air quality can provide some information on the technical condition of the compressor. Reduced oxygen content, combined with elevated levels of carbon monoxide and carbon dioxide can indicate auto ignition inside the compressor (although the loss of oxygen to the burning process may be too low to be detected). High carbon dioxide and carbon monoxide without loss of oxygen may also indicate that the compressor inlet is too close to the exhaust of a combustion engine. That could be the engine that is used to provide rotation to the compressor.

High moisture and high oil indicate that the filter of the compressor is not working properly. This can be because the filtering material has not been replaced in time. It could also be that the air is passing the filter too fast (at too low a pressure) because of a problem with the pressure hold valve.

Filtering

Filtering starts before the air enters the first stage of the compressor. Connected to the first stage you will find a housing for an air filter, similar to the air filters found in cars. The size of the air filter is an indication for the filling speed of the compressor. The bigger the filter is, the more air can pass through (and be filtered) per unit of time. Normally compressors with big filters have a high filling speed.

Actually, filtering can already start before the air filter. In many cases a corrugated hose is connected to the air filter in order to bring air from a "cleaner and/or cooler" location to the compressor inlet. In that case a pre-filter will be added to the receiving side of the hose to prevent mosquitoes, leaves and other contaminations from entering the hose and ending up in the air filter.

The corrugated hose used to draw air from another location than where the compressor is running may not be too long. If a longer hose is fitted than the one that came with the compressor, it should be of a larger diameter to avoid an increased air-resistance.

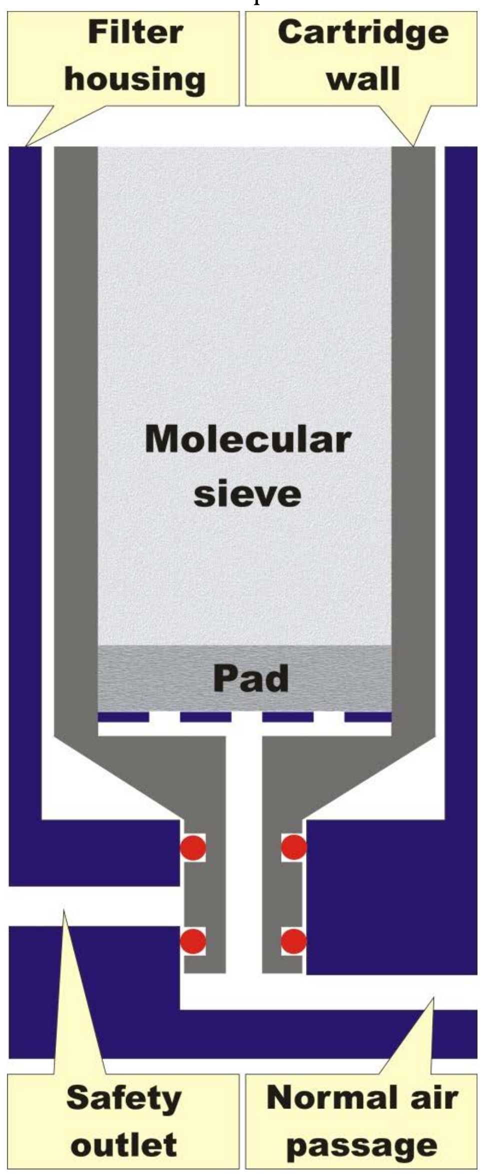
The assembly of pre-filter, corrugated hose and air filter does require some attention from the user. If any of these parts increase the resistance for the air to pass through, the compressor will draw air from where the resistance is lower. That could be the oil bin (and thus air contaminated with oil vapour). As covered before, there is always a certain fraction of the air drawn in from the oil bin. This is for the most part air that has seeped through between cylinders and pistons (maybe 5 to 10% of the total air volume).

A substantial increase in the fraction of the air that is pulled from the oil bin will result in higher quantities of oil passing through the compressor. This increases the risk for auto ignition (and thus the creation of carbon monoxide) and it will saturate the filter at the end of the system long before the filter is due for change. A good indication of a problem with the air resistance on the inlet is the coloration of the liquid from the separators.

As you can see on the picture of the housing for the air filter, air is always drawn through the same part of the filter. Many compressor users have made it a habit to use the same filter four times. When placing a new filter, they mark on which side the air inlet of the housing is located (along with the date). After a quarter of the duration specified in the handbook from the compressor, they turn the filter 90° to use another spot for the air to pass through. That procedure is repeated until the filter is back at the first mark and is thus used four times. Using the inlet filter in this way prevents an increase in resistance. Cleaning the pre-filter from time to time and paying attention that the corrugated hose is free of bends and other obstructions do the rest. Later we will cover considerations for Nitrox installations that take the position of the pre-filter. Similar considerations to prevent resistance on the air inlet of the compressor apply.

In between stages and immediately after the last stage of the compressor, the quality of the air is improved in a mechanical manner. This is the role of separators that were already discussed. After the last separator, chemical filters are used to improve the quality of the air to meet standards for breathing quality. If the compressor is used in accordance with the instructions for use, the manufacturer guarantees the quality of the air. The intervals for replacing filters are such that the manufacturer is sure that adequate filtering of the air will take place. To document that manufacturer recommendations have been followed, compressor users maintain a logbook in which actions such as filter changes are entered. This is the reason why compressors are equipped with an electronic counter that allows keeping track of the number of hours the compressor has been running.

Three substances are used in filters. These are molecular sieve, activated carbon and Hopcalite. Molecular sieve only removes moisture. The small white pellets have a structure that traps water molecules. Drying the air is mainly done to protect the diving cylinders against corrosion, but is also necessary to assure a proper functioning of the activated carbon. Activated carbon removes hydro carbons. That includes oil and other combustibles, but also aromatic hydro carbons, which have a circular structure. Aromatic hydrocarbons have been given that name because of the wide range of odours they produce. The activated carbon thus not only removes oil, but also neutralizes odours. Hopcalite is a catalyst for a reaction that changes carbon monoxide (CO) to become CO_2 (carbon dioxide). Although high levels of carbon dioxide do pose a problem, it is not as toxic as carbon monoxide is. Hopcalite is not a "standard" addition to air filters for compressors. As a matter of fact, its use is not widespread. Activated carbon and molecular sieve are used in virtually all compressors.



The filter housing has to withstand the final pressure at which the compressor is working (200 bar or 300 bar) and can thus be compared with a diving cylinder. The actual filtering material is filled in a cartridge that is placed in that housing. Single use cartridges are made of plastic or aluminum. Cartridges that are meant to be refilled by the user are mostly made from steel. Different manufacturers each have their own philosophy with respect to filter cartridges. Some require the use of factory filled cartridges, while others recommend that the user fills the cartridges.

There are different methods for placing the cartridge in the filter housing. One method provides for additional safety – that is – a method that prohibits filling cylinders when no filter is in place. To do this, the end of the filter has two O-rings (red in the drawing) that seal of a safety outlet connecting to the normal air passage. When a filter is in place, one O-ring above and one O-ring below the passage prevent air from escaping through the outlet. When no filter is in place (and thus no O-ring seal) the safety drain is the way of the least resistance for the air and all compressed air will escape, rather than being filled in the diving cylinder.

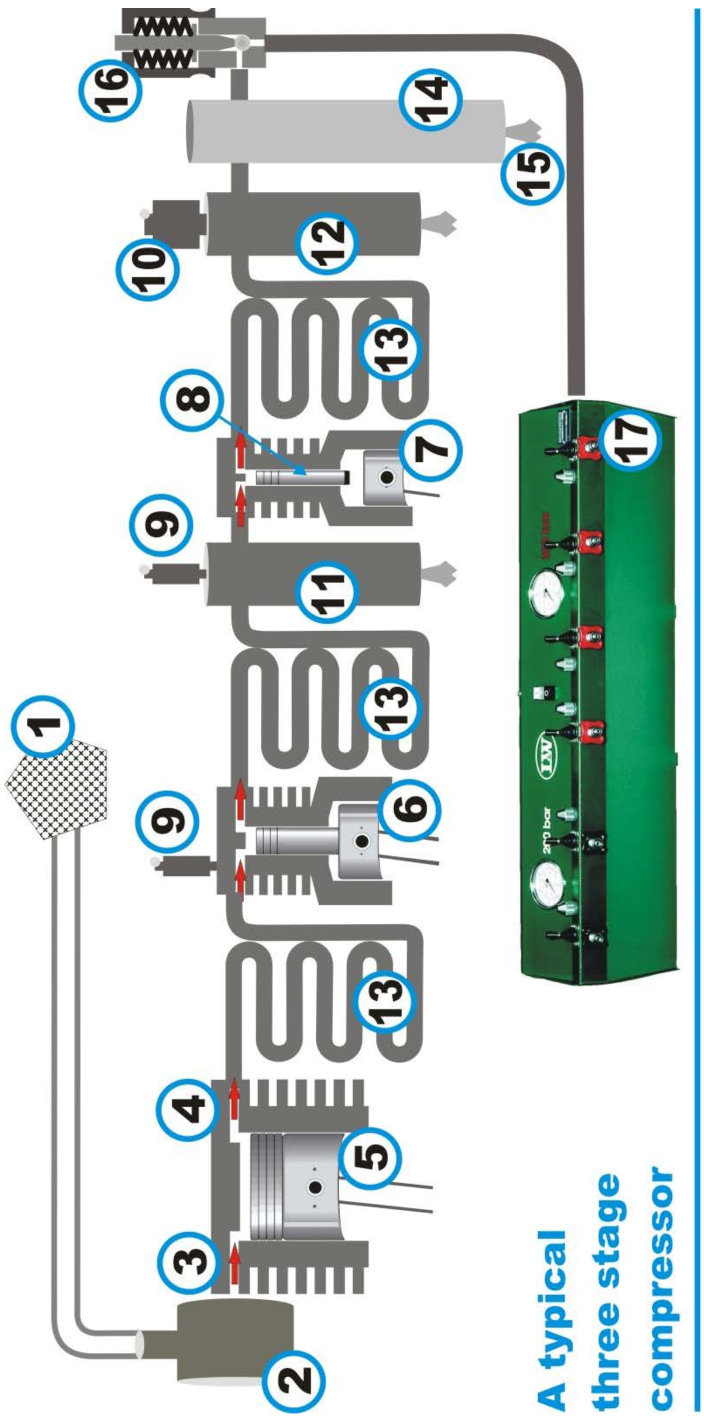
Many other filters have threads with which they are screwed in the lid of the filter housing. The advantage is the easy removal of a used filter. As it is connected to the lid, it is easily removed from the housing. This is not always the case for a cartridge that is sealed with O-rings in the bottom of the housing. The type of cartridge that is screwed in the lid does not prevent filling cylinders when no filtering material is in place.

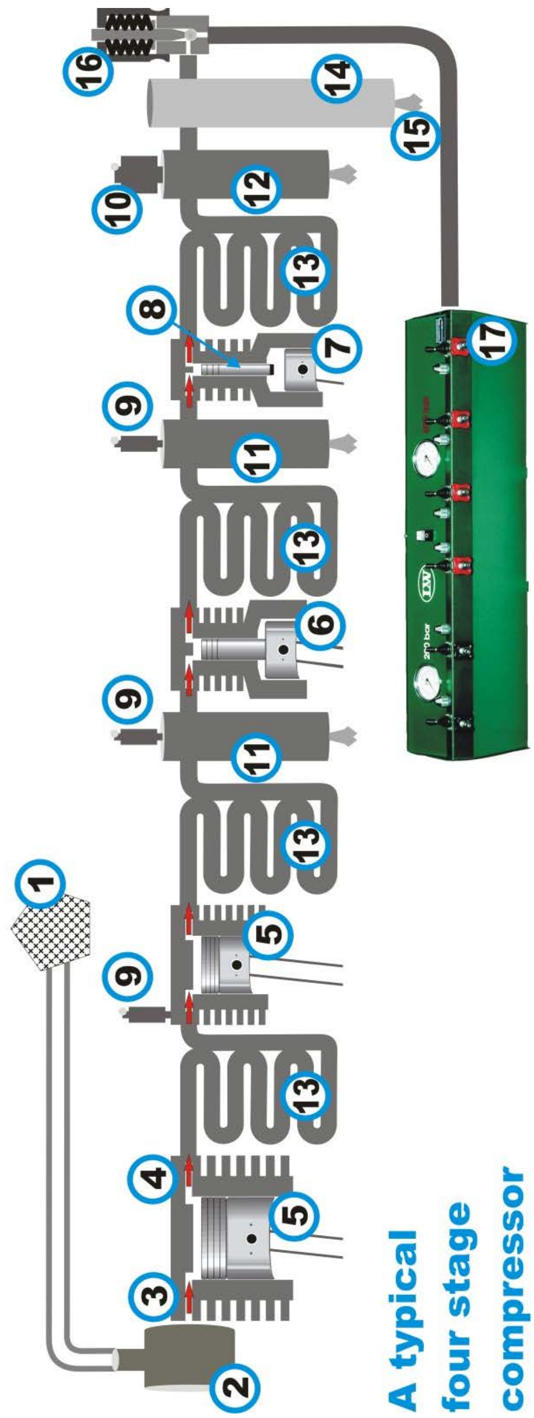
Regardless of the type, the housing for the filter cartridge must be drained of pressure before it is opened to replace a cartridge. Its position between the compressor and the pressure hold valve causes the filter to be pressurized all the time. To drain the filter, it is equipped with its own drain valve and in most cases a pressure gauge to verify proper draining.

In any case, filter cartridges have pads between the different filtering materials and on other locations. One reason for placing pads is to prevent loss of filtering materials via grids. Another is to prevent mixing between different filtering materials. The main reason is to prevent channelling. Channelling means that air passing through the filter creates a channel of least resistance. All air passing follows the same channel and only a part of the filtering material gets in contact with the air to be cleaned. As the duration of a filter is based on the total quantity of filtering material, channelling would result in an air quality that falls short of the standard for breathing air.

All Basic Parts Combined

With the discussion on filters, all "standard" parts of a compressor have been covered. Later some (optional) additions will be discussed, but it is now time to bring all the individual parts in relation. In the following drawings, all parts are placed in the order in which they are found in a compressor.





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The compressor parts in the drawings on the previous page		
Number	**Name**	**Function**
1	Pre-filter	A pre-filter is only used when a corrugated hose draws air from an area remote from the compressor. It is meant to prevent leaves, mosquitoes or other to pass through the corrugated hose and to end up in the air filter from the compressor.
2	Air filter	The air filter prevents dust and particles from being drawn in the first stage of the compressor. The filter requires attention because clogging of the filter can hamper proper compressor functioning.
3	Inlet valve	All cylinders are equipped with an inlet valve. The valve must open while the piston is moving down in order to let air enter. The inlet valve must close when the piston starts moving up.
4	Outlet valve	The outlet valve (on all cylinders) must be open while the piston is moving up in order to allow air to pass on to the next stage. The outlet valve must close when the piston starts moving down to prevent air from flowing back to the cylinder where it just came from.
5	Normal piston	The same type of piston as found in combustion engines.
6	Stage piston	A piston with two different diameters to provide space for the swinging movement from the connection rod, while at the same time allowing for a small diameter of the cylinder.
7	Guiding piston	The piston that pushes the floating piston up. The downward movement is caused by the pressure in the final stage and depends on the proper functioning of the pressure hold valve.
8	Floating piston	The floating piston is responsible for the typical starting sound of a compressor.
9	Intermediate pressure safety valve	Every compression stage has its own safety valve. Each valve has a "typical location" and is adapted to the pressure expected from the cylinder for which it is meant.
10	Final pressure safety valve	The final pressure valve defines if a compressor is meant for filling 200 or 300 bars cylinders. Its location can vary, but is mostly combined with the final separator.
11	Intermediate separator	There is mostly no separator between the first and second stage, but from that point on, a separator is needed to prevent condensation of water in the cylinders.
12	Final separator	The separator after the final stage is not meant to prevent condensation in the compressors cylinders, but should reduce the workload of the chemical filter by already removing some humidity and oil vapour.
13	Cooling spiral	After each compression step, the air must be cooled. Separators only work on temperatures lower than 100°C, which is the reason why the spiral comes before the separator.
14	Chemical filter	There are standards for pure air. Separators only provide partial removal of moisture and oil vapour, which is not enough to meet pure air standards. The chemical filter is a necessary addition for compressors that are used for diving.
15	Purge for the chemical filter	The chemical filter is "trapped" between the cylinder valves of the last stage of the compressor and the pressure hold valve. Pressure remaining in the filter after filling cannot escape. To change a filter purging is necessary, so the filter has its own purge to allow draining remaining pressure.
16	Pressure hold valve	The valve that allows the air to pass to the diving cylinder only when it has enough pressure to allow the floating piston to function correctly and to assure slow passage of the air through the filter.
17	Filling console	Not yet covered.

Accessories and selection

The subjects covered here are the logical continuation of the previous chapter. They include parts of the filling installation such as an air bank or filling ramp. These, and other, parts have not yet been covered. Another part will address optional equipment (such as automatic filter monitoring) that are often used, but are not part of the standard features of a filling installation.

The chapter is completed with a discussion of the procedures for filling cylinders and the considerations for the selection of a compressor for a diving operation or personal use.

Electronic Filter Monitoring

The activated carbon and molecular sieve in a filter need to be replaced in defined intervals. The duration of a filter can be defined in a number of hours the compressor is running, or a number of diving cylinders to be filled. The conditions under which a compressor is used can vary. In order to guarantee that the air from a compressor meets standards for breathing air, time based filter intervals must be based on "worst case scenarios".

Electronic filter monitoring allows taking the real conditions under which the compressor is functioning into account. In many cases this would mean that the same filter can be used longer, because the compressor is running under "good" conditions. The initial investment of adding the filter monitoring system would in time become economically valid. At the same time it provides some extra assurance of good air quality, because the inverse also holds true. If conditions are really bad, the filter monitoring system will ask for a replacement of filtering material sooner than normal.

In some cases, electronic filter monitoring can be connected to the engine from the compressor. If a filter change is due, the system can prohibit the engine from starting. That can be useful if the filling location and the location of the compressor are not the same or when many different people make use of the compressor. Because of the noise a compressor makes, dive stores place the compressor away from the location where clients are served. A distance of more than 30 meters between the compressor and the filling console is not an exception. Electronic functions that shut down the compressor, when proper functioning is not assured, can help to prevent problems in such set-ups.

A typical situation in which a bigger distance between the compressor and the location where the filling takes place is found is an outside filling station. In some countries these are very popular. It allows divers to fill their cylinders themselves whenever they want. Some use a system where each diver has a key to the box. Others are equipped with a payment system for coins or credit cards. You will not find filling options like these in all countries. Some countries require every compressor-user to have formal training, which cannot be controlled with outside filling stations.

Compressor Cooling

In order for the inter stage cooling and the separators to work properly, the entire compressor must be kept relatively cool. A common standard to prevent problems with the oil vapour in the cylinders is to keep the temperature of the air in the compressor under 160° Celsius. This requires a relatively cool ambient temperature and results in a "maximum operational temperature" for individual compressor models. Above that temperature, the manufacturer is not sure that the temperature inside the circuit can be kept under the threshold.

The ambient temperature is not the only consideration. The compressor must be placed in a location that provides adequate arrival of cool air – or better – adequate evacuation of air already heated by the compressor. The room in which the compressor runs must be large enough and the compressor should not be placed too close against a wall.

As warm air moves up, while colder air stays below it, it would be ideal if the compressor could draw cool air close to the ground. The air that is warmed-up while cooling the compressor should then be able to escape upward. Any mixing between the cooler air arriving at the compressor and the warmer air being evacuated should be avoided. In some compressor stations, a hole in the wall allows the arrival of cooler air from outside. A ventilator assists the warmed-up air to be evacuated in a direction that assures mixing of the two air-streams does not take place. Dive centres in colder climates sometimes lead the warm air coming from the compressor to the room in which they dry rental equipment.

Sometimes, the last cooling spiral of the compressor is ribbed. The ribs increase the surface that is in contact with the cooler air that is passing over the compressor and make cooling more efficient. The length of the cooling spiral can be reduced by a factor two or three and still achieve the same cooling.

Ribbed cooling spirals require attention. The ribs must increase the surface that is in touch with moving air. If dust, dirt, oil or other material starts clogging the space between ribs, the opposite will happen. Clogged ribs isolate the cooling spiral, rather than making cooling more efficient. If a compressor is equipped with this kind of cooling spiral, the ribs must be brushed free of any deposits from time to time.

The Engine

A compressor needs an external source of rotation. This can be tapped form a machine that is already “turning”, such as a generator on a boat. In most cases, a compressor is equipped with its own engine. This would then either be an electric engine or a combustion engine. The choice of engine depends on considerations such as sensitivity to moisture, availability of reliable electricity, noise reduction, and transport needs.

If no restrictions apply, an electrical engine is preferred. These engines make less noise than combustion engines, need less maintenance and do not have toxic (carbon monoxide) exhaust that could end up in the compressor inlet. There are some restrictions that could outweigh the inconveniences of a combustion engine. Most compressors (with the exception of the smaller models) would require an engine that runs on three-phase electricity. This makes it hard to transport the compressor to different locations, because 380V is not always available. A combustion engine can be used anytime and anywhere.

Reliability of the electricity is a similar consideration. If power outings are a regularly reoccurring event, an electrical engine could not be used. Generating your own electricity (with a generator) and then running the compressor with that electricity is not an economically valid option. A generator has a big energy loss when transferring energy provided by burning of fuel into electricity. This is also the case for power plants, but not to the same extent. If fuel is to be used at the location of the compressor, then the compressor should be run directly with the combustion engine using that fuel.

A last inconvenience of electric engines is their sensitivity to water and moisture. For compressors used on boats or in areas that are frequently inundated, that can be a consideration. Combustion engines are not sensitive to water. As long as the air inlet and exhaust are above water, a combustion engine can run. You do have to accept the inconvenience of (a lot of) noise, an increased need for maintenance and a need to pay attention to the direction of the wind in order to prevent the exhaust of the engine to end up in the compressor inlet.

Three phase engines do have an inconvenience. When an engine at rest starts rotating (a hard start), it pulls six to twelve times the amperage that it uses while running. This would blow the fuses protecting the electrical system of the compressor. In order to provide for a soft start, star-delta switches are used. During starting the switch reduces the electrical current to the engine. Once the engine starts moving, that supply of electricity is switched of and simultaneously the normal power supply is activated. This procedure (which only takes a few moments) requires lots of wires to activate and deactivate magnetic switches and other items. Because the electric box is mounted on the compressor frame, it moves a lot. Many compressor users have made it a habit to open the box every couple of months (with the electricity disconnected) and to retighten all cable connections with a screwdriver. The idea is to prevent a false contact, rather than to start looking for the one cable that causes a problem when the compressor refuses to start.

In most compressors, the rotation of the engine is transferred to the crankshaft by a V-belt. A pulley on the engine drives one side of the V-belt. The movement is transferred to a (bigger) pulley on the compressor. The same V-belt also rotates the cooling fan. The speed of the engine must be brought into balance with the required rotation speed of the compressor. This is done by calculating the correct size of both pulleys. The V-belt must be under tension. This is something that you must verify from time to time. For installations with the engine beside the compressor, the tension can mostly be adjusted by moving the engine to the side (it is placed on rails). In systems where the engine is placed under the compressor, the weight of the engine is used to maintain tension on the V-belt. If the tension is not adequate, the V-belt slips in the pulleys, resulting in loss of rotation energy and a high pitched sound.

Sometimes the same compressor model is offered in different versions, each with a different filling performance. In many cases this is only an adaptation of the speed at which the compressor rotates. As a rule of thumb, you could say that compressors that run at a lower speed fill fewer cylinders per hour, but have a substantially longer lifetime.

Most dive centre owners opt for a compressor running at a low RPM (Rotations Per Minute). Normally the compressor is started and stopped by the user, but an electric engine can also be activated by a pressure switch. For many compressors this is only done in order to stop the compressor when it reaches its final pressure. Remember that the final pressure safety valve is a mechanical part that vents air from the system when the pressure gets too high. It does not “tell” the engine to stop running. If the compressor is used in combination with air banks, a pressure switch that starts the engine when the pressure in the air banks gets too low can be of help. This is especially the case when the filling of the air bank is done during night in order to benefit from a lower electricity price.

Air Banks and Cascade Systems

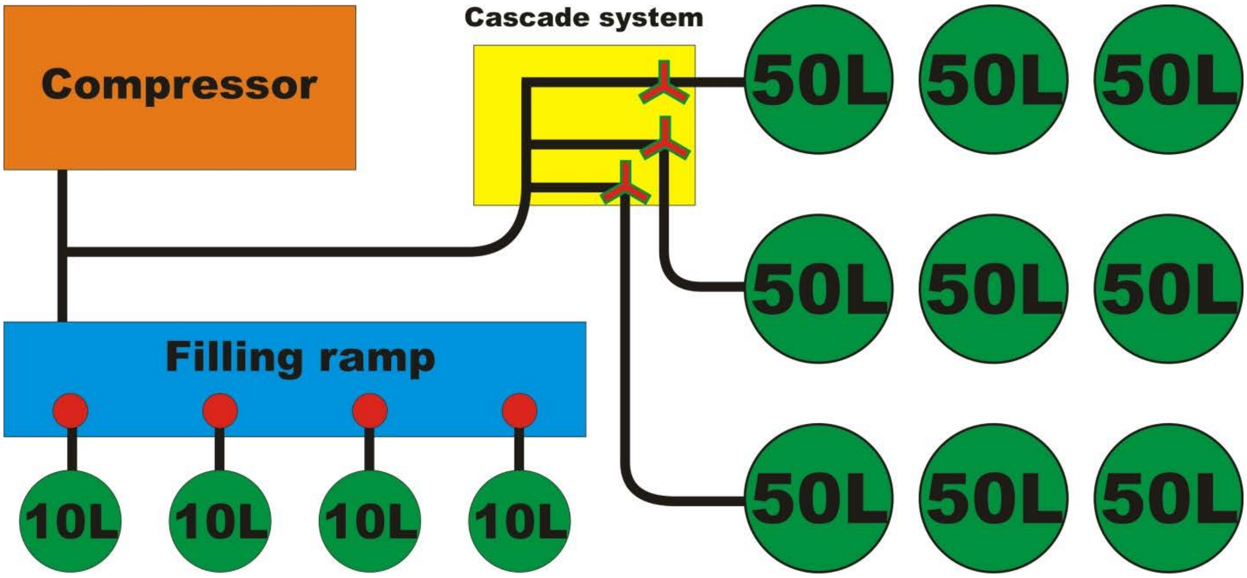
In diving, we are often dealing with peak demand for air fills. A group of divers departing with the same boat all come back with empty cylinders at the same time. Often the filling has to be completed before the next departure. If all filling depends on the speed of the compressor, the dive centre must have a large installation. It would be more economically valid if the size of a compressor can be calculated on the daily demand for air fills. That would be possible by either having enough cylinders for two or three rotations, or to have a possibility to stock the air (in air banks) to be available when a number of cylinders must be filled.

An air bank consists of one or more large cylinders. Normally the size of each cylinder is 40 or 50 litres. They are rated for either 200 or 300 bars. If an air bank at 300 bars is used to fill 200 bar cylinders, the air bank must be equipped with a pressure reducer and a safety valve to avoid too high a filling pressure.

Air banks are not only useful for meeting demand during peak hours, but also allow continuing service when the compressor is down for maintenance. Air banks can also serve to run the compressor during hours when electricity is cheap. In many regions, the price of electricity is lower at night than during daytime.

There is a choice to be made on how to connect the air bank to the system. All cylinders of the air bank could be combined as a single volume of high pressure air (9 cylinders of 50 litres each then become a single 450 litre volume), or they could be connected as small groups of cylinders. That last option is called a cascade system. The 9 cylinders mentioned above would be combined to three groups of three cylinders each (three groups having a volume of 150 litres each).

In most cases, air banks and cascades are connected to the pressure line leading from the compressor to the filling console. The pressure line leading from and to the big cylinders can be closed with a valve. If the valve is open, it allows air to flow from and to the air banks.



Cascade system

The same line is used to fill the air bank and to flow air from the air bank to the filling console (and thus the cylinders to be filled). If no one-way valves (covered later) are included in the system and if the three valves leading to the air bank are in the open position, all cylinders (9 times 50 and 4 times 10 liters = 490 liters) form a single volume and will equalize to the same pressure.

The idea of an air bank (and cascade) is to connect two pressure containers at different pressures and to allow them to equalize to the same pressure. To calculate the pressure after connecting the two containers, the quantity of air must be divided by the combined volume. The quantity of air is expressed in bar litre. This is the multiplication of the pressure and volume of the individual (isolated) containers. The final pressure is then found by dividing the quantity of air (bar litres) by the combined volume, after opening the valve connecting the two containers (litres). For example: a 50 litre air bank at 200 bars is connected to a 10 litre diving cylinder at 50 bars. The quantity of air then is (200 bars x 50l) + (50 bars x 10l) = 10.000 bar litres + 500 bar litres = 10.500 bar litres. The combined volume of the containers is 50 litres + 10 litres = 60 litres. 10.500 bar litres divided by 60 litres gives 175 bars. After equalization, both the diving cylinder and the air bank thus have the same pressure. In this case that would be 175 bars. The relatively small air bank has a rather big drop in pressure after filling a single cylinder, which is the reason why most dive operations prefer a cascade system.

The calculations on the next page show the difference between an air bank (all buffer capacity combined to a single volume) and a cascade (the buffer volume partitioned in smaller groups). The installation in the illustration serves as the calculation example. Before starting on filling a series of cylinders, all air bank cylinders are filled at 200 bars. The cylinders to be filled are all 10 litre cylinders with a remaining pressure of 20 bars each. As in the illustration, four cylinders are filled at a time.

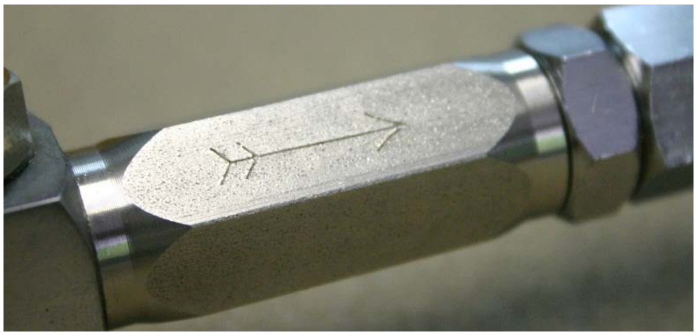
Filling with an air bank at 200 bars, consisting of 9 cylinders of 50 litres, all combined to a single volume of 450 litres. All cylinders to be filled are 10 litre cylinders with 20 bars pressure remaining.				
Series of 4 cylinders	Start pressure cylinders	Start pressure air bank	Calculation Attention: the 40 litres represent 4 cylinders of each 10 litres as in the drawing.	End pressure air bank & cylinder
1st	20 bars	200 bars	((450 litres x 200 bar) + (40 litres x 20 bar)) / 490 litres =	185.3 bars
2nd	20 bars	185.3 bars	((450 litres x 185.3 bar) + (40 litres x 20 bar)) / 490 litres =	171.8 bars
3rd	20 bars	171.8 bars	((450 litres x 171.8 bar) + (40 litres x 20 bar)) / 490 litres =	159.4 bars
4th	20 bars	159.4 bars	((450 litres x 159.4 bar) + (40 litres x 20 bar)) / 490 litres =	148.0 bars
5th	20 bars	148.0 bars	((450 litres x 148.0 bar) + (40 litres x 20 bar)) / 490 litres =	137.5 bars

Filling with a cascade at 200 bars, consisting of 9 cylinders of 50 litres combined in 3 groups with a volume of 150 litres each. The 10 litre cylinders to be filled have 20 bars pressure remaining.				
Fill step	Start pressure cylinders	Start pressure air bank	Calculation: Note: C1, C2 and C3 stand for the cascade group (first, second and third). The end pressure (right) in the cylinders is the same as the end pressure in the cascade group.	End pressure cascade & cylinder
The 1st series of 4 cylinders (10 litres each with 20 bars remaining pressure) to be filled.				
Step 1	20 bars	C1 - 200 bars	((150 litres x 200 bar) + (40 litres x 20 bar)) / 190 litres =	C1 - 162.1 bars
Step 2	162.1 bars	C2 - 200 bars	((150 litres x 200 bar) + (40 litres x 162.1 bar)) / 190 litres =	C2 - 192.0 bars
Step 3	192.0 bars	C3 - 200 bars	((150 litres x 200 bar) + (40 litres x 192.0 bar)) / 190 litres =	C3 198.3 bars
The 2nd series of 4 cylinders (10 litres each with 20 bars remaining pressure) to be filled.				
Step 1	20 bars	C1 - 162.1 bars	((150 litres x 162.1 bar) + (40 litres x 20 bar)) / 190 litres =	C1 - 132.2 bars
Step 2	132.2 bars	C2 - 192.0 bars	((150 litres x 192.0 bar) + (40 litres x 132.2 bar))/190 litres =	C2 - 179.4 bars
Step 3	179.4 bars	C3 - 198.3 bars	((150 litres x 198.3 bar) + (40 litres x 179.4 bar))/190 litres =	C3 - 194.3 bars
The 3rd series of 4 cylinders (10 litres each with 20 bars remaining pressure) to be filled.				
Step 1	20 bars	C1 - 132.2 bars	((150 litres x 132.2 bar) + (40 litres x 20 bar)) / 190 litres =	C1 - 108.6 bars
Step 2	108.6 bars	C2 - 179.4 bars	((150 litres x 179.4 bar) + (40 litres x 108.6 bar))/190 litres =	C2 - 164.5 bars
Step 3	164.5 bars	C3 - 194.3 bars	((150 litres x 194.3 bar) + (40 litres x 164.5 bar))/190 litres =	C3 - 188.0 bars
The 4th series of 4 cylinders (10 litres each with 20 bars remaining pressure) to be filled.				
Step 1	20 bars	C1 - 108.6 bars	((150 litres x 108.6 bar) + (40 litres x 20 bar))/190 litres =	C1- 89.9 bars
Step 2	89.9 bars	C2 - 164.5 bars	((150 litres x 164.5 bar) + (40 litres x 89.9 bar))/190 litres =	C2 - 148.8 bars
Step 3	148.8 bars	C3 - 188.0 bars	((150 litres x 188.0 bar) + (40 litres x 148.8 bar))/190 litres =	C3 - 179.7 bars
The 5th series of 4 cylinders (10 litres each with 20 bars remaining pressure) to be filled.				
Step 1	20 bars	C1 - 89.9 bars	((150 litres x 89.9 bar) + (40 litres x 20 bar)) / 190 litres =	C1 - 75.2 bars
Step 2	75.2 bars	C2 - 148.8 bars	((150 litres x 148.8 bar) + (40 litres x 75.2 bar))/190 litres =	C2 - 133.3 bars
Step 3	133.3 bars	C3 - 179.7 bars	((150 litres x 179.7 bar) + (40 litres x 133.3 bar))/190 litres =	C3 - 170 bars

The example illustrates that the pressure in the air bank drops rather fast when filling several sets of 4 cylinders. The fourth set does not even reach a pressure of 150 bars. In practical situations this means that the compressor will have to top-off the remaining pressure. The time needed for that can be calculated by establishing the missing quantity of air (in the case of the fourth series that would be 200 bar minus 148 bar = 52 bars, which is multiplied by the volume of 40 litres to find 2080 bar litres). A compressor pumping 250 litres per minute would then need a bit more than 8 minutes to top-off the fourth series. A bigger air bank would lose pressure less fast, but there is another way to make more “economic” use of the stocked air, which is a cascade. The idea behind a cascade is to make use of the valves (red and green) in the drawing. In a cascade only one group of buffer cylinders is opened at a time. The same sequence is maintained for all fills. In the illustrated installation this means that there are three filling steps (or four if you count topping with the compressor after cascading is competed). There is no standard number of cascade groups. You could just as well have a cascade with four or even five groups of buffers.

A cascade is used as follows. After connecting the diving cylinders (in this case four 10 litre cylinders with a remaining pressure of 20 bars), the first cascade group is opened to allow the diving cylinders to equalize with the first group. The valve for the first group is then closed, followed by opening the second group. The second group then equalizes with the diving cylinders, which had already received some of the needed air from the first group. The same procedure is repeated. Closing the second group and then opening the third (and in this case last) group. After equalization with that group is completed, the last group is also closed and the compressor is used to top-off the cylinders.

With the cascade, the pressure of the fifth series of 4 cylinders is almost the same as for the second series with an air bank of the same total volume. This limits the time needed for topping the cylinders with the compressor and thus allows for faster filling during peak demand. The number of hours the compressor has to run in total (the filling of the diving cylinders plus the time needed to fill the air bank or cascade again) stays the same. The quantity of air to be filled in the cylinders is not affected by the way it is organized. The advantage of a cascade is only the limited time needed for topping-off the cylinders.



In order to prevent air flowing in directions that are not useful, it might be an option to place one-way valves on selected locations. This would be at the connection of the filling console to prevent air from diving cylinders to flow back to the compressor.

Filling Console

The filling console is the location where the diving cylinders are filled. The console can either be part of the housing around the compressor, or can be at some distance from the location where the air is actually pressurized. If the console is mounted at distance, it needs to have an electronic connection with the compressor, as well as a hose to transport the compressed air to the console. Some manufacturers supply a console that is fitted on the housing of the compressor, but that can be easily removed to serve as a remote station. When cylinders are filled in an area that is accessible to clients, safety and noise considerations will normally make a “remote” console preferable.

Precautions must be taken for the safety of the person filling the cylinder. A set of procedures (explained later) must be followed, but there should also be some technical precautions. A filling hose without a cylinder connected is not under pressure. On many consoles, the valve to pressurize the hose is found on the console itself. The same lever is also used to depressurize the hose before disconnecting it from the cylinder. You could imagine that somebody could connect the hose at the left of the console to a cylinder, but by mistake open the second valve. Especially if an air bank is connected to the system (but a compressor would do as well), the second hose would whip around with a very real potential of hurting somebody standing close to it.

If all cylinders to be filled have DIN valves, there is a safety connector on the market that will close the filling hose until it is firmly connected to the cylinder valve. A pin in the connector obstructs the air passage until the connector is screwed in the valve far enough to depress the pin. If by mistake a hose is opened (at the console) to which no cylinder is connected, the hose will not release large quantities of air and will thus not whip around. Unfortunately the system does not work with (all) adapters for yoke connectors. If the dive centre caters for a mix of cylinders with different valves, this safety feature will not provide the desired protection.

Another option to achieve some level of safety for the user, is to opt for filling hoses that have the valve to open and close the passage for the air (and for draining the pressure from the hose) at the end to which the cylinders are connected. In that solution, the user has the hose that is opened in the hand while manipulating the valve. That by itself should already prevent the hose from whipping around, but it should also be clear that the chance of making a mistake is very limited with this solution. You would surely notice that the hose you are opening does not have a cylinder attached when the opening is done at the end where the cylinder is supposed to be.

A frequently used option to limit risk is leading the hoses through a metal ring at the wall. The hose coming from the console is first passed through the metal ring, a bit higher than the height of the cylinders. This gives enough play to connect the hose to different sizes of diving cylinders, but does not allow a lot of play for the hose if it starts whipping around. If from a one and a half meter hose only the last fifty centimetres can move around, chances of the user being hit by the hose are remote. The user normally stands behind the cylinders.

Compressor Logbook

A compressor logbook is used to control and document what you want the users of your compressor to do before starting it. Most compressor logbooks are homemade, because different compressors have different points of attention and can have a variation of side equipment that needs some attention as well. The example below is for a three stage compressor without any special side equipment, without electronic filter verification and without an oil pump (otherwise oil filter change would be listed as well).

The owner of the compressor indicates the hours at which some maintenance is due and lists the actions to be taken before starting the compressor (such as checking the oil level). The first user of the day would then check-off all items after verification and checking the current hours against the hours listed for a next maintenance procedure.

If a maintenance procedure is completed, it is clearly listed in the logbook, either by using another colour (as done in the example), by circling the item or any other method. The hour indication at the top of the page is deleted and replaced with the new hour-reading for the next time that procedure has to be done (in accordance with the user manual from that compressor).

Logbook Compressor XYZ Dive Centre ABC		Next oil change		1300	Next change inlet filter		1000	Next filter change		~~730~~ 940
		Next complete service including valves					2000	Oil type	Rarus 829	
Date	Hours	Name	Oil level	Next oil change	Next inlet filter change	Next filter change	Next valve change	Start noise	General condition	Signature
15/03/10	722.4	John	100ml	ok	ok	ok	ok	ok	ok	J. Do
16/03/10	728.1	Bill	✓	✓	✓	✓	✓	✓	✓	B. Xyz
18/03/10	731.6	John	ok	ok	ok	Done	ok	ok	ok	J. Do
19/03/10	732.4	John	ok	ok	ok	ok	ok	ok	ok	J. Do

Filling Procedures

Filling starts with an inspection of the diving cylinders to be filled. The date of the last hydrostatic test and visual inspection must be in accordance with local regulations. Attention must also be given to the pressure for which the diving cylinder is rated. Although they are rather seldom, you might find a reserve valve on a cylinder. If this is the case, the reserve lever must be placed in the down position; otherwise air from the compressor will be restricted in passing to the cylinder. As a consequence the volume inside the valve will soon reach the final pressure, while the cylinder is still more or less empty when the compressor shuts down.

Every cylinder valve must be opened momentarily to blow out moisture. Any moisture remaining in the valve when the filling starts will be pushed into the cylinder. In the filter from the compressor, molecular sieve is used to dry the air. If the user does not take precautions to remove moisture that is accumulated after the filter, humidity will enter the cylinder anyway. This will provoke corrosion of the inside wall of the cylinder. Also the compressor itself is an issue with respect to moisture (as well as carbon dioxide). While the compressor is not in use (not connected to a cylinder) moist air enters the filling hose. As the filling hose comes after the filter, the molecular sieve will not remove this moisture. Allowing some of the air to escape from the hose before connecting the cylinder will solve this issue. This action also helps to reduce the carbon dioxide content in the first fill. During filling, the filter material adsorbs carbon dioxide. While the compressor is not in use, the adsorbed carbon dioxide is released again. The consequence is that the first cylinder filled is always richer in carbon dioxide than the cylinders following after that. Draining some of the air from the compressor before connecting the first cylinder will solve that issue as well.

The actual filling process starts with connecting the cylinders to the filling hoses. At that moment, the valve for draining pressure from the hose is in the "open" position (this applies to most fill hoses, but there are exceptions). Would you now open the cylinder valve, then pressure remaining in the cylinder would be lost via the drain valve. The next step is thus to pressurize the filling hose. Often the same valve closes the drain valve and opens the connection to the compressor with a single action (the exception mentioned before applies when the drain and the valve to open the connection to the compressor are not combined). Once the filling hose is pressurized, the diving cylinder can be opened for filling.

When air is compressed, the temperature rises. A few techniques can be used to limit the rise in temperature from the cylinders. The more cylinders are filled at the same time, the slower the filling will go, which limits the rise in temperature. Using a console with six cylinders, rather than four, will thus limit heating. Another option is to cool the cylinders with water while they are being filled. Limiting the rise in temperature will reduce the pressure drop when the temperature of the cylinders returns to ambient temperature. If you want to deliver a cylinder with 200 (or 300) bars to the client, the actual filling pressure needs to be higher to account for the pressure drop after filling. The more you can reduce the rise in temperature during filling, the less over-pressure needs to be filled.

When the final pressure is reached, the compressor can be shut down, or can be switched to filling the air bank. To allow switching to air bank filling without losing pressure from the cylinders that you have just filled, the filling console must be equipped with a one way valve that prevents the air from the cylinders to flow back in the direction of the compressor and air bank. As a first step, the cylinder valves must be closed. Then the pressure from the filling hose must be drained. In most cases, draining the pressure and disconnecting the filling hose from the compressor are done in a single manipulation. As mentioned before, there are exceptions in which case each action requires a manipulation for itself. Once the filling hose is drained of pressure, it can be removed and the system is ready for filling the next series of cylinders.

Contrary to what some divers think, not all DIN connectors are rated for 300 bars. There are two different DIN connectors. The difference is the number of threads (the length of the connector). The 300 bar connector is longer. The idea is that only a 300 bar connector is long enough to enter sufficiently deep in a 300 bar valve to provide a seal for the O-ring. A 200 bar valve is less deep. Connecting a 300 bar regulator to a 200 bar cylinder is thus no problem. Connecting a 200 bar regulator to a 300 bar cylinder will not work, because the O-ring cannot reach the bottom of the valve and will thus not seal. For filling the opposite holds true. The difference in connection that serves well to prevent the diver from using a regulator for a pressure it was not constructed for, poses a risk for the person filling the cylinder. A filling hose for 300 bar could be connected to a 200 bar cylinder without any problem. This could result in over-filling the cylinder. A note not concerning safety: the owner of a 300 bar rated cylinder might find it hard to get his cylinder filled. Most compressors are set for filling at 200 bars. Even if the owner of the higher rated cylinder would want to accept a 200 bar fill, it would not work. The filling hoses of a 200 bar filling station cannot seal on a 300 bar cylinder.

Which Compressor to Choose?

Choosing a compressor for a dive centre is not an easy task. After all, it is something a dive centre owner would do only once in many years. A choice for a compressor that is too big is an economic disadvantage. Bigger compressors cost more and spare parts are often more expensive. Too small a compressor leads to an increased workload for the staff. Filling would have to continue after hours to get all cylinders ready for the next day. Another issue is the brand.

The choice of a brand of compressor should mainly be based on the level of service that is provided in the region where the compressor is used. The availability of spare parts and after sales service can guide the choice between one brand and the other. Some brands have a better reputation for reliability than others, but you should be aware that such opinions are often based on information from the past. In recent times, the differences in reliability between different brands are substantially reduced. A weak point in compressors could be the electrical parts of the system, but that could apply to all brands.

For the choice of the size of a compressor, it is best to show an example. Imagine that the boat of a dive operation offers space for 15 divers. There are two outings per day (the next departure one and a half hour after the boat has returned from the first dive). Additional needs mount to two or three cylinders per day for introduction dives. The centre is opened every day during eight hours. To allow for some unexpected filling, a calculation could be based on 34 cylinders per day that are to be filled in six hours maximum.

Assuming the centre has 12 litre cylinders and that the average remaining pressure is 35 bars, the centre would have to fill 34 times 2.000 bar litres per day. The total volume to be filled (if the boat is full for both dives) is 34 times 2.000 bar litres = 68.000 bar litres. That is 11334 bar litres per hour (based on maximum 6 hour filling time), which equals 189 bar litres per minute. With this number we can now turn to a manufacturer's brochure for compressors. In the brochure, we find a 3 stage compressor which is rated for 190 litres per minute. We notice a rather high RPM. A compressor like this might give some noise and temperature issues. A bit further in the brochure a 4 stage model is offered at low RPM and with 210 litres per minute.

A 4 stage (X-type) compressor offers better promises for durability than a (more or less) equivalent 3 stage model, especially if it turns at a speed of only 950 RPM like the model in the brochure. The choice for a more expensive compressor is most likely compensated by the longer duration of the 4 stage model. This results in a lower annual overhead. For the remainder of the calculations, it is assumed that the X-type was chosen.

15 cylinders to be filled correspond to 30.000 bar litres. With a compressor that delivers 210 litres per minute, that would be a time investment of two and a half hours. The requirement to have the boat ready for departure after one and a half hour (as mentioned before) can thus not be fulfilled. A choice has to be made. Either the centre needs enough diving cylinders to allow two rotations, or the filling has to be accelerated with the use of an air bank or cascade. Let's have a look if a 200 litre air bank (4 cylin

Filling with an air bank at 200 bars, consisting of 4 cylinders of 50 litres each combined in a single volume of 200 litres. All cylinders to be filled are 12 liter cylinders with 35 bars pressure remaining.				
Series of 4 cylinders	Start pressure cylinders	Start pressure air bank	Calculation Attention: the 48 litres represent 4 cylinders of each 12 litres as in the drawing.	End pressure air bank & cylinder
1st	35 bars	200 bars	((200 litres x 200 bar) + (48 litres x 35 bar)) / 248 litres =	168.1 bars
2nd	35 bars	168.1 bars	((200 litres x 168.1 bar) + (48 litres x 35 bar)) / 248 litres =	142.3 bars
3rd	35 bars	142.3 bars	((200 litres x 142.3 bar) + (48 litres x 35 bar)) / 248 litres =	121.5 bars
4th	35 bars	121.5 bars	((200 litres x 121.5 bar) + (48 litres x 35 bar)) / 248 litres =	104.7 bars

Required fill time for a compressor with a filling speed of 210 litres per minute and for topping the cylinders as indicated in the air bank calculation above.				
Series of 4 cylinders	Start pressure cylinders	End pressure	Calculation Attention: the pressure given in the calculation is the pressure missing in the cylinders as in 200 bar – 168.1 bar = 31.9 bar.	Minutes needed for topping
1ste	168.1 bars	200 bars	(31.9 bar x 48 litres) / 210 litres pro Minute	7½ minutes
2te	142.3 bars	200 bars	(57.7 bar x 48 litres) / 210 litres pro Minute	13½ minutes
3te	121.5 bars	200 bars	(78.5 bar x 48 litres) / 210 litres pro Minute	18 minutes
4te	104.7 bars	200 bars	(95.3 bar x 48 litres) / 210 litres pro Minute	22 minutes

ders of 50 litres each) would provide enough additional air to speed up the process to the extent that the one and a half hour fill time can be met.

As the calculation shows, the fill time to respond to peak demand is reduced to just over an hour when an air bank (not a cascade) of 200 litres at 200 bars is in place. In the ideal case, a dive centre owner would calculate different scenario's before deciding on the compressor and air bank to install. It is not too complicated to enter the calculation in a program such as excel with the option to vary the volume of the air bank and the number of cascade groups. Investing a little time in the calculation of the system demands is always better than to be confronted with the consequences of a wrong decision later on. You may have noted that the end pressure used in the calculations is 200 bars, although filling is normally done at pressures between 210 and 220 bars to compensate for the pressure drop when the cylinder is cooling to ambient pressure. This is done in the assumption that compressor manufacturers provide data on the performance of their compressors for ambient temperature and do not add the heat expansion to the values listed in their brochures.

Nitrox Installations

In the nineties, Nitrox has established itself as the second breathing gas for recreational divers. Most dives are still done with air, but a book about compressors would not be complete without information about filling Nitrox cylinders.

The discussion is started with the consequences of high oxygen partial pressures. This is meant as preparation for the more technical part of this chapter. Next the different grades of oxygen that could be considered for filling Nitrox are discussed. The technical part of this chapter starts with filling Nitrox at high pressure. After that, blending at ambient pressure and membrane installations are explained.

Additional Oxygen

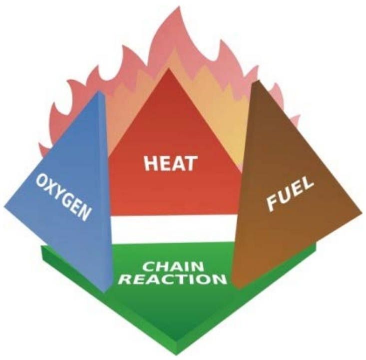
Diving with Nitrox has become very popular. Divers need to complete additional training before using Nitrox because of concerns that are the consequence of increased oxygen content in the breathing gas. In this book, these concerns are not covered. Instead the filling considerations are discussed.

You cannot see, smell or taste oxygen, but oxygen readily oxidizes with other substances. Such a reaction can either be fast, or slow. Fast oxidation could be fire or explosion, an example of slow oxidation is corrosion. Contrary to what you may read in publications on the use of Nitrox, explosion is not the main issue. There is a fundamental difference between fire and explosion. Fire results when a substance ignites and when the resulting reaction creates enough heat to sustain a continuation of the reaction. The substance burns. A fire depends on the arrival of oxygen from the surroundings of the substance that is on fire. The surface of the burning substance (oil for example) is in touch with the atmosphere containing oxygen. The lower layers are not and do thus not burn until they reach the surface.

With gases, an explosive mix can be created when a combustible gas and air (containing oxygen) have enough time to blend in a ratio that combustible molecules are close to an oxygen molecule before the mix is ignited. The difference between a fire and an explosion thus depends on the presence of oxygen "in the mix". Explosives are a mix of combustible material and oxygen in "an ideal ratio". An explosion is a situation in which all available material "burns" instantly, regardless if it is in contact with oxygen from the environment or not.

An increased rate in the arrival of oxygen to a fire will increase the intensity of the fire. This can either be done by increasing air movement (like blowing air over a barbeque), or by increasing the oxygen content in the gas arriving at the fire (such as Nitrox). If a fire intensifies, it could get hot enough to melt the wall of a container (or burn it). If that container was under pressure, then the hole will allow an instant loss of pressure. This is sometimes called an explosion ("a tire of my car exploded"), but it is not.

With compressors, its side equipment and diving cylinders, we are concerned with grease or oil. Chances of a substantial explosion are remote. It is more likely that small amounts of oil vapour ignite (auto ignition) or that oil or grease starts to burn. If this happens within the metal parts of the installation, it will go unnoticed. If it happens in a hose, it may be that the hose melts, which results in a release of pressure. The main concerns are thus (very) small fires and ignitions (sparks). These events burn oxygen and create carbon dioxide and carbon monoxide as waste products. Carbon monoxide is a poison, which means that our main concern when filling Nitrox is contamination of the cylinders which the divers are going to use. As "explosions" are small and fires not hot enough to melt a wall, there is no way for the person operating the compressor to know what is going on.



The risk of fire or explosion depends on three factors. These are the availability of a substance that can burn (fuel), an ignition source (that could be heat) and an oxidizer (oxygen). In a compressor all these factors are present. The temperature in a compressor is elevated, the air is compressed, which increases the partial pressure of oxygen and the compressor must be lubricated, which requires the presence of oil. If one of the three factors is absent, a fire is impossible. If one of the three factors is higher than normal, the risk of fire can be reduced by decreasing the presence of the other two factors.

As covered before, the rise in temperature in a compressor is limited to 160° Celsius (although this is not formalized in most countries). Different types of oil have different ignition characteristics. To reduce the risk of auto ignition, some recommend the use of synthetic oils, rather than mineral oils. The availability of oxygen is limited by the percentage of oxygen in the air and by the maximum pressure of the compressor. When filling Nitrox, we take away the upper limit imposed by the oxygen content of the air. The partial pressure of oxygen will be "higher than normal" and the risk of fire and auto ignition will be increased. When filling Nitrox, this factor must be accounted for.

Although there is an additional risk, this does not mean that it cannot be controlled. As mentioned, the same compressor can be used to fill either 200 bars or 300 bars cylinders. A compressor used to fill air at 300 bars, has a partial pressure of oxygen of 63 bars (0.21 x 300) in the final stage and following equipment. When filling Nitrox32 at 200 bars, that would be 64 bar (0.32 x 200). This is almost the same. The comparison between air at 300 bars and Nitrox 32 at 200 bars indicates that the upper limit for oxygen passing through a compressor is not 21%. The question on an acceptable upper limit is not easy to answer. The risk that a substance ignites depends on the characteristics of the substance itself, the temperature and the partial pressure of oxygen. The partial pressure of oxygen in turn depends on both the final pressure and the percentage in the blend. As a first step to limit risk, the maximum pressure at which oxygen rich blends pass through a compressor should be 200 bars.

The highest percentage that may be passed through an oil lubricated compressor has been established by convention. This is referred to as the 40% rule and does not only apply to compressors, but also to other items, such as diving cylinders. In general the rule says that blends up to a maximum of 40% oxygen content are handled as if they were air. Higher blends are handled as if they were pure oxygen. Be aware that there might be local norms or regulations that prohibit the use of the 40% rule. In the end, it is not the percentage that counts. It all depends on the partial pressure of oxygen, combined with the temperature and the flashpoint of the substances the oxygen comes in contact with. A rule based on a percentage should always be used with caution.

Different Grades of Oxygen

Most techniques for blending Nitrox require the use of pure oxygen. Oxygen is simply O_2, which means that there is only one type of oxygen. There are different grades. There are some considerations for the choice of the oxygen grade to be used for blending. Medical grade oxygen fulfils the requirements for being "pure oxygen", but it is considered prescription medication in many countries and cannot be used if that is the case. Mostly the standard for medical grade oxygen requires 99.5% of oxygen, with the remaining 0.5% impurity being tested on the absence of carbon dioxide (although the standard may vary from country to country).

Prescription medications can only be used on doctors' orders, which restrict its use for blending. In most countries a consumption grade oxygen is available that meets the same standard, but is sold without the legal restriction applying to medical grade oxygen. Consumption grade oxygen can be used for blending. Another option is aviation grade oxygen. This is consumption grade oxygen that has been passed through molecular sieve during filling. In order to prevent freezing of the oxygen equipment in airplanes, moisture is removed from the oxygen.

All three types of oxygen mentioned above are filled with procedures that prevent impurities of ending up in the cylinder, or remaining there. The cylinders are drained from any remaining pressure before being filled again. Theoretically seen, industrial grade oxygen, or oxygen for welding, would not go through such procedures and could thus be contaminated with other gases. In order to prevent problems with the quality of the oxygen, blenders should thus only use consumption grade or aviation grade oxygen and not industrial or welding oxygen. As mentioned before, a verification of local standards and availability is necessary before making a decision on the oxygen grade to be used.

Blending at High Pressure

The first choice to be made for blending Nitrox is to either mix at ambient pressure (and then pass the Nitrox to the compressor), or to first pressurize the air and then blend it with high pressure oxygen. Both options have advantages and inconveniences. When blending at high pressure, the oxygen rich blend does not pass through the oil lubricated compressor, which means that the “40% rule” does not apply. When blending at high pressure, any mix ranging from air up to 99% oxygen can be prepared. If catering for technical divers (and rebreather divers) that is an advantage, because these divers frequently use oxygen rich blends.

Blending at ambient pressure systematically limits the oxygen content to a maximum of 40%. It is possible to mix higher blends, but the compressor is the limiting factor. An advantage is that there is no limit to the speed of filling and that the level to which the diving cylinders have to be cleaned is lower (the cylinder only comes in contact with already mixed nitrox and not with pure oxygen).

Filling at high pressure is called partial pressure blending. It is done by first filling pure oxygen into a cylinder and then topping the cylinder with the compressor. Limiting the rise in temperature is important for two reasons. If the oxygen expands due to rising temperature, the amount of oxygen filled in the cylinder will not be the calculated amount (the pressure gauge reads too high). This results in another blend than intended. The second reason is safety. When filling 100% oxygen, the temperature should be kept as low as possible. It is recommended not to exceed a filling speed of 5 bars per minute.

When catering for divers who pass by to have their cylinder filled with Nitrox, the low filling speed is an inconvenience. Some dive centres circumvent that problem by filling Nitrox40 into an air bank and then blending that down in the customers’ cylinder. Nitrox 40 can be handled as if it were air, so the low filling speed does not apply anymore.

Any equipment getting in contact with oxygen at a high partial pressure must be cleaned for that purpose. If the diving cylinder is used for blending, both the cylinder and the valve must be oxygen clean. It is hard to control the level of cleaning from a customers’ personal cylinder, so most blenders only mix high blends in cylinders owned (and controlled) by the dive centre. Due to the mentioned inconveniences, partial pressure blending is hardly used anymore for blends lower than 40%.

The most primitive way to do partial pressure blending is with a filling (or transfer) whip. First the cylinder is connected to the oxygen cylinder and oxygen is added up to the calculated pressure. The cylinder is then disconnected from the oxygen and connected to the compressor for topping. To prevent connecting the same cylinder twice, a Nitrox filling console can be used.

Although the oxygen is filled first, the source cylinder must have enough pressure to reach the desired pressure in the diving cylinder (unless a booster pump is used). This means that the last 50 bars or so cannot be used. The problem with "lost" oxygen can be limited by cascading with more than one oxygen cylinder (which is why the console in the picture shows more than one oxygen source). It is also hard to fill more than one cylinder at a time. Each cylinder will have a different remaining pressure and a different residue of a blend. In partial pressure blending it often happens that only one cylinder can be filled at a time. To prevent this, either any remaining Nitrox could be vented from the cylinders (which would be a shame), or the dive center could decide to only fill one Nitrox blend all the time. You will find many dive operations to only offer Nitrox32 for that reason.

Blending at ambient pressure thus has the advantage of filling faster; reducing the need for oxygen cleaning and to reduce training requirements for the person operating the compressor (anybody doing partial pressure blending must be trained as a gas blender). The remaining problem (if offering different blends) is to account for any Nitrox remaining in the cylinder from a previous dive. The calculation is simple though. The only thing needed is to calculate the blend to which the installation must be set, as there is only one source of oxygen. With partial pressure blending, two calculation steps must be completed. One step to calculate the percentage of oxygen in the blend and one step to split the oxygen between oxygen from the air and from the oxygen source.

The example below shows the calculation for a cylinder that is presented with a remaining pressure of 55 bars and a residue of Nitrox36. The cylinder should be filled with Nitrox32 and to allow for some heat expansion is filled to 210 bars (to assure a 200 bars fill when the cylinder cools down to ambient temperature). If blending at ambient pressure, completing calculation step 1 provides all information needed. If doing partial pressure blending, both step 1 and step 2 must be calculated. Values are transferred if a box has the same number.

Step 1 - find the percentage to be added to the blend – must be calculated for all systems.

I want	… 210	bar	at (multiply) %	0.32	= 67.2	bar
I have	† 55	bar	at (multiply) %	0.36	= 19.8	bar
Subtract row 2 from row 1 to find:						
Pressure to add	• 155	bar		Oxygen to add	, 47.4	bar

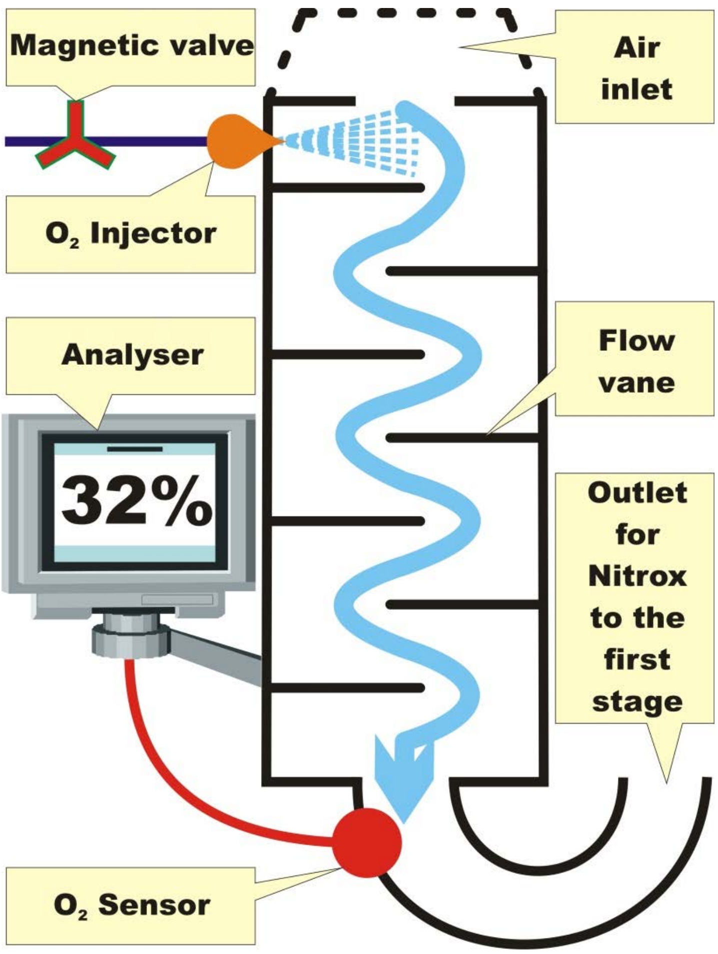
Oxygen to add	, 47.4
Divided by pressure to add	• 155
Percentage to add	ƒ 0,306 ≈ 31%

Step 2 - find how much oxygen to add to the cylinder – only needed for partial pressure blending.

Percentage to add	Minus O_2 percentage in air	Times pressure to add	Gives the result of oxygen to add in bar
ƒ 0,306	-/- 0.21		
0.79		x • 155	= „ 18.8 bar
Divided by N_2 percentage in air			

Remaining pressure in cylinder	† 55	bar
Plus oxygen to add	„ 18.8	bar
Fill with oxygen to a pressure of	73.8	bar	Then add air to desired pressure …

Blending at Ambient Pressure



When mixing oxygen with air at ambient pressure, no minimum pressure is required to allow a nitrox fill. This means that there is no loss of oxygen. The entire cylinder can be used. A stream of oxygen is injected in the air flowing to the compressor and is mixed to create a homogenous blend of Nitrox. This mix then flows to the compressor inlet. The continues flow unit could theoretically create very high blends, but as mentioned before, all blends higher than 40% have to be done using the partial pressure blending method.

The flow of oxygen can be adjusted to create different blends. At the end of the blending unit, an oxygen sensor is fitted to allow real time analyses. The blender can now adjust the injector (mostly a small needle valve) until the analyser reeds the desired blend. This could be Nitrox32. To preserve that blend, the air integrity from that point on (all the way to the compressor inlet, including the air filter) must be perfect. Any ambient air drawn into the system after the blending unit will reduce the oxygen content and thus change the Nitrox blend.

To respect the 40% rule, it is not enough if the final blend in the cylinder is lower than the maximum percentage. If the flow would fluctuate between 50% and 30%, the resulting blend could very well be Nitrox40, but that is not acceptable. The construction of the unit must assure that the blend is at no moment higher than 40%. This requires creating enough movement of the blend in the unit to achieve a homogenous mix. For this purpose, the blending unit is equipped with flow vanes.

Another requirement is that the flow of oxygen is stopped the moment the compressor stops running. If that would not be the case, oxygen would accumulate in the unit while the compressor is not drawing air through it. That would result in a very high blend when the compressor starts again.

Synchronizing the injection of oxygen with the start and stop of the compressor can be achieved with a magnetic valve that is connected to the electrical system of the compressor. The valve should open when the compressor is started and close again when the compressor stops running (regardless if this is done manually or with an automatic pressure switch). Magnetic valves work on 220 Volts, while the electric engine of a compressor works on 380 Volts. A good place to attach the valve to the electrical system of the compressor is the counter. The counter works on 220 Volts and starts and stops simultaneously with the compressor engine.

For the injector to maintain a regular flow of oxygen, it must be supplied with a constant pressure. For that purpose, a regulator is needed that is attached to the oxygen supply and set to deliver an intermediate pressure suited for the needle valve used. Often this is a pressure between 3 and 6 bars. When the cylinder pressure drops below the intermediate pressure, the flow rate will diminish and the blend will be lower than was set.

A continuous flow blending unit must be adapted to the size of the compressor. If the diameter is too small to let the volume pass that the compressor requires, the compressor may start drawing more air from its oil bin. This will not only corrupt the blend (a lower oxygen content than set), but will also draw more oil vapour into the first stage. Continues flow units come in different sizes and the instructions for use should indicate the maximum flow in litres per minute for which the unit can be used.

There is no way to fill Nitrox in an environmentally friendly manner. No matter which method is used, the energy needs are substantially higher than for filling a cylinder with air. From the available methods (partial pressure blending, continues flow blending and the use of a membrane installation) continues flow units perform best with respect to energy consumption. Filling cylinders does not require more energy than for filling air and the cylinder of oxygen (for which rather a lot of energy is needed for separating the oxygen from other gases, for filling and for transport) is used completely. In partial pressure blending part of the oxygen is lost because of pressure requirements, or a booster pump will consume energy when the user is opting for a technical solution to prevent loss of oxygen (or helium). As will be covered later, membrane Nitrox filling is environmentally seen the most unfriendly method.

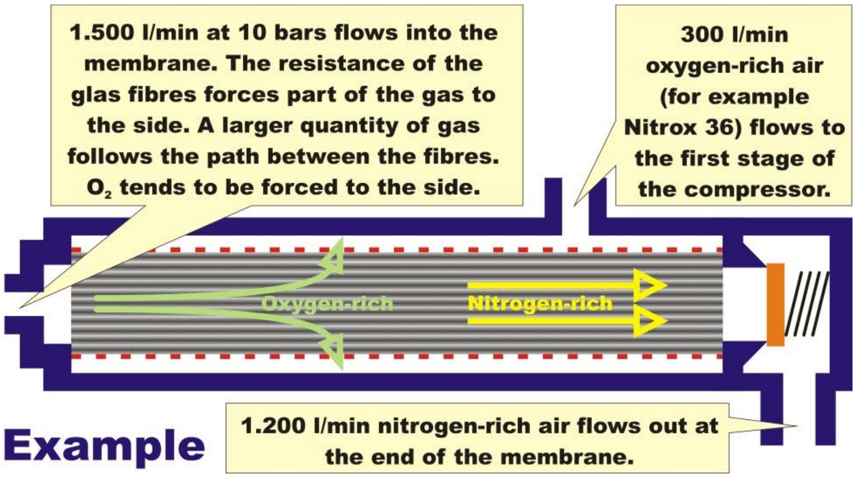
Constant flow blending is economically seen an interesting method. The equipment does not cost a lot more (if at all) than the equipment needed for partial pressure blending, while it permits to use all the oxygen from the source cylinder. The cost per cylinder of Nitrox filled depends only on the price of oxygen in the region where the dive centre operates. There is a need to verify local regulations. There may be restrictions on the manipulation of pure oxygen and on transport. Another issue may be the technical requirements that must be fulfilled to get a compressor installation approved for commercial purposes. Such regulations vary substantially from country to country and cannot be covered in a text that is used in countries all over the world.

The restriction of the 40% rule is well compensated by the environmental and economic advantages and by the fact that the filling speed is not limited. There is one other disadvantage that applies when blending takes place at ambient pressure. Between setting the blend on the continues-flow unit and the moment that that blend arrives at the filling console, there is a (substantial) delay. The Nitrox blend first has to fill the cylinders from the compressor, the separators, the filter and all other air spaces. Until that time, the blend just pushes the air in the system ahead (or the Nitrox setting from the previous fill). When using a continues-flow unit, the delay from setting a blend up to arriving at the console must be timed (in subsequent fills, the delay will be the same). Depending on the volume of the filter and separators, the delay could range from one to several minutes. Many users of this type of system use one connection on the filling console for a cylinder in which the “intermediate blend” flows and open the target cylinder(s) the moment the intended blend arrives at the console. The cylinder accepting the “intermediate blend” will have a low Nitrox and can be used for sessions in the pool or training sessions in open water.

Membrane Systems

If the availability of oxygen, its price or regulations are an issue, both partial pressure blending and continues flow blending are problematic. There is another solution, which is to remove nitrogen from the air. The result is also a blend that is rich on oxygen. Rather than increasing the oxygen content of the air, the nitrogen content of the air is reduced. There could also be economic reasons to opt for a membrane system. A membrane is substantially more expensive than the other systems already presented, but the operational cost can be lower. When using a membrane, you do not need an external company as a supplier for oxygen. The energy demand and need for maintenance are higher than for the other systems (substantially). Compared to the cost of oxygen, the overhead might prove lower. With an increasing number of Nitrox fills per day, at some point a membrane becomes the most economically valid option. In central Europe that could be at a volume of 10 to 20 cylinders per day, while in a remote area as little as 3 or 4 cylinders could justify the investment in a membrane installation (due to high transport cost for oxygen cylinders).

Membranes share most of the advantages and inconveniences with continues-flow blending. They also are restricted by the 40% rule, have a delay between setting a blend and the moment that blend arrives at the filling console and need to be adapted to the size of the compressor. On the up-side, the filling speed is not restricted and the requirements for oxygen cleaning of the diving cylinders and valves are limited. For membrane filling, two compressors are running at the same time. This means that the environmental advantage of continues flow units does not apply to membranes.

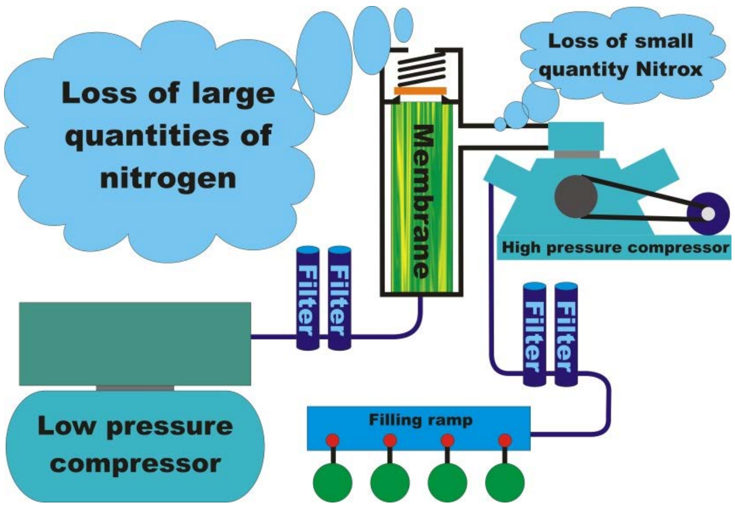


The functional part of a membrane installation is the membrane itself. Glass fiber is packed in a tube. Between the wall of the tube and the pack of glass fiber, there is an empty space from which gas can be collected to leave the tube at the side. Air is injected (under pressure) into the pack of glass fiber on one side of the tube. Without resistance, the glass fiber would force all injected gas to pass through the pack linearly and to be blown out of the tube at the other end.

To achieve separation of oxygen and nitrogen, some resistance is applied to the end of the tube. The resistance will result in some of the gas choosing a radial path, rather than following the fibres linearly. With the right choice of fibres, the gas forced to take a radial path will be rich in oxygen, while the gas blown out at the end of the tube is rich in nitrogen. The precise blend depends on the amount of resistance applied to the end of the tube. A big resistance will result in a lot of gas sorting at the side of the membrane, but this gas will have a low oxygen content. Minor resistance at the end of the tube will reduce the volume leaving the tube sideways, but in that case the oxygen content will be higher. Separation is based on physical differences between oxygen and nitrogen molecules.

The amount of air that must be pumped through a membrane in order to feed the compressor with the volume of Nitrox it demands is enormous. If a compressor would need 300 litres per minute of Nitrox36 at the inlet, the amount of air to be pumped through a membrane could easily be 5 times as much (1,500 litres per minute). Theoretically seen, that air could be supplied from an air bank that is first filled with the same compressor. The air from the air bank would then pass through a regulator to reduce the pressure and fed to the membrane. This however is not a reasonable solution. If the membrane needs 5 times as much air than it supplies Nitrox, a compressor needing 10 minutes to fill a cylinder would first need 50 minutes to fill the air bank and then 10 minutes for the actual fill. Filling a single cylinder would take one hour of compressor time.

To supply the air demanded by the membrane, the use of a low pressure compressor is the only reasonable solution. Most membranes work at pressures between 3 and 12 bars. The low pressure compressor should then be of an adequate size to meet the air demand from the membrane. This air must be of (very) good quality. As discussed before, the resistance at the end of and within the membrane defines the quantity of gas taking a radial path. Any additional resistance would force more gas to the side. The air blown into the membrane must thus not contain any impurities that can block passages between the fibres. Any air fed to a membrane must be filtered adequately to assure that the membrane stays functional for a long time.



The quantity of Nitrox coming out of the membrane depends on the blend for which it is set. The maximum (not for the membrane, but for the compressor) is Nitrox40. When set at a rich blend, the membrane produces less Nitrox. When selecting a membrane, the "right size" thus depends on the flow at the maximum blend at which the membrane is used (Nitrox40). At lower blends, such as Nitrox32 the membrane will produce a bigger volume. The compressor will not draw in all the Nitrox that has been produced. There is thus a second location where gas is vented from the system. Any Nitrox produced that is not entering the first stage of the compressor is lost via a valve.

If the selected membrane does not produce enough Nitrox for the demand of the compressor, the compressor might start drawing more air from its oil bin, because that could become the path that offers the least resistance. The consequences of that problem have already been discussed before. A similar (but more dramatic) problem is potentially possible when the low pressure compressor stops working while the membrane is still attached and the high pressure compressor still running. A "closed" connection to a membrane would not allow any gas to enter. The compressor could hardly draw any gas at its intake.

In order to prevent problems relating to a malfunctioning low pressure compressor or another membrane related problem, such as a hose rupture, some sort of safety system must be in place. This could simply be a valve that opens when the pressure in the hose leading to the first stage falls under ambient pressure. Some manufacturers use a more elegant solution. Rather than setting the desired blend by changing the resistance at the end of the membrane, they systematically produce Nitrox40. This Nitrox blend does not go directly to the first stage of the compressor, but is injected into a continues-flow unit. Nitrox40 is thus taking the place of the pure oxygen normally used in this equipment. The rest of the procedure is the same. If the arrival of Nitrox is disrupted, the compressor will simply draw in air that is not enriched with a flow of Nitrox40.

Limiting the Oxygen Risks

Preparing a compressor system and diving cylinders for contact with elevated oxygen content is the responsibility of certified gas blenders. It is not the intent to replace such a certification with the information given here. A technical course on compressors and nitrox installations is not complete without covering the basics of oxygen safety, which is the reason for this section.

A first step to limit the risk of auto ignition inside the compressor is the choice of oil. Because of top lubrication (lubricating from the inside of the cylinders downward), the air or nitrox to be compressed will come in contact with (small) quantities of oil. The lower the flashpoint of the oil is, the lower the risk that carbon monoxide will be created during the filling process. The flashpoint of different brands and types of oil varies. For every compressor a list of suitable oil types is provided. Not all oils in the list are an option. In most cases different oils are recommended for different working temperatures. For a compressor in the tropics, other oil types are used than for a compressor in a temperate climate. This is because of the viscosity of the oil at different temperatures. In most cases synthetic oil will perform best. If the compressor has already been running on mineral oil, the advice of a specialist has to be sought for the procedures to follow when passing to synthetic oil (the other way around is normally not a problem).

With an increased risk of carbon monoxide production, it is recommended to add Hopcalite to the fill of the chemical filter. Molecular sieve and activated carbon are standard substances for filtering, but Hopcalite is not. Adding this to the filtering process will go a long way in preventing contamination of the diving cylinders.

During the filling process, the temperature of the gas rises. As covered before, the compressor is designed to limit the rise in pressure to a maximum of 160° Celsius. The compressor was designed assuming adequate cooling. This means that the compressor must not be used above its maximum "operational ambient temperature" and that any warm air is evacuated efficiently. If a compressor can draw back the air that has already passed over the compressor (and was thus already heated up), a spiral could result in which the air gets hotter and hotter. Split well between the arriving cool air and make sure the warmed up air is blown away from the compressor.

Heat of compression also results if a section of pipe is pressurized quickly. If a valve is opened instantly between a cylinder at 200 bars and a section of pipe at ambient pressure that is closed on the other end, the temperature at the end of that pipe can rise as high as 800° Celsius. To prevent instant opening of valves, ball valves (valves that open and close with a quarter of a turn) are not recommended. Users should be trained to open valves slowly and that is hardly possible with ball valves. Another precaution is to give the pressure somewhere to go. First open the receiving cylinder, before opening the donor cylinder. As a last precaution to limit the risk of heat of compression, all flexible hoses in the system (for example the hoses on the filling console) should have a metal end part that is at least 15cm long. If a mistake is made, it will be the end of the hose that is heated up, which is not so dramatic if the end of the hose is a metal part.

Particles in the system could ignite if they strike with sufficient speed (approximately 46 meters per second). Such high speeds normally only occur in sections of pipe that have too small a diameter for the volume passing through. To avoid problems with particles, the entire system should be purged with an inert gas, before using it with oxygen rich blends.

The idea of purging is to blow all particles out of the system. This can be done with a "real inert gas" like nitrogen, but normally air will do. During construction of the system, some metal particles or other materials may be left behind in the conduits and other air spaces. They are removed by blowing a gas through the system at high speed. It should also be avoided that new particles find their way into the system. Titanium and aluminium parts are (for that reason) not recommended. The corrosion of these metals is not very well connected to the mother material. If high speed air passes along a titanium or aluminium surface, it could take the oxides (corrosion) with it as particles.

Although less likely, static electricity could also pose a problem. To avoid static electric discharge, it would help to connect the compressor frame to a metal structure that has good earth contact, such as water pipes or the heating system. The "standard" grounding of the electricity system is connected to the engine, but it may be that the connection to the rest of the compressor is not good enough to conduct static electricity from there.

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