The Trailing Edge

April 2023

Why You May Want to Use Supplemental Oxygen at Lower Altitudes Than Required

Hypoxia Onset Altitudes

This article is not about hypoxia, its symptoms, or how to treat it. There are plenty of resources available on those subjects. However, we will briefly discuss hypoxia as it provides background for the topic at hand.

As a pilot, you are probably familiar with the FAA rules on supplemental oxygen use, straight out of 14 CFR 91.211:

Altitude	Requirement
Below 12,500 feet	No supplemental oxygen required
Above 12,500 feet	Supplemental oxygen use required for durations greater than 30 minutes
Above 14,000 feet	Supplemental oxygen use required for crew members
Above 15,000 feet	Supplemental oxygen must be available for all passengers

You may be familiar with the US Air Force rules on supplemental oxygen use:

Altitude	Requirement
Below 10,000 feet	No supplemental oxygen required
Above 10,000 feet	Supplemental oxygen use required
25,000 feet	Maximum cabin altitude with supplemental oxygen
Above 50,000 feet	Full pressure suit required in pressurized aircraft
60,000 feet	Maximum altitude in F-22 with a partial pressure suit
Above 5,000 feet	Supplemental oxygen use recommended at night

If you go to altitude chamber training (highly recommended if you can get it), the emphasis of the training relative to the altitudes listed above is on Time of Useful Consciousness (TUC), or how long you can function in a high-altitude environment without supplemental oxygen before you go stupid or pass out. Because the TUC can get very short, the emphasis is on recognizing your hypoxia symptoms and getting on supplemental oxygen before your TUC runs out. Here is an FAA table of typical TUC, lifted directly from Wikipedia (Ref 1). Your mileage may vary.

Pressure Altitude	TUC (normal ascent)	TUC (rapid decompression)
FL180 (18,000 ft; 5,500 m)	20 to 30 minutes	10 to 15 minutes
FL220 (22,000 ft; 6,700 m)	10 minutes	5 minutes
FL250 (25,000 ft; 7,600 m)	3 to 5 minutes	1.5 to 3.5 minutes
FL280 (28,000 ft; 8,550 m)	2.5 to 3 minutes	1.25 to 1.5 minutes
FL300 (30,000 ft; 9,150 m)	1 to 2 minutes	30 to 60 seconds
FL350 (35,000 ft; 10,650 m)	30 secs to 1 minute	15 to 30 seconds
FL400 (40,000 ft; 12,200 m)	15 to 20 seconds	7 to 10 seconds
FL430 (43,000 ft; 13,100 m)	9 to 12 seconds	5 to 6 seconds
FL500 (50,000 ft; 15,250 m)	8 to 10 seconds	5 seconds

At 10,000 feet a reduced ability to learn new tasks can be measured (Ref 2). Additionally, a person who normally lives at sea level who finds themselves at 10,000 feet pressure altitude for an extended period of time (such as 12 hours or more) will eventually reach a blood oxygen saturation of around 84%, which is generally accepted as qualifying as “clinical hypoxia”. Long exposures at higher pressure altitudes rapidly get worse (Ref 3).

Thus, the Air Force set the requirement for supplemental oxygen use at a cabin altitude above 10,000 feet. The Air Force has one advantage while mandating supplemental oxygen use. All of its aircraft intended to operate above 10,000 feet either have pressurized cabins (such that the cabin altitude never exceeds 10,000 feet) or the aircraft are equipped with supplemental oxygen systems. The last Air Force aircraft I know of that did not have a pressurized cockpit but was expected to operate above 10,000 feet was the Cessna T-37. In the T-37 the aircrew wore helmets with oxygen masks, and supplemental oxygen was supplied through a regulator.

However, many general aviation aircraft are not pressurized, do not have supplemental oxygen systems, and yet operate at altitudes just above 10,000 feet. The body has some spare capacity to operate at an acceptably degraded state slightly above 10,000 feet (Ref 3). Thus, the FAA allows for operations up to 12,500 feet without supplemental oxygen, and over 12,500 feet (but below 14,000 feet) for no more than 30 minutes. One possibly apocryphal tale states that these limits were set because it was possible for unpressurized commercial airliners, such as the DC-3, to cross the Rocky Mountains through certain passes without violating these rules, thus allowing the airlines to avoid the cost of installing oxygen systems in non-pressurized aircraft. Whether this story is true or not, it is possible to cross the Rocky Mountains without supplemental oxygen without violating the FAA regulations.

The altitudes for supplemental oxygen use are set assuming an individual with a healthy respiratory system. Those with asthma or other respiratory issues may notice hypoxia symptoms at lower altitudes. One person I know with asthma starts to feel the effects above 5,000 feet.

So, while very important, your altitude chamber training would lead you to believe that the sole purpose of supplementary oxygen use is to extend your Time of Useful Consciousness to longer than necessary to complete your flight. That is certainly one reason, but just like Yoda said, "there is another".

The Experiment That Started All This

Back in 2002, Gary Aldrich and I were flying in the Fightin' Skywagon to Oshkosh for AirVenture. On our first day we flew from Fox Field (KWJF) to Hays Kansas (KHYS). To get there, we had to fly over Colorado through the Cumbres Pass (V368) and La Veta Pass (V83-210). Both of these passes can be flown VFR without exceeding 12,500 feet, but not much lower. After flying all day without supplemental oxygen with one leg at 11,500 feet, at dinner that night we realized that we were both very fatigued, like we had been mountain climbing all day, even though it seemed to us that all we did all day was to sit. We did that at the office all day and still felt good enough to have a full evening of activities. How could sitting all day be so fatiguing?

For the next Oshkosh trip (2004), we flew from Fox Field (KWJF) to Casper Wyoming (KCPR). This route would require similar high altitude legs around 11,500 feet, mainly over the Provo River from Provo to Heber City Utah. This time Gary directed me to buy my own cannula so we could try using his oxygen system. This time we used the oxygen at altitudes below the required 12,500 feet, and when we arrived at Casper, we felt no more fatigued than after a day at the office. This was sufficient anecdotal evidence that supplemental oxygen could be useful at altitudes below where it is required.

Altitude Induced Fatigue is a Thing

So now we had reason to believe it was useful to use supplemental oxygen at altitudes below where it is required to ensure "Useful Consciousness", but for years I have been trying to understand why. After all, sitting in my desk chair at a pressure altitude of 2300 feet doesn't *feel* any different than sitting in an airplane seat at 9500 feet, but clearly something is going on.

We are about to start talking about human physiology, and I will admit that I am not an Aerospace Physiologist, nor do I play one on TV. I did do well in my biology classes, but to make sure I had the details correct I consulted with the USAF TPS Staff Aerospace Physiologist (Ref 3).

At any given moment, the cells in your body have a certain demand for oxygen for metabolism. This demand depends on what you are doing. If you are sitting watching the pregame festivities for the Super Bowl and eating Tuki's yummy food, you don't need very much oxygen. However, if you are at Mountain Valley airport pushing a glider out to the runway or running inside to get a replacement yaw string, your demand for oxygen will be higher.

We all know how we get more oxygen to our cells when exercising. Exercise increases the metabolic demand of the cells. The blood needs to flow faster while (ideally) maintaining the same blood oxygen saturation (percentage of arterial red blood cells carrying oxygen) to supply the increased demand. Our heart rate gets faster (increase in rate) and the stroke volume increases (increase in volume) which pushes the oxygenated blood to the cells faster to keep up with the increased demand. Now that the blood flow has increased, the flow of oxygen in the lungs into the blood must increase to keep the blood oxygen saturation the same. To accomplish an increased flow of oxygen, our breathing gets deeper (increase in volume) and more rapid (increase in rate).

Our bodies (when functioning properly) have an absolutely wonderful control system to manage the blood pumping and breathing right to the minimum level required to meet the oxygen demand. If you exercise hard enough to overwhelm the ability of the heart and lungs to supply the required amount of oxygen, then you go into oxygen debt. However, if your oxygen demand remains within the capability of the heart and lungs, the body's control system will ensure that the effort required for blood pumping and breathing stays at the minimum required. This is because blood pumping and breathing both require muscular work, and this work consumes your energy supplies and contributes to overall fatigue, just like that muscular work you used to walk that 10K.

So, we understand that if we exert ourselves, that will cause increased effort to deliver more oxygen to the cells. "But I thought we were going to talk about why I get tired just sitting in the airplane, not from walking that 10K with Stormy and Mary." That's right, we are. The difference is that your body's demand for oxygen isn't that much different between sitting in your office chair and sitting in your airplane, but your body's ability to deliver that oxygen is different.

For oxygen to be absorbed into the bloodstream in the lung's alveoli, the pressure of the oxygen in the lungs must be higher than the pressure of the oxygen in the bloodstream. More specifically, the partial pressure of oxygen in the lungs must be greater than the partial pressure of oxygen in the bloodstream. Partial pressure is the pressure of a gas in a mixture as if it alone occupied the entire volume of the mixture at the same temperature (Ref 4). In the case of oxygen, the partial pressure is about 20% that of atmospheric pressure, because air is 20% oxygen by volume. Because the partial pressure of oxygen in the lungs is greater than that in the bloodstream, the oxygen is "pushed" into the blood and latches on to some waiting hemoglobin. (Likewise, the partial pressure of carbon dioxide in the bloodstream is higher than the partial pressure of carbon dioxide in the lungs, so the carbon dioxide is pushed out of the bloodstream.)

When we go up in altitude, the atmospheric pressure decreases and thus the partial pressure of oxygen decreases. Because the partial pressure of atmospheric oxygen is less, but the partial pressure of bloodstream oxygen is the same, the difference (or gradient) between them is reduced. When the gradient is reduced, the amount of force "pushing" the oxygen into the bloodstream is reduced, **so less oxygen gets into the bloodstream**, reducing the blood oxygen saturation. Herein lies the big problem.

The demand of the body cells for oxygen has not changed, so the required mass flow of oxygen needs to remain the same. Mass flow is given by the continuity equation

$$\dot{m} = \rho A V$$

which says that the mass flow can be calculated as the product of density, cross sectional area, and velocity. In our example, we will assume the cross-sectional area of the arteries stays the same. Because less oxygen was absorbed into the bloodstream (because of the lowered partial pressure of oxygen in the atmosphere), the blood oxygen saturation (represented by density (ρ)) is reduced. If the density of oxygen is reduced, then the only way to maintain the required mass flow is to increase the velocity. That is, if fewer red blood cells are carrying oxygen molecules, then they need to be pumped faster such that the same number of oxygen molecules are pumped by the cell as at lower altitudes. This increase in blood flow comes from a faster heart beat (higher frequency) and an increase in heart stroke volume (higher volume).

Once again, because the blood flow rate has increased, the rate of oxygen absorption in the lungs must increase to maintain whatever blood oxygen saturation is possible. This is accomplished by breathing deeper (more oxygen available in the lungs) and by breathing faster (bringing in more oxygen per minute).

So, when less partial pressure of oxygen is available to the body, the body responds by pumping what it has faster so that the cells still see the same amount of oxygen, and by breathing deeper to capture more oxygen to maintain the blood oxygen saturation. All of this extra breathing and blood pumping takes energy, and **this leads to the additional fatigue caused by flying at high altitude**.

The real kicker to this problem is that this additional workload goes mostly unnoticed by the conscious brain, so you don't realize you are working harder. Generally, you won't notice a difference unless you are at least at 10,000 feet, and then only if you are doing mild exertion, such as walking up a hill. However, your body actually starts trying to compensate for the reduction in available oxygen at altitudes as low as 4500 feet. Remember the recommendation to use supplemental oxygen above 5000 feet at night for better vision? The eyes are perhaps the most sensitive organs in your body to a reduction in available oxygen, and the reduction of oxygen even at this low altitude reduces the cones' ability to detect colors.

Thus, avoiding Altitude Induced Fatigue is the best reason for using oxygen at lower altitudes than required by the FAA, especially if you don't like feeling tired. I generally use oxygen starting at around 9500 feet, and sometimes even lower.

Increasing the Partial Pressure of Oxygen Available in the Lungs

So how do we increase the partial pressure of oxygen available in the lungs? No, it doesn't require attaching a hose to your face and inflating you like a party balloon. The key is that we need to increase the partial pressure of oxygen, not the overall pressure of gases in the lungs. To increase the partial pressure of oxygen in the inspired gases we must increase the percentage of oxygen in the mixture of gases. This can be done as simply as just adding pure oxygen to air, which will increase the percentage of oxygen in the mixture above 20 per cent.

However, just adding oxygen only works up to a certain altitude. At 35,000 feet pressure altitude, the ambient pressure is roughly equal to the partial pressure of oxygen at about 8,000 feet pressure altitude. Thus, at 35,000 feet pressure altitude, the mixture of breathing gases must be 100 per cent oxygen just to get the required partial pressure of oxygen for proper respiration. I have heard less informed sources state that the pressure inside an astronaut's space suit while on a spacewalk is equivalent to being at 35,000 feet. While strictly true, they leave out that the gas mixture inside the space suit is 100 per cent oxygen, so it is nothing like standing on top of Mount Everest, where the oxygen is only 20 per cent.

Flying above a cabin altitude of 40,000 feet does actually require inflating you like a balloon with 100 per cent oxygen at a pressure higher than the air pressure surrounding you. This is called "pressure breathing" and it is extremely exhausting and dangerous. The danger comes about because your breathing process is reversed. In normal breathing, you use muscular exertion to draw air into the lungs. Relaxing the chest pushes the air out of the lungs. Under pressure breathing, relaxing causes the lungs to fill with air. To exhale, muscular exertion (like blowing hard to inflate a balloon or pool toy) is required. The body's control system does not understand this, and it requires conscious effort just to breath. Relaxation will cause you to suffocate with inflated lungs.

The other option to increase the partial pressure of oxygen available is to inflate the airplane with air, which is usually referred to as pressurization. Most pressurized aircraft can only pressurize to a particular difference above the outside air pressure because of leaks or structural strength. Thus, above some critical altitude, the cabin pressure of a pressurized airplane will start to reduce as altitude is increased. Most airliners only pressurize the cabin to about 8,000 feet pressure altitude. This is sufficiently low that most people will not significantly notice the effects. Pressurizing to a lower altitude requires more bleed air from the engines, which reduces the thrust, which requires an increase in fuel flow to compensate. Additionally, higher pressure will put more stress on the structure of the fuselage, causing it to fatigue and crack quicker. If you've ever felt fatigued after a long flight in an airliner, even though you were just sitting there, refer to the discussion above. An altitude of 8,000 feet is sufficient for you to start feeling Altitude Induced Fatigue, especially after six or more hours.

Military fighters and bombers don't overpressurize for another reason besides structural airframe weight. An ejection at high altitude would clearly fit the definition of a rapid decompression. The likelihood of suffering decompression sickness (DCS, also known as "The Bends") is increased as the amount of pressure change is increased. It is quite possible that an aircraft at 50,000 feet pressure altitude might have a cabin pressure as high as 25,000 feet, the maximum allowed without pressurization. The aircrew remain fully oxygenated because they are breathing from a demand regulator with a sealed mask. A rapid decompression from 25,000 feet pressure altitude to 50,000 feet pressure altitude is much less jarring to the physiological system than going from 8,000 feet to 50,000 feet. This is not as big of a problem for airliners, as a small hole won't depressurize that fast. A hole big enough to cause a rapid decompression in an airliner is going to be big enough to cause even bigger problems. Aloha Airlines Flight 243 comes to mind.

Acclimatization to Lower Atmospheric Pressure

Yes, there are people living in La Paz Bolivia (elevation 11,942 feet) who don't seem to be passing out on a regular basis. When you moved from Texas to Colorado, you felt kind of krappy for a while but eventually felt better. Another compensation available to the body when exposed to a lower partial pressure of oxygen for an extended period of time is to increase the number of red blood cells in the bloodstream. This doesn't happen overnight, though. It actually takes about six months. More blood cells to carry oxygen helps with increasing the amount of oxygen in the blood at the same blood oxygen saturation. Of course, when you then move back to Texas, over the next six months your body slowly reduces the number of red blood cells by not replacing them as fast as they are removed because it has no need to maintain that many red blood cells.

A popular thing with athletes is to spend a few weeks at high altitude, thinking it will improve their endurance. The Arizona Cardinals will go to Spring Training for about three weeks in Flagstaff AZ (elevation 6,910 feet), then return to Phoenix. This brief time does not really increase the oxygen capacity (VO_2) of the players. At most, it teaches them to push through the discomfort and pain of oxygen debt to allow temporary bursts of increased output.

How Can I Detect Early Onset Hypoxia?

One way you can detect hypoxia is by going to the altitude chamber and learning what your hypoxia symptoms are. Of course, that's not available to everyone, and by the time you feel your symptoms it's really later than you had wished it would be.

Fortunately, there is instrumentation available! Remember the last time you went to the doctor and somebody clipped a thing over one of your fingertips and then wrote down some cryptic numbers? Well, the little electronic marvel that revolutionized medical care has applications in the cockpit too. Best of all, they're dirt cheap! Do a search for "pulse oximeter" and you will be presented with hundreds of choices. At the time of this writing, I saw one on Amazon for as little as $16.

Pulse Oximeter

This magic little battery powered device will tell you your current pulse rate (PR_{bpm}) and your blood oxygen saturation ($SpO_2\%$).

How does this non-invasive magic happen? Inside the device on one side are two LEDs. One is colored red and the other is colored infrared. On the other side of the device is a photocell which can detect red light and infrared light. If you put your finger over a flashlight, you know that some light will pass through your finger. When the light comes out of your finger, it tends to look red, because all of the other color wavelengths were absorbed based on the colors of your tissues. Using this idea to advantage, the key principle at play is that red blood cells with oxygen (oxygenated) and red blood cells without oxygen (deoxygenated) are different colors, both in the visible spectrum and the infrared spectrum. As such, oxygenated cells absorb different amounts of red and infrared light when compared to deoxygenated cells. Deoxygenated blood (venous) is not colored "blue" like all of those diagrams in your biology book imply, but it is a different color than oxygenated blood.

"Okay, Spectrum Absorption Boy," you're probably thinking, "how do you separate that out from the absorption by bones, skin, fat, and the little guys who open and close the capillaries (Ref 5)?" The red and infrared absorption caused by those things remains constant, but the absorption caused by the blood cells pulses, because of, well, your pulse. The microprocessor in the oximeter ignores the constant part of the signal and focuses on the pulsing part. By counting the pulses, it can tell you your pulse rate (frequency). By looking at the intensity of the colors of light received and comparing it with the known intensity without a finger, the microprocessor can do some maths and figure out what percentage of the red blood cells are carrying oxygen.

For a more complete explanation of how a pulse oximeter works, watch the Technology Connections video at https://youtu.be/4pZZ5AEEmek (Ref 6).

While no one will publish what blood oxygen saturation values "should" be (because it varies person to person), it seems generally accepted that while sitting at rest, values from 100% down to about 95% are generally okay. Another generally accepted value is if you see 90% or less in flight you really need to take action—either get on supplemental oxygen or descend.

For those of you competitive types out there (you know who you are), you'll just have to be satisfied with 99% $SpO_2\%$, because most pulse oximeters only have two characters on the display and thus can't display "100%".

One last faulty indication to be aware of—red blood cells bonded to carbon monoxide (CO) are the exact same color as they are when bonded to oxygen molecules. As such, the pulse oximeter can't tell the difference between carbon monoxide and oxygen, so it won't work as a carbon monoxide detector. You'll need a separate device for that.

Portable Oxygen Systems

If your airplane doesn't come with a pre-installed oxygen system then you are probably going to want a portable oxygen system. Having a portable oxygen system is also useful in your car, if you happen to be driving up Pikes Peak or have someone with asthma or otherwise compromised breathing in your family.

I bought my portable oxygen system, an Aerox 4M system, from the nice man in the Aerox booth at Oshkosh 2009 (https://www.aerox.com) . (If you bring your Aerox oxygen cylinder to the Aerox booth at Oshkosh, they will refill it for you right there. This is always my first order of business on Monday morning when at Oshkosh.) There are other brands available, such as Sky-Ox, but Aerox acquired Sky-Ox in 2022, so it is now just one company. They continue to support the Sky-Ox brand. Why did I choose Aerox? Probably because that is what Gary Aldrich had. Since I am familiar with Aerox, that is the style I will be talking about here.

When you order a portable oxygen system, it will come with all of the bits and bobs that I will talk about. The one difference you may have to choose is what type of cannula or mask you want.

Cannula

Cannula is a funny word that reminds me of canoe, but actually comes from the word “cane” like a reed. Strictly speaking, a cannula is some sort of tube. It this case, it is a tube that introduces oxygen into your nose. In its simplest form, an oxygen cannula is a tube with two small tubes to stick in your nostrils.

Standard cannulae for adults (left) and children (right)

This cannula may remind you of what a patient in a hospital would use, because that is exactly what it is. The children’s cannula is the same except the nostril tubes are smaller and closer together.

These cannulae are actually rather wasteful of oxygen. To address this, Aerox offers their Oxysaver cannulae.

Oxysaver “mustache” cannula (left) and pendant cannula (right)

Standard cannula (left), child cannula (center) and "mustache" oxysaver cannula (right)

With the standard cannula, the flow rate of oxygen must be high enough that sufficient oxygen is drawn in during inhalation. During exhalation, the oxygen that is flowing is just blown into the atmosphere with the exhaled gases.

With the oxysaver cannula, oxygen flows at a much lower rate, about half to a third of the rate with the standard cannula. When inhaling, some of the oxygenated air enters the nose but never reaches the lungs, being caught in the trachea and nasal passages. When exhaling, this oxygen rich air is the first air to come back out of the nose. In the oxysaver cannula, this oxygen rich air inflates an 18 ml bladder in the "mustache" or pendant. During the remainder of exhalation, the exhaled air passes around the cannula, while new oxygen from the cylinder is added to the air trapped in the bladder. On the next inhalation, this super-oxygenated air is the first air to be inhaled, meaning it is then drawn into the deep parts of the lungs. Oxygen from the cylinder continues to flow and is drawn in with the rest of the inhaled gases. Thus, all of the oxygen from the cylinder makes it into the lungs instead of part of it being wasted with the exhaled gases. In the pendant style oxysaver cannula, the bladder is on your chest instead of in a stylish mustache.

A recently introduced variation on the cannula is the "boomula", which is mounted to your headset instead of running tubes around your head. A pendant farther down the tube contains the oxysaver bladder.

Oxysaver Boomula

For hopefully obvious health reasons, any person using your oxygen system should have their own personal cannula, and should not use one used by someone else. Having a personal cannula is not really a big deal, since the cost of the cannula is under $40. The remainder of the system can be used by multiple people without problems.

According to Reference 7 from the FAA, "**Nasal cannulas**. These are continuous-flow devices and offer the advantage of personal comfort. They are restricted by federal aviation regulations to 18,000 feet service altitude because of the risk of reducing blood oxygen saturation levels if one breathes through the mouth or talks too much."

For higher use, up to 25,000 feet, you can buy an Oral-nasal re-breather mask.

Oral-nasal (mouth and nose) re-breather mask

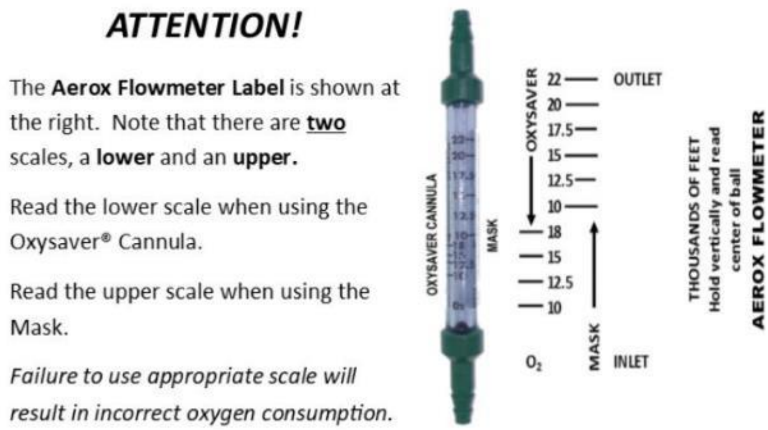
Again from Reference 7, "it has an external plastic rebreather bag that inflates every time you exhale. The purpose of the rebreather bag is to store exhaled air, so that it may be mixed with 100% oxygen from the system. These masks supply adequate oxygen to keep the user physiologically safe up to 25,000 feet."

The downside of the masks is that they require a higher oxygen flow rate, so the supply does not last as long. Part of this high flow rate is caused by the higher altitude, and part of it is caused by a less efficient use of the oxygen.

For cabin altitudes higher than 25,000 feet, a completely different type of oxygen system from the one being discussed here will be required. Then again, if you have an airplane capable of flying above 25,000 feet, it's probably pressurized and none of this matters.

Flowmeter

In the oxygen tube from the cylinder to the cannula you will find a flowmeter. This device is used to measure the proper oxygen flow rate.



Flowmeter

On the bottom of my flowmeter there is a needle valve that when turned one way stops the flow of oxygen. Turning it the other way slowly increases the flow of oxygen. Other systems may have a separate needle valve. The flowmeter contains a simple ball-in-cone flow rate sensor, and must be held vertically to set the flow rate. The lower (and thus slower) scale is used for oxysaver cannulae. The upper scale is used for standard cannulae or the mask.

My flowmeters glow in the dark, which I assume helps with using them at night.

For using oxygen at altitudes below 10,000 feet, I set the flow rate to the 10,000 feet line, which is about the minimal reasonable flow rate.

Regulator

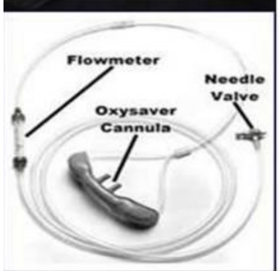
The oxygen in the cylinder may be at a pressure of 2000 psi or slightly more. In the plastic hose running to your cannula, the pressure needs to be just barely above atmospheric pressure. This pressure drop is accomplished by the regulator.

Four place regulator

This regulator is screwed to the top of the oxygen cylinder. Aerox sells this regulator with one, two, four, or six outlets. My oxygen system is labeled a “4M” system. The “4” specifies the number of outlets, and the “M” specifies the size of the cylinder. The number of outlets determines how many people can simultaneously use the system.

Cylinder

Of course, there needs to be a cylinder to store the oxygen in. We are covering high-pressure cylinders, storing oxygen at 1800-2200 psi.



Some Oxygen Cylinder Sizes Available

My recommendation on cylinder size is to get the biggest one you can fit into your airplane. For me, the “M” size cylinder fills the space under the rear seat very nicely. Where ever you choose to place the oxygen cylinder, I highly recommend that the ON-OFF valve be accessible in flight. It doesn’t help much to be airborne with oxygen on board and decide you want to use it, but you can only open the valve on the ground. In my Bearhawk, I can reach the ON-OFF valve of the oxygen cylinder while strapped in the pilot seat.

Oxygen cylinders can be made from aluminum or steel. There is conflicting information on the Interwebs about testing and service life, so I can’t remember which is correct. I will restrict my comments to aluminum cylinders, as that is what I have. Aluminum cylinders, by law, are required to be hydro-tested every five years. Hydro-testing is simply pressure testing to a pressure well above the service pressure to check for cylinder integrity. It is called hydro-testing because the cylinder is filled with pressurized water for the test. If pressurized air was used and the cylinder fractured, the result would be a low-yield bomb (it would still cause a lot of damage) as the air expanded. Since water is incompressible, if the cylinder fractured, the water would simply spray out of the crack but would not send shrapnel all around the shop. Of course, after the test, the water must be drained out and the cylinder dried, which is apparently done by heating the cylinder or blowing hot air into it for a while. Of course, when you get the cylinder back, it will need to be refilled with oxygen. The sooner the better to keep moisture from getting into the cylinder.

Hydro-testing is required for all gas cylinders, so the service is usually readily available. I have mine done at Fire Ace in Lancaster CA. Their normal stock-in-trade is fire extinguishers, but that test equipment works just as well for oxygen cylinders. They don’t even flinch when I take it in, as it is a normal service for them.

Besides the ON-OFF valve, the cylinder comes with a pressure gauge. The pressure decreases pretty linearly with use. Pressures below 500 psi are marked in red, hinting that if your pressure is below 500 psi you should really consider getting it refilled.

Filling the Oxygen Cylinder

Filling your oxygen cylinder would seem to be a simple process: go to the FBO, they fill it (assuming they even offer this service), and you hand them a wad of cash. Done.

Yes, that works, but it doesn't have to be like that. The first thing you may notice is that the price for an oxygen fill is a flat rate, regardless of the size of your cylinder. That is because the actual cost of the oxygen that goes in your cylinder is mere pennies. The high price you are paying is essentially the hourly wage of the person who filled your cylinder, since he or she can't be doing any other billable activity while filling your cylinder. Add in a little bit for the insurance premiums for pumping high pressure gas into a cylinder that the FBO has no idea of its integrity.

There is no "certification" requirement to refill oxygen cylinders, so if you are willing to spend money, you can do it yourself. Typically, your small cylinder that goes in the airplane is filled from a large cylinder that stays in your shop. Of course, filling your small cylinder will remove oxygen from the large cylinder, causing its pressure to drop. The two cylinders will stabilize at some pressure below where the large cylinder started. Keep doing this, and the pressure that you can fill your small cylinder to decreases with each fill.

One way to stave off this loss of pressure is to use a series (or cascade) of large cylinders to fill the small cylinder. The large cylinder with the lowest pressure is used first to do the grunt work of getting most of the oxygen into the small cylinder. Then a large cylinder with higher pressure is used to add a little more oxygen to raise the pressure further. A third large cylinder can be used to further raise the pressure. This uses very little oxygen from the third cylinder. More cylinders could be used, but the benefit drops off rapidly after the third cylinder.

When the third cylinder gets to an unacceptably low final pressure, the first cylinder is swapped out for a new, full large cylinder which takes the place of the third cylinder. The previous second cylinder becomes the first cylinder, and the previous third cylinder becomes the second cylinder.

So how well does that work? Let's do some recreational maths to find out. Starting with the Perfect Gas Law (Equation of State)

$$P = \rho RT$$

Let's break the density apart into mass and volume.

$$P = \frac{mRT}{V}$$

When we connect two cylinders together, then the total mass of the gas must fill the total volume of the two cylinders. Using a subscript "1" for the first large cylinder and a subscript "T" for the target cylinder, the equation becomes

$$P = \frac{(m_1+m_T)RT}{(V_1+V_T)}$$

ASSUMPTION ALERT: This very simplified equation has several assumptions that we should be aware of. Even with these assumptions, it still gives a good indication of how the pressures will drop.

1. The equation assumes all of the gas in both cylinders is at the same temperature. As the gas moves into the low pressure cylinder it will be compressed, which will raise its temperature (just like that bicycle pump you dropped because it got hot). This temperature rise requires energy. This is known as pressure-volume work (Pv work) in the trade. The faster the compression, the more energy is lost to heat from the rising temperature. In practice, the target cylinder is typically submerged in water to absorb this heat. For purposes of this discussion, we will assume that the transfer of gases happens very slowly so there is no significant Pv work and hence no rise in temperature.

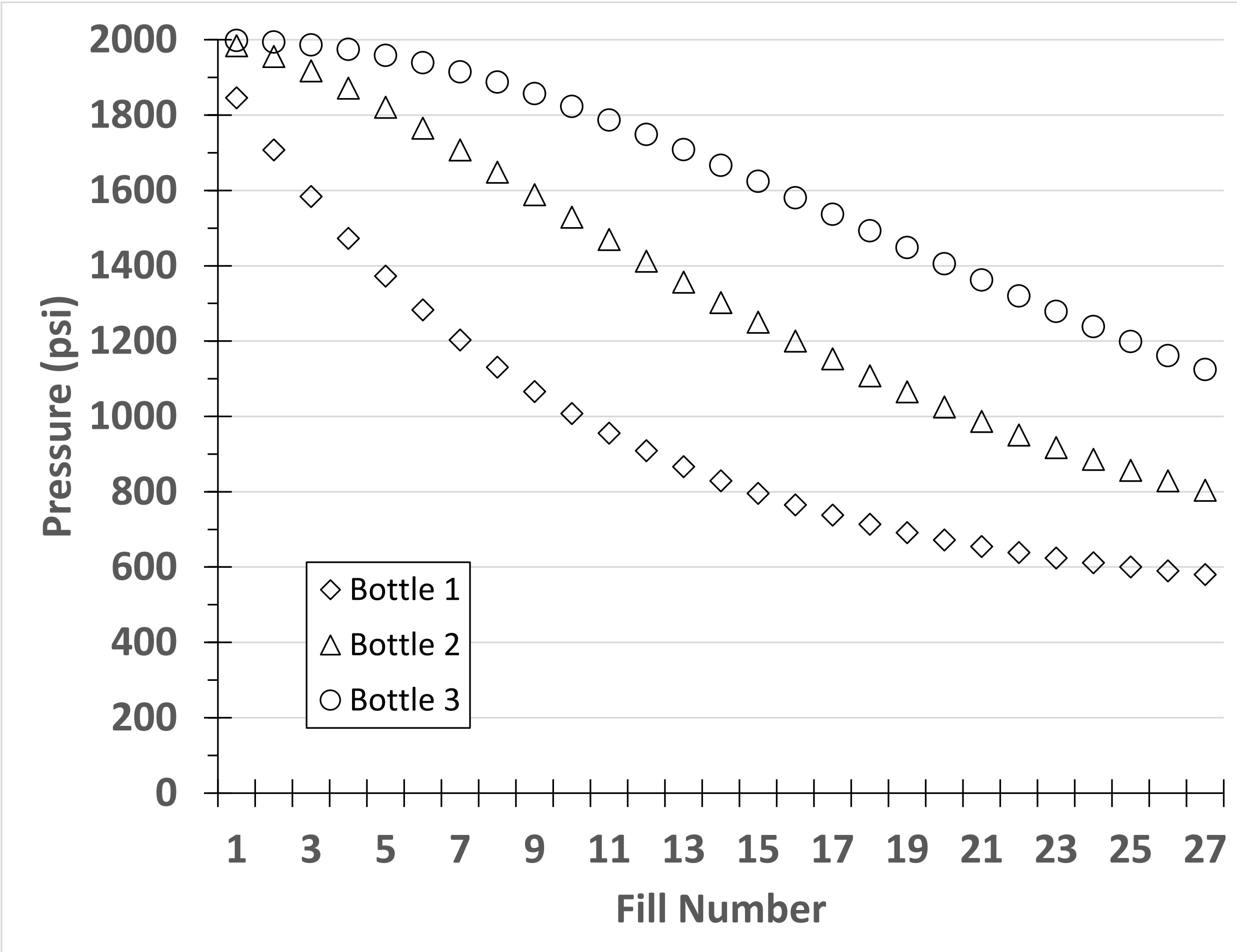
2. The gas constant to be used is not the familiar gas constant for air, but rather the gas constant for pure oxygen.

$$R_{O_2} = 2797.2 \frac{ft^2}{sec^2\text{-}K}$$

Now let us assume we have three source cylinders, each at 2000 psi pressure and a labeled volume of 200 cubic feet. That means that the gas inside the cylinder would have a volume of 200 cubic feet at standard temperature and pressure (STP), which would be 59° F and 14.7 psi (Sea Level Standard). Doing some maths, we find the actual volume of each of these three cylinders is 1.47 cubic feet.

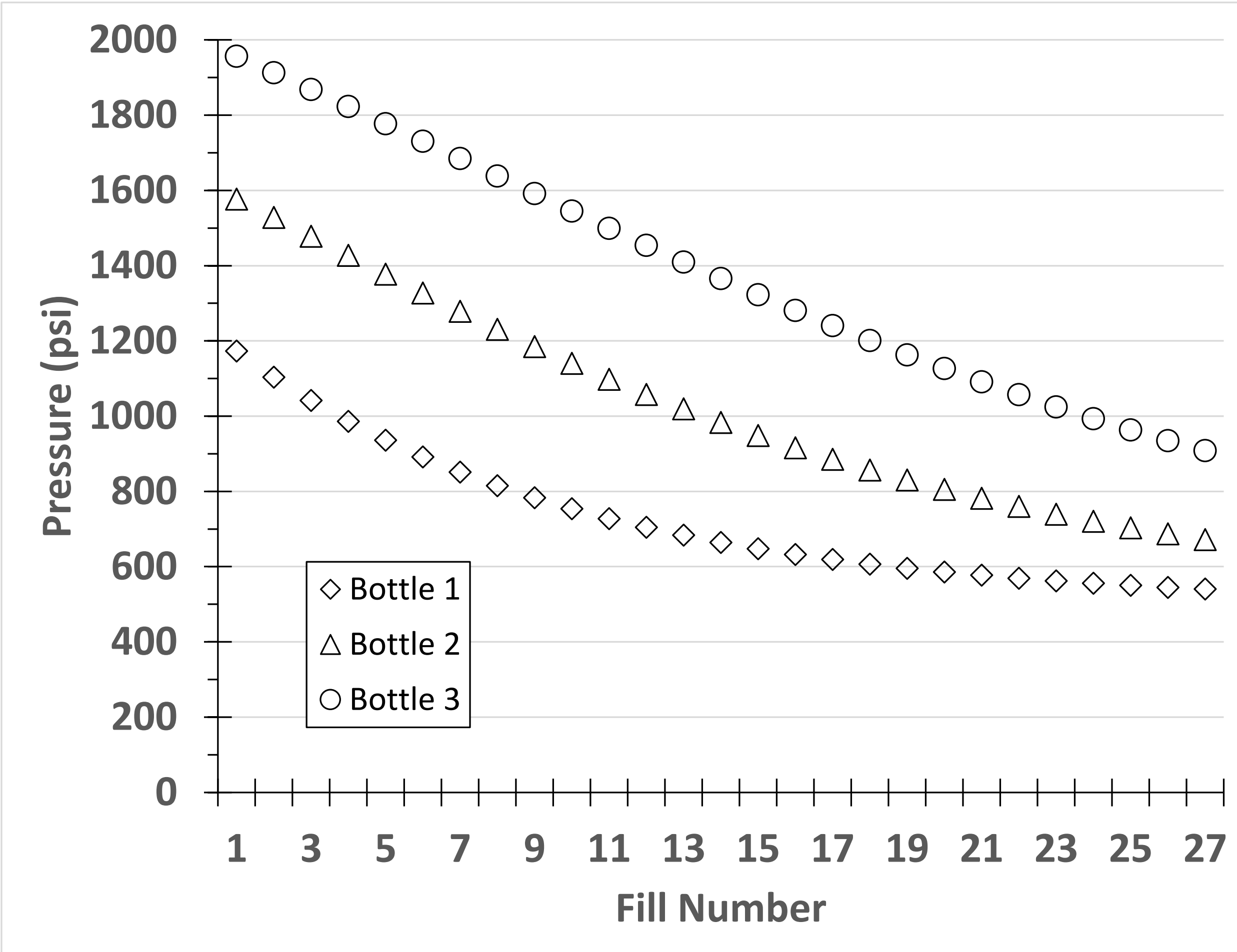
The target cylinder has an advertised volume of 648 liters at 2000 psi pressure. This calculates to an actual volume of 0.168 cubic feet. The target cylinder will be assumed to be at 500 psi at the beginning of each fill cycle. (I would later find out that my cylinder has a service pressure of 2216 psi. That means the actual volume is 0.152 cubic feet. I'm not changing the graphs because the conclusion is the same.)

We will do the analysis at a temperature of 59°F, although strangely the temperature doesn't affect the final pressure, just how much oxygen is in the cylinder at that pressure.



Cascade Pressure of Each Cylinder. Target Cylinder Pressure Equals Cylinder 3

With this setup, we can accomplish 15 fills with the final pressure only getting down to 1623 psi. At this point, Cylinder 1 is getting close to the starting pressure of the target cylinder, and therefore not contributing much to the fill. If we then swapped out Cylinder 1 for a new cylinder at 2000 psi and moved it into the third position, then the graph would look like this:



Cascade Pressure of Each Cylinder After Renewing Cylinder 1 as Cylinder 3

Now we can get eight fills before the target pressure falls below 1600 psi. Compare this to using only one cylinder (see previous chart) where we would only get three fills with the pressure already slightly below 1600 psi.

Where Does the Oxygen Come From?

From the atmosphere, of course! The real question is how is it separated from all of the nitrogen, argon, and other stuff. The answer is surprisingly similar to the way gasoline or kerosene is separated from crude oil—by taking advantage of differing boiling points.

Per Reference 8, air is filtered, and then alternately compressed (which raises the temperature) and then cooled. This is done several times, until the air is at about 2000 psi and 70°F. High pressure air cannot hold as much water vapor as low pressure air, so water is drained out at each step as it condenses out, resulting in almost perfectly dried air. Then the pressurized air is cooled to -275°F and the pressure is dropped to about 90 psi. At this point, oxygen and nitrogen are liquid and everything else is frozen and filtered out. By playing with the temperatures, the oxygen vapor is boiled off. The oxygen vapor, still at about 90 psi, is re-cooled, liquified, and stored in double-walled containers. (Atmospheric air is about one per cent argon, so during this process the argon is separated out to be used for inert gas welding and other processes.)

To get the oxygen to the state that it comes to us, the liquid oxygen is boiled off and the gaseous oxygen is compressed to 2000 psi to go into the cylinders you pick up at the distributor.

The Aviator's Breathing Oxygen (ABO) myth

According to the FAA (Ref 7), "Aviator's oxygen must meet certain standards to ensure that it is safe to be taken to altitude. Only aviator's grade breathing oxygen meets this specification. Neither medical grade nor industrial grade oxygen is safe to substitute because they do not meet the same stringent standards as ABO." Strangely, this statement is not supported by any extant regulation. In lives on because it is “common knowledge” passed by oral tradition from pilot to pilot. Reference 8 tells that oxygen type is not mentioned in any regulation, only in Advisory Circulars (non-regulatory). Even those Advisory Circulars say the Aviators Breathing Oxygen **or equivalent** must be used. Reference 8 goes on to say “Some really heavy-duty experts have scoured government documents, and queried many government agencies, trying to find out just what the heck ‘equivalent’ means in this context. Its meaning appears to be nowhere specified, which leaves it up to the user.” If anyone ever starts claiming it is against the regulations to use oxygen sold under different names, ask them to show you the regulation they are referring to. Nobody has found it yet.

Oxygen is typically sold (at differing prices) as Aviator’s Breathing Oxygen, Medical Oxygen, or Industrial (or Welder’s) Oxygen. Remember that part about boiling off the LOX and compressing the resulting oxygen gas? This differentiation comes about because long ago Aviator’s Breathing Oxygen and Medical Oxygen were compressed with water-sealed compressors to reduce the impurities added, while Welder’s Oxygen may have been compressed by machinery using oil for lubrication.

However, modern industrial processes demand pure gases, so the old ways of compressing died out. Now all oxygen is compressed in compressors using dry lubricants, leading to the same standards of purity and cleanliness for all oxygen. All three types come from the same source. The only difference is the label they put on it.

Medical oxygen is just as dry as the other types. The humidity is added by bubbling the gas through water after it comes out of the cylinder and just before it gets to the patient. Any moisture in the cylinder would threaten to freeze as the pressure drops and block the flow path.

Have you seen all of the oxygen equipment that says “Use No Oil”? Oil in the presence of high-pressure oxygen tends to explode, so why would anyone let oil get into the cylinder?

What does this mean? If you are setting up your own oxygen fill station, it doesn’t matter how the oxygen is labeled on the cylinder, because it is all the same stuff.

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- Russ Erb