Engineering Nitrox Partial Pressure Blending Systems © 2002

by

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OVERVIEW

The design and installation of oxygen systems is a genre generally foreign to dive store personnel. While handling compressed air is routine in most stores, dealing with oxygen demands a much stricter discipline and poses certain departures from familiar procedures and designs. In general, greater care in construction and operation must be taken if accidents are to be prevented. Oxygen fires or explosions can occur and the annals of such industries as transportation, aerospace, welding, commercial diving, and emergency medical services contain reports of assorted serious accidents. During the brief time in which pure oxygen has been widely utilized in sport and TEK diving, a number of mishaps have already taken place. In this bulletin, we will point out some crucial considerations that must be pondered during the planning, design, and fabrication of oxygen systems and the subsequent handling of this highly reactive gas.

OXYGEN COMPATIBLE AIR (OCA)

A common method for producing Nitrox is by partial pressure mixing where pure oxygen is introduced into an oxygen-clean scuba tank that is then topped off with oxygen-compatible air (0CA). OCA is currently defined as a modified CGA (Compressed Gas Association) Grade E Air, containing no more than 0. 1 milligram per cubic meter (mg/m^3) of hydrocarbon contaminants, 2 parts per million (ppm) or less carbon monoxide, 1000 ppm or less carbon dioxide, and a dewpoint of at least -50^o F. When hyper-filtration standards where originally formulated, the gas was first called "modified Grade J air". This has been changed to "modified Grade E" because hyper-filtered air aligns more closely to Grade E than to Grade J specifications. Since normal Grade E scuba air is permitted to have up to 5 mg/m^3 of hydrocarbon material, OCA is usually obtained by reprocessing that air through a special hyper-filter to reduce the concentration to below 0.I mg/m^3. Hyper-filtration differs from Grade E processing in a number of respects, including the filtrants used, internal flow pathways within the filter, flow rate, and certain other physical parameters.

There are several approaches to the production of OCA. In truth, many scuba stores and resort facilities already produce diving air that is of higher quality than Grade E and could be mixed safely with pure 0_2. Knowing this fact has caused some dive shops to assume that they can simply use their regular scuba air to make Nitrox. However, before this is attempted, one must be absolutely positive that their air is OCA and that this status can be routinely maintained. This should be accomplished through regular air tests performed by a certified analytical laboratory familiar with OCA standards. Be aware that OCA tests are more specific and precise than Grade E analyses. Grade E reports often simply certify that the hydrocarbon level is less than 5 mg/M^{3,} whereas OCA results specify the exact concentration.

The downside of this approach is that it allows almost no margin for error. If the air unexpectedly should become non-OCA (e.g. a compressor piston ring cracks or after-separator element clogs), an explosion could occur during mixing operations with absolutely no warning. For this reason, most dive shops prefer to hyper-filter their Grade E air, since this method does provide a safe guard against fluke system failures or unexpected incidents of contamination.

We must point out that no scientific studies exist which establish an ultimate OCA limit for even one standard set of conditions, more or less for the highly variant conditions found among dive shop air stations! In other words, the present OCA mixing standard was set based on what meager information was available in the early 1990's. It is thought to be a conservative limit that should be safe most of the time if ALL other mitigating factors are under control. While it has been reasonably successful, it alone has not entirely prevented "oxygen accidents", which suggests enough extenuating factors exist to perhaps make it impossible to create a standard that works 100% of the time.

Regarding the production of OCA, what little data is currently available on this matter suggests that at least 15% of the dive shops examined produced air that is NOT OCA. There is NO nationwide data showing whether the dive shops that pass OCA tests can routinely maintain that level of cleanliness in their regular scuba air. This is why most prudent dive shops choose to hyper-filter their Grade E air … it provides a substantial safety backup against variable and unknown factors that have yet to be researched and categorized with regard to their intrinsic dangers.

INHERENT HAZARDS OF PRESSURIZED OXYGEN

The greatest danger in badly engineered, poorly maintained, or carelessly operated partial pressure apparatus is an oxygen fire which is a very different "animal" than an air-driven blaze. Normal fires can be characterized as a classic Fire Triangle, consisting of three parts - air, fuel, and ignition. The fuel is any substance that can be burned by the oxidizer, usually air, and ignition is any energy source sufficient to initiate combustion. In the normal scenario where air is the oxidizing agent, if any of the three elements is removed from the triangle, the fire will be prevented. However, in oxygen systems, this principle does not apply because the three elements are inseparable. The fuel is, in reality the fittings, valves, seals, regulators, or piping of the system itself which contains or is exposed to the oxygen. A logical approach to this problem would be to fabricate all components out of the most oxygen-compatible materials available, expunge all easily combustible substances and contaminants from the assembly, and eliminate or control sources of ignition.

Unfortunately, ignition can come from the oxygen itself. When compressed gas flows from high to low pressure, it quickly reaches sonic velocity (speed of sound), especially at constrictions such as valve seats, regulator poppets, blind passageways, or angular fittings. (In these applications, flow velocities exceeding 148 feet / sec. [45 m / sec.] are considered to be dangerous). When speeding gas strikes an obstruction, it is instantly recompressed and the ambient temperature instantly skyrockets because no heat is lost to the surrounding materials. The higher the initial pressure, the greater the temperature generated. With 2,000 psi oxygen, temperatures well over I,500^o F can be momentarily produced, sufficient to ignite even such inert substances as Teflon and stainless steel. This phenomenon, similar to diesel ignition, is called ADIABATIC COMPRESSION, and it must be judiciously controlled.

This is done by careful design and operation. A number of O_2 fires have already occurred during the preparation of diving gas mixtures due to cavalier attitudes toward adiabatic compression. Mishaps include oxygen hose fires where Teflon-lined hoses with stainless steel over-braid detonated and burned like giant sparklers, throwing molten particles around the facility. Another spectacular accident blasted open the neck of a scuba tank and launched its valve skyward! To prevent accidental detonations, always open 0_2 tank valves very slowly and pressurize systemic components as "gently" as possible. Design your system using slow-opening globe or needle valves that contain seats made from oxygen-compatible polymers. Transfer oxygen gas slowly to prevent excessive heating. The maximum transfer rate for pure 0_2 is 200 psi / minute and rates during mixing are usually 50 - 70 psi / minute.

OXYGEN TERMINOLOGY

The previously mentioned term OXYGEN-COMPATIBILITY is often misunderstood and thought to mean immunity to combustion even in the presence of pure oxygen. This is untrue. It actually means that all materials in contact with the gas are compatible at that pressure and temperature. A given material that is compatible at 500 psi and 50^o F might lose that compatibility at 2,000 psi and 200^o F. Even such inert polymers as Teflon can be ignited under severe conditions in O_2 environments. Therefore, oxygen-compatibility is a relative term, dependent upon the prevailing physical conditions in any given system. In high-pressure oxygen systems like Nitrox mixing apparatus, one should engineer for extreme conditions. The Compressed Gas Association considers 0_2 pressures above I,000 psi to be severe service!

OXYGEN-CLEAN and OXYGEN-SERVICE are two more terms which can be confusing. OXYGEN-CLEAN refers to a state of cleanliness suitable for oxygen service where all undesirable and unsafe contaminants have been removed. Examples of such contaminants, include fingerprints, lint, dust, metal chips, solvent or cleaner residues, petroleum-based oils, grease, paint, and rust. However, oxygen-clean does NOT equate to oxygen-compatibility; a component can be made oxygen-clean, but still may be chemically incompatible for use with pure 0_2. Likewise, oxygen-compatible materials are not always oxygen-clean when purchased. Never assume a component to be oxy-clean unless it is so certified by the vendor. OXYGEN-SERVICE demands that a material be both oxy-clean and oxy-compatible under the prevailing conditions within a given system!

Oxygen-cleanliness can be achieved by a number of methods that are described in various publications by the Compressed Gas Association, military agencies, NASA, and several Nitrox instructional organizations. There is no universally accepted, ultimate, singular process. Techniques range from simple methods such as hand-scrubbing and detergent soaking to high tech operations like ultrasonic cleansing. These publications also explain inspection / test procedures to verify oxy-clean status. Select a procedure that is workable in your store and commensurate with your facilities and skill level. Follow that procedure exactly as described and do not revamp, co-mingle, or improvise processes. Serious errors have been made by individuals who, for purposes of expediency, intermixed or changed the chemicals, time requirements, dilution rates, or specified equipment from distinctly different cleaning techniques. Such tinkering may alter or totally negate the effectiveness of the procedure and leave behind dangerous residues or other contaminants.

SOURCES OF OXYGEN FIRES

Oxygen fires can be caused by any of the following: (A) system design errors, (B) use of the wrong metals or plastics within the gas pathway, (C) dirty / contaminated systems, (D) errant operating procedures due to mistakes by careless or untrained personnel. As already pointed out, increased oxygen concentration and / or pressure can change the ignition temperature at which a material will burn. Thus many substances that would not burn in air at atmospheric pressure may readily ignite in oxygen environments, especially if the temperature or pressure (or both) is raised. To design 0_2 systems correctly, one must select the best oxygen-compatible components available, i.e. those that will resist ignition under the prevailing conditions. Nonetheless, be aware that no system can be infallible in this regard!

As previously explained, ADIABATIC COMPRESSION may be the primary culprit for O_2 fires within valves, regulators, Teflon-lined hoses or other components that are suddenly subjected to compressive heating. Another source of unexpected ignition is PARTICLE IMPINGEMENT. This happens when a small metal particle, Teflon fragment, or plastic seal shaving gets accelerated within a high velocity gas stream. Common rust is a primary offender in this regard. If such speeding material strikes another component or hits an obstruction in the gas passageway, it may ignite much like a meteor hitting the Earth's atmosphere. In pure oxygen, this could be disastrous since the reaction is usually self-sustaining once it's been initiated. In other words, once begun, the fire rapidly consumes one component after another, including certain metals, because of the presence of pure O_2. Impingements are prevented by carefully selecting and assembling components and by using particle filters at the gas source, since large commercial gas cylinders are notorious sources of rust particles.

Steel components which can rust and release debris into the gas stream are a common source of particulate matter. Never use plain steel fittings in oxygen systems; brass or stainless must be employed, depending on the pressure. Brass is suitable to about 3,000 psi; stainless should be used for higher pressures. Exotic materials like Monel and Inconel are also excellent alloys, but are usually too expensive for dive facility use. In general, brass / bronze is the preferred metal for use with pure 0_2.

Thermoplastic air hoses with steel end fittings should NEVER be used in oxygen systems. Most dive store AIR systems employ synthetic hoses, which have plated steel end fittings, since brass or stainless models are rather uncommon. While the core of such hoses may be oxy-compatible, the fittings are NOT and will corrode internally with age. Hose fires instigated by rusty end fittings have already occurred during gas mixing operations. A common mistake is to use an AIR whip (having steel hose fittings) to add OCA to an oxygenated scuba tank. If a rust particle is released within the air hose, it may impinge and detonate the 0_2 at the tank valve! ALL hoses used in mixing systems should be Teflon-core types with stainless steel sheathing and end fittings made of brass or stainless.

The danger of particle impacts can be lessened by proper design. For example, eliminate sharp angles such a 90^o elbows and minimize long, narrow, or blind passages when plumbing your system. Right angle bends create flat surfaces where particles can impact or ricochet. In addition, blind passageways or large cavities can be collecting points for minute debris, thereby promoting contaminant buildup. Also, examine all fittings for sharp edges, protruding metal burrs, or loose threads. Design / inspect your system to eliminate or minimize such unwanted hazards.

DESIGNING AND CONSTRUCTING OXYGEN SYSTEMS

Below is a list of other important facts and considerations to be evaluated when designing and constructing oxygen systems:

> A detonation within an oxygen system can result from an electrical arc following a static charge buildup. Large mixing systems and manifold bars should be properly grounded to prevent static electrical accumulation. Fortunately, static generation is uncommon in 0_2 systems because the gas is already dry and clean. Static discharge is actually more likely in air filter apparatus since the air is moist prior to filtration. Many dive facilities do not realize this and fail to properly ground their equipment.
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> Design your ENTIRE system for oxy-compatibility if there is any chance that pure oxygen might enter an area which normally would NOT be exposed to that gas. For example, a poorly engineered system may have a sector designed exclusively for OCA air and another for oxygen; both sectors are oxy-clean, but only the oxygen segment contains totally 0_2-compatible materials. These two segments are interconnected, but each is isolated by a check valve or other shut-off device. However, if an isolator valve fails, high pressure 0_2 will enter the air section that was NOT designed for oxygen service; thus a fire may occur. This is known as a single-barrier failure. On the other hand, if both air and 0_2 segments had been built for oxygen service, the isolator failure would be largely inconsequential.

Cleanliness in oxygen systems is of paramount importance. Using air that is not OCA or is of suspect quality can increase the danger of 0_2 fires because it hastens contamination of the system. Even the cleanest air still has minuscule amounts of hydrocarbon pollutants that collect within the apparatus over time. Therefore a fire becomes more likely with prolonged use. The equipment should be periodically re-cleaned, but at this time there is no industry-wide standard or accepted recommendation for the frequency for such maintenance. Present consensus suggests yearly maintenance, but this is not based on any scientific documentation or historical field data. Numerous inherent variables make any "universal recommendation" difficult to derive. Degree of use, quality of the air / gases employed, system design and environment, as well as operator skill and training are just a few of the "fudge factors" that differ from unit to unit. Let good judgment be YOUR guide.

Choose your sealants and lubricants carefully. Teflon tape is the most common thread sealant, but not all Teflon tape is oxy-compatible or oxy-clean. Some tapes contain unwanted additives or may become contaminated with hydrocarbons during manufacture or packing. Look for MIL-SPEC #T27730A which certifies suitability for use in pure oxygen. Tape fittings so that the first thread on the tip remains uncovered; this prevents tape fragments from being extruded internally into the gas stream. Paste sealants and lubricants must be fluorocarbon compounds certified for oxygen service. Common brand name oxy-lubes include Christolube, Krytox, Lox-8, Fluorolube, Halocarbon, and Tribolube. Silicone greases are NOT oxy-compatible except at VERY LOW pressures (200 psi or less). Locktite thread-sealers are not oxy-compatible and are readily flammable in oxy-environments. Mild thread-locking compounds such as fluorocarbon Lox-8 paste (GMC #42145) should be substituted for Locktite.

Aluminum and low alloy steel can ignite easily and burn rapidly in high-pressure oxygen, producing tremendous heat and generating explosive molten debris. In oxy-environments, aluminum can be set afire by frictional heating or adiabatic compression. Therefore, aluminum or low-alloy steel components SHOULD NOT be used in high-pressure O_2 systems. Several years ago, the medical gas industry issued a national recall on all aluminum-bodied oxygen regulators because of a rash of fires in such devices! Titanium is also TOTALLY UNSUITABLE for use with pure oxygen. Other metals that are undesirable for 0_2 service include cadmium, beryllium, magnesium, and mercury.

Select valves for controlling oxygen with great care. Fast-opening valves must NEVER be used in 0_2 systems because they can produce adiabatic surges. Therefore, BALL VALVES ARE FORBIDDEN in oxy-systems; use slow-opening types like needle or metering valves. Oxygen fires can also occur within valves from high friction, improper sealing materials or lubricants. Any valve that sticks, grinds, or operates "hard" should be promptly repaired. Sticky valves can also cause valve seals to shred off tiny fragments that get into the gas stream where they may ignite. Typical line valves of the kind commonly used on scuba-filling apparatus are designed for rapid opening and are usually not set up for oxygen service. The same is true of most scuba tank valves. However, certain valves can be oxygen cleaned and made oxy-compatible by replacement of their internal seats and seals. When combined with a metering orifice (gas-flow governing device with a "pin-hole" aperture), such valves can successfully and safely control oxygen delivery. The prudent technician should check with a valve’s manufacturer to learn if it is suitable for oxygen service or can be rendered so.

Valve and regulator seats are of extreme importance because they are subjected to molecular bombardment and heating as the compressed gas passes through the valve orifice. These seats must be made of the most oxy-compatible polymers available such as Teflon, Kel-F / Neoflon, Vespel, or Kalrez. Where 0-rings are employed, their composition should be of Viton, Kalrez, or similar fluorocarbon material. Scuba tank valve seat assemblies are usually Nylon 6/6 which should be replaced whenever possible with Kel-F / Neoflon poppets.

Combine metallic and non-metallic / plastic components wisely. In pure oxygen, many polymers can ignite at very low pressure and temperatures. In turn, burning polymers fueled by 0_2 will ignite the metallic parts, causing a major deflagration or meltdown. Remember that the use of polymers resistant to ignition or combustion cannot completely eliminate the possibility of fires in elevated oxygen environments. In 0_2, even inert materials may be set ablaze by mechanical impact, high friction, or adiabatic compression. These factors must be controlled by operator skill and training as well as by proper maintenance.

Some partial pressure systems incorporate booster / transfer pumps such as the Haskel unit. Models used for 0_2-service must be constructed or converted and cleaned for that duty. Also, these devices can produce rapid heating due to their speed of compression and therefore must be CAREFULLY plumbed, maintained, and operated! A number of significant (and expensive!) fires have been reported in these machines. In the late 1990's, a series of oxygen fires occurred as divers attempted to use AIR AMPLIFIERS for mixed gas operations. These devices, related to boosters, are cheaply available in surplus markets and over the Internet. Unfortunately, they are NOT suitable for O_2-service and are dangerous in such applications. Moreover, AIR AMPLIFIERS CANNOT be converted for safe oxygen use!

Keep 0_2 delivery lines as short as possible. In most welding and medical applications, a regulator located at the source tank reduces the pressure of the oxygen. However, in gas mixing operations, high-pressure gas must often be transferred to the blending apparatus through long tubing or hoses. The longer the delivery line, the greater the risk for adiabatic mishaps. This risk can be lessened by keeping lines as short as possible and by using metering orifices to control flow rates and surges.

Special care must be taken to minimize potential impact points near gas restricting areas such as valve seats, orifice plates, or reducer fittings. At such places, the gas pressure drops, molecular collisions increase, and ambient pressure rises. If a speeding particle strikes a polymer softgood, such as a valve seat, the energy released may detonate it. Many instances of vaporized scuba tank valve seats have been recently found, several of which have been associated with fires or explosions! The engineering rule here simply says: Avoid / eliminate impact sites within a distance, which is equal to 10 times the diameter of the restriction and downstream of it. For example, since most line valve orifice diameters are approximately 0.12", the "danger zone" would extend approximately 1-1/4 inches downstream.

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