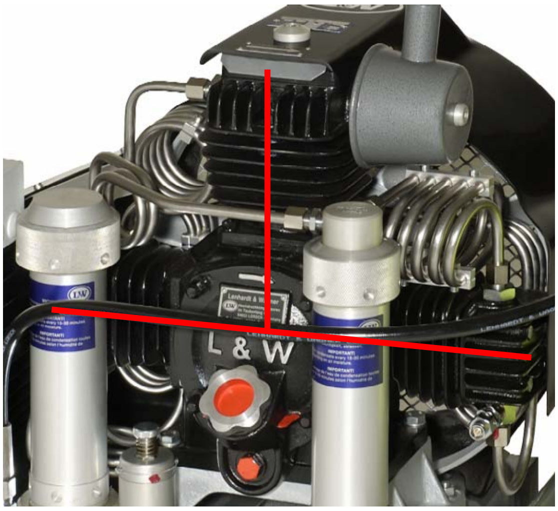
stage horizontally at the sides. A W compressor also has 3 cylinders, with the only difference that the second and the third stage are placed under a slightly upward angle. W compressors are bigger than T models. X compressors have four cylinders, which are mounted in the shape of an X.



T-shaped compressors have a 90° angle between the first stage on the top and the two horizontally mounted cylinders on the sides.

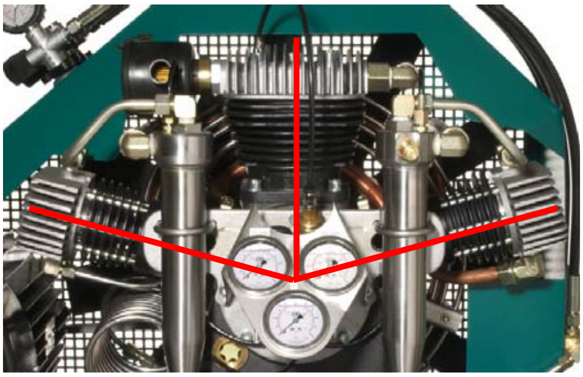
T-shaped compressors are meant for personal use. They are small and filling a single cylinder can take as long as 20 minutes. Divers who travel to remote areas use this type of compressor to fill their own cylinders.

The main problem with these compressors is the lubrication. The compressor does not have an oil-pump or other efficient mechanism to distribute the oil while cylinders are filled. It has a sort of spoon mounted on the crankshaft. Oil is spooned from the oil bin and drops are thrown-up 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 make 2.500 rotations per minute. At this speed the machine heats up fast. That problem, combined with poor lubrication leads to the advise 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 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 to get in contact with all the moving parts in the machine.

Most W compressors can run 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 are heavier; mostly they weigh more than 100kg.



W-shaped compressors also have the first stage on top, but the second and third stages are mounted in a slight upward angle.

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 centers. 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 amount of air that is compressed by 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.

X-shaped compressors have 4 cylinders mounted in the shape of an X. The second stage is mounted opposite the first stage and the fourth stage 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.

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 on the right) must be replaced.

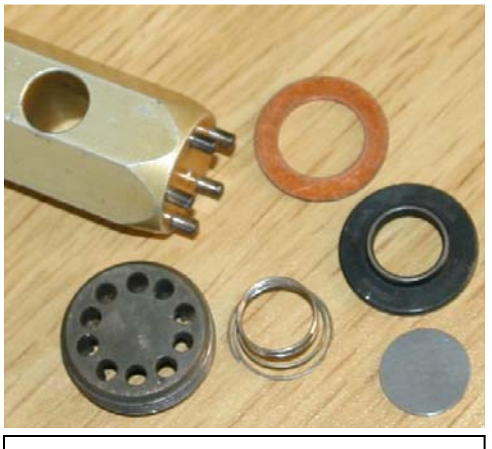
piston starts moving up. There is always one valve in the open position, while the other is closed, depending if the piston moves up or down.

In the drawing on the previous page, 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 in 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 to 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 where it flows to the next cylinder.

The valves of the last stage are smaller and can't be disassembled.

Not all brands have outlet valves that can be disassembled in individual parts. In some, the outlet valve is a single peace in which all the individual parts are assembled and sealed. If an outlet valve is malfunctioning, in most cases the seat has cut through the small valve. The picture above shows a damaged valve next to a new one. If the outlet valve can be disassembled, only replacing the small valve and the cupper washer (the parts on the right) would repair the compressor. If the outlet part 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 under an angle. In order to assemble an outlet valve, the cylinder head must be placed 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 under any angle, which makes the procedure faster and easier.

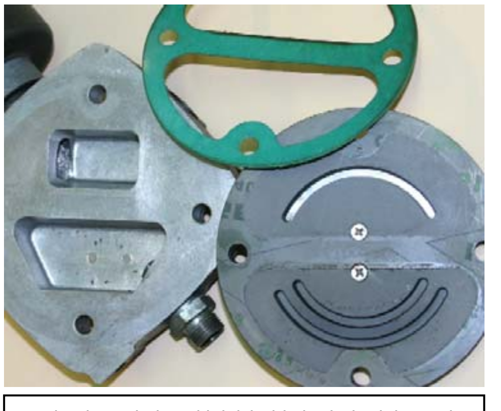


The parts of a second stage inlet valve including the special tool needed for assembly and disassembly.

For most compressors, the small inlet and outlet valves of the last stage (the cylinder with the floating piston) are a single piece. In case of a valve malfunction in the last stage of the compressor, the entire valve must be replaced.

The construction of the inlet valve is a lot 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 for that purpose is thus less necessary.

The washer is put in place first, followed by the seat, with the sharp edge in the direction of the small valve which follows next. The spring is placed in the housing and then screwed in position in the cylinder head to keep all the 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 has to be repeated. The special tool to the left in the picture is required for removing and assembling the inlet valve.



A laminated plate (right) holds both the inlet and the outlet valve for the first stage of modern compressors. It is simply mounted between the cylinder head (left) and the cylinder. Air integrity is assured by adding sealing material (top).

The air filter from a three stage compressor.

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 seek to draw in air from where the resistance is lower. That could very well be the oil bin (and thus air contaminated with oil vapor). 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 of 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, the air is always drawn through the same spot on 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 completely 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, improving the quality of the air is achieved in a mechanical manner with the use of separators that are already discussed. After the last separator, chemical filters are used to improve the quality of the air to the extent that it meets 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 maintenance such as filter changes is 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.

Two combined filters. Most compressors are equipped with a single filter.

Three substances are used in filters - molecular sieve, active coal and hopcalite. Molecular sieve only helps to remove 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 active coal. Active coal 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 odors they produce. The active carbon does thus not only remove oil, but also neutralizes odors. Hopcalite proposes an extra O to carbon monoxide (CO), so it transfers CO into 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 in not widespread. Active coal and molecular sieve are used in virtually all compressors.

A cascade control panel for three groups.

The idea of an air bank (and cascade) is to connect two pressure containers at different pressures and to allow them to equalize to achieve the same pressure. To calculate the pressure after connecting the two containers, the quantity of air available must be divided by the combined volume. The quantity of air is expressed in bar liter – the multiplication of the pressure and volume of the individual (isolated) containers. Final pressure then follows from dividing the quantity of air (bar liters) by the combined volume after opening the valve connecting the two containers (liters) - for example: a 50 liter air bank at 200 bars is connected to a 10 liter diving cylinder at 50 bars. The quantity of air then is (200 bars x 50l) + (50 bars x 10l) = 10.000 bar liters + 500 bar liters = 10.500 bar liters. The combined volume of the containers is 50 liters + 10 liters = 60 liters. 10.500 bar liters divided by 60 liters gives 175 bars. After equalization, both the diving cylinder and the air bank thus have the same pressure – in this case 175 bars. The relatively small air bank has a rather big reduction in pressure after filling just one cylinder, which is the reason why most dive operations prefer a cascade system.

In the below calculations, the difference between an air bank (all buffer capacity combined to a single volume) and a cascade (the buffer volume partitioned in smaller groups) is illustrated. 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 liter 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 liters each combined in a single volume of 450 liters. All cylinders to be filled are 10 liter cylinders with 20 bars pressure remaining.				
Series of 4 cylinders	Start pressure cylinders	Start pressure air bank	Calculation Attention: the 40 liters represent 4 cylinders of each 10 liters as in the drawing.	End pressure air bank & cylinder
1st	20 bars	200 bars	((450 liter x 200 bar) + (40 liter x 20 bar)) / 490 liter =	185.3 bars
2nd	20 bars	185.3 bars	((450 liter x 185.3 bar) + (40 liter x 20 bar)) / 490 liter =	171.8 bars
3rd	20 bars	171.8 bars	((450 liter x 171.8 bar) + (40 liter x 20 bar)) / 490 liter =	159.4 bars
4th	20 bars	159.4 bars	((450 liter x 159.4 bar) + (40 liter x 20 bar)) / 490 liter =	148.0 bars
5th	20 bars	148.0 bars	((450 liter x 148.0 bar) + (40 liter x 20 bar)) / 490 liter =	137.5 bars

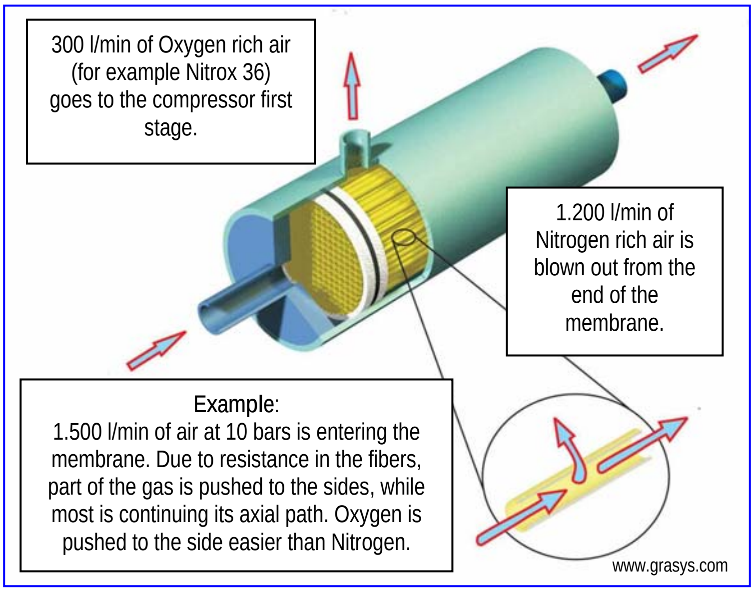
The example illustrates that the pressure in the air bank drops rather fast when filling several sets of 4 cylinders. The fourth set does not even reach a pressure of 150 bars anymore. In practical situations this means that the compressor will have to top-off the remaining pressure. The time needed 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 liters to find 2080 bar liters. A compressor giving 250 liters per minute would then need a bit more than 8 minutes to top-off the fourth series. A bigger air bank would loose 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 also 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 liter 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 first group valve 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

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 decreased. 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), but compared to the cost of oxygen that overhead might prove lower. With an increasing number of EANx 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 or 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 some 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 on 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 fibers linearly. With the right choice of fibers, 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 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 liters per minute of EANx36 at the inlet, the amount of air to be pumped through a membrane could easily be 5 times as much (1.500 liters 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.