Cleaning to Avoid Fires in Nitrox Scuba and Fill Systems

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Abstract

Cleaning systems and components for nitrox service has been a highly controversial issue in the recreational diving industry. It has divided the industry into two main factions: those who support a special-cleaning threshold for oxygen service at 40 percent oxygen, and those who support a threshold of 21-25 percent, or standard air. The objective of this paper is *not* to get hung up in a debate of numbers concerning oxygen concentration, but instead to communicate a broader perspective on the issue, that is, to assess the risk of fire in these systems and how cleaning affects this risk. The risk of fire in nitrox systems is real and requires special consideration, different from standard air systems. Materials are more flammable and ignition mechanisms are more active in oxygen-enriched environments. A risk management approach is presented that shows many factors must be considered to avoid fires, including system design, operations and maintenance, and cleaning. Because all these factors require consideration to avoid fires, it is difficult to specify a single value where special-cleaning is required for all scuba and fill systems. Standard practice in most industries is to be conservative in these situations. The bottom line is that technical judgment is the key. The limitations of history of use are also discussed as they apply to the risk management approach. Some final recommendations are presented that may prove helpful concerning the topic of cleaning to avoid fires in nitrox scuba and fill systems.

Introduction

As the use of nitrox as a breathing gas continues to increase in the recreational diving industry, questions concerning the requirements to clean these systems are rampant. There are many reasons to desire a "clean" nitrox system, one free of contaminants, including proper function and physiological safety. But the most immediate and critical reason to clean nitrox systems is to minimize potential fire hazards.

The topic of cleaning systems to avoid fires can be complex and controversial. Our organization spends two full days teaching an ASTM course focused on minimizing fire hazards in oxygen systems. This presentation is limited to 30 minutes! Therefore, I will not even begin to address all the issues, much less begin to lessen the emotional distress that I know many in the industry have suffered over the past 10 years regarding this topic! But I do hope to present an unbiased and objective look at the real issues of fire hazards in nitrox systems and how cleaning affects them.

Further, the recreational diving industry is not alone in its struggle for definition regarding thresholds for cleaning nitrox systems. Just within the past month, the Atmospheric Gases Committee of the Compressed Gas Association, Inc. (CGA) submitted a draft of a Position Statement on the "Definition of a Threshold Oxygen-Mixture Concentration Requiring Special Cleaning of Equipment" (CGA PS-13, 2000). The draft, expecting to be approved and released within six months, is an attempt within CGA to provide a single definition for an oxygen-cleaning threshold. It states that equipment systems exposed to 23.5 mole percent oxygen or greater should be specially cleaned to reduce the risk of fire. In addition, industries that routinely use oxygen-enriched gas mixtures generally advocate that in cases where special cleaning thresholds exceed 21-25 percent oxygen there be a well-defined basis for allowing it, including such things as oxygen hazards analyses per accepted ASTM practices.

The primary objective of this presentation, however, is *not* to get hung up in a debate of numbers concerning oxygen concentration, but instead to communicate a broader perspective on the issue, that is, to assess the risk of fire in these systems and how cleaning affects this risk. To properly address this topic, it is necessary to first put aside any emotional attachment to a favorite oxygen concentration value. Then we can gain a perspective of the specific issues at hand and develop an understanding as to how these issues relate to the diving industry. Next we need to identify and characterize the specific hazards, if any, of *not* cleaning nitrox systems. It is also necessary to define the risk involved and decide what level of risk is tolerable in the recreational diving industry, realizing that it can differ between industries, and even between organizations within an industry. Only then can we ultimately decide which specific systems require cleaning and when cleaning is appropriate. The bottom line is that technical judgment is the key.

The Great Divide

Though my professional involvement with the recreational diving industry only spans a few years, qualifying me as a neophyte compared to the pioneers who established nitrox diving, I have become keenly aware of the division within the recreational industry regarding oxygen-cleaning thresholds, which I have entitled, "The Great Divide."

It is widely accepted in the diving industry that systems that contain oxygen concentrations greater than 41 percent oxygen are treated as 100 percent oxygen systems regarding their need to be cleaned for oxygen service to minimize the risk of fire. It is also widely accepted in the diving industry that systems containing oxygen concentrations approximately equivalent to air, from 21-25 percent oxygen, require no special cleaning for oxygen service. The Great Divide, however, occurs in systems with less than or equal to 40 percent oxygen, where there exists a major difference in opinion regarding the need to clean nitrox scuba and fill systems.

The majority follow a rather obscure but popular approach known as the "40 Percent Rule," based on an OSHA standard written for commercial diving. This faction boldly states that scuba and fill systems traditionally used for air service can be used for nitrox service up to 40 percent oxygen with no modifications or special cleaning required. They tend to rely on a vast experience base, or history of use, as their rationale for adopting this threshold.

Others follow approaches based on industry standards from CGA, NFPA, NASA, US Navy, or other OSHA standards, which typically recommend cleaning any system exposed to oxygen concentrations higher than standard air, from 21 to 25 percent oxygen. This faction takes a more conservative approach to nitrox safety, as they require systems to be cleaned and dedicated only for nitrox use to avoid contamination. The rationale used for this approach is based on materials flammability data and recommendations from other industries that have a long history of using oxygen systems.

Figure 1 illustrates The Great Divide as I've interpreted it. Systems employing oxygen concentrations less than 21-25 percent do not require special cleaning, which pleases everyone. Systems that contain over 40 percent oxygen require cleaning and everyone calls upon Mr. Clean without hesitation. However, systems that use between 25 and 40 percent oxygen still deliberate, "To clean or not to clean, that is the question."

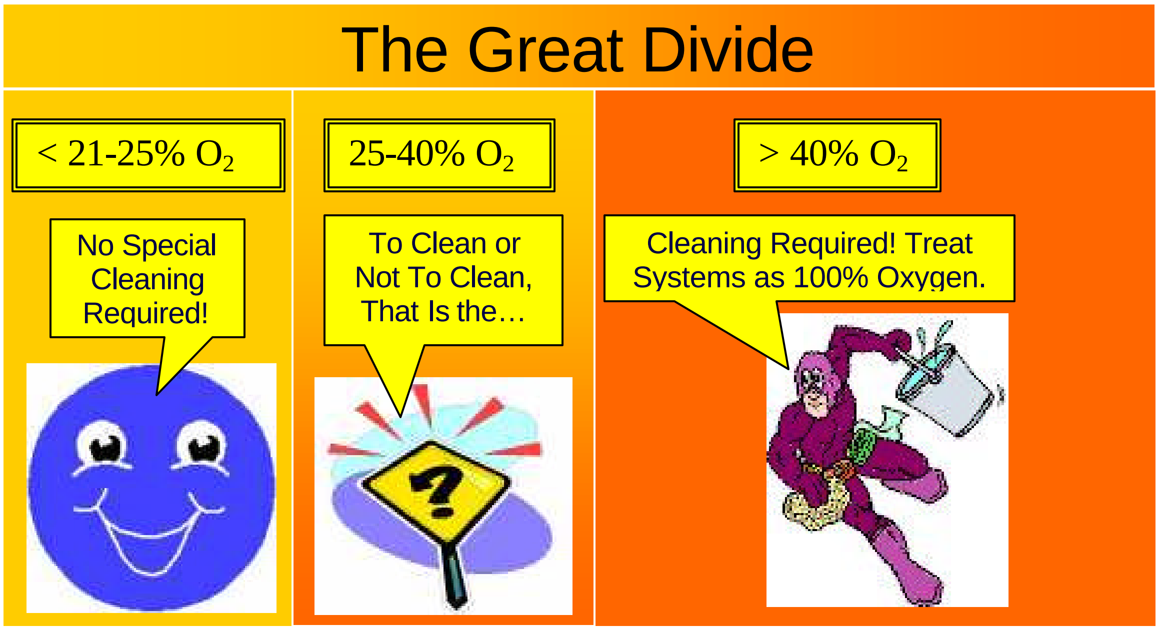


Figure 1 – Illustration of The Great Divide regarding oxygen cleaning thresholds

The Fire Hazard Defined

Now that the dividing point regarding oxygen-cleaning thresholds have been put into perspective, it is important to define the immediate fire hazards of using nitrox. First, nitrox contains oxygen, an agent that supports combustion. Oxygen by itself will not burn, but, generally, it makes other materials in its presence more flammable and ignitable. Increasing the oxygen concentration above that found in standard air will make the materials in those systems more flammable and more easily ignited than they would be in air. Furthermore, if a fire were to occur in a system with an increased oxygen concentration, the flame spread rate and combustion rate would be increased over normal air environments.

The nature of fires that occur in oxygen and nitrox systems also contribute to the hazard. Fires in these systems tend to be subtle and erratic, exhibiting themselves infrequently and usually without warning. Many systems that experience a fire have been in operation for years without incident. In training courses, we commonly use the analogy of a cigarette lighter to describe the erratic nature of oxygen fires: in a system designed to create a small fire (the flame), with all the elements required to sustain a fire present (the oxidizer, fuel and ignition source), how many attempts does it take to get ignition from the lighter? Sometimes ignition occurs on the first try; sometimes it takes two flicks of the lighter; but sometimes it requires several attempts to "flick your Bic" to get ignition. Oxygen and nitrox fires are similar. Ignition, in itself, is a low-probability event and, as such, does not exhibit itself often. This aspect of the hazard can lull users to sleep, making them lose awareness and even forget the hazard is real.

Complicating the problem is the fact that in most oxygen or nitrox systems, the potential ignition sources cannot simply be "turned-off," as they can in other environments. This makes the fire hazard and its associated risk inherent to these systems. This concept is counter to the traditional "fire triangle" prevention method, where removing a leg of the triangle (either the fuel, the oxidizer, or the ignition source) "prevents" a fire. Most people relate to Smokey the Bear when he "prevents" fires by extinguishing campfires, or simply removes the ignition source. However, in most oxygen or nitrox systems, one can't remove the oxidizer leg (it's the oxygen itself), one can't remove the fuel (as nearly all materials can be ignited in high pressure nitrox or oxygen), and finally, one can't completely remove potential sources of ignition as heat-generating sources are always present (like adiabatic compression heating from cylinder valves and frictional heating in compressors). In short, all the elements necessary to create a fire are present in our systems in one form or another, making the hazard difficult to completely eliminate. Because of this, fires have occurred in nitrox and oxygen systems, from compressed air to 100 percent oxygen.

Fires in Oxygen-Enriched Environments

Most people who routinely use enriched-oxygen gas mixtures are aware that fires occur in systems using 100 percent oxygen. They have either heard or seen first-hand evidence of these fires in industrial gas systems, aerospace oxygen systems, medical oxygen applications, or even recreational diving applications using 100 percent oxygen in oxygen booster pumps or partial pressure blending systems. The awareness to fires in these systems explains the universal acceptance by the recreational diving industry to clean systems using high concentrations of oxygen.

However, less common is the understanding that fires occur even in systems using lower oxygen concentrations. For example, at least two fires in cylinder valve seats have been investigated at NASA's Neutral Buoyancy Lab (NBL) in 46 percent nitrox scuba systems. Figure 2 shows the crown orifice of the valve from one of the incidents. Figure 3 shows the seat retainer of the valve and the combustion remains of the nylon seat. Some would question if this same ignition is possible in a 36 or 40 percent oxygen environment. The answer is, "Yes!" Nylon is flammable under these conditions and similar fires have been reported in cylinder valves using even standard breathing air.

The most misunderstood concept regarding nitrox fire hazards is that many materials in scuba and fill systems that are *not* flammable in air *will burn* in oxygen-enriched environments, even up to 40 percent oxygen. Table 1 lists the oxygen index (OI) of several common polymeric materials used in scuba and fill systems. The OI values given are per ASTM standard test D 2863, measuring the minimum oxygen concentration required to support combustion at atmospheric pressure.

Per this table, PEEK, neoprene, PVC, silicone rubber, nitrile rubber, nylon and EPDM may not support combustion in ambient air, but would in a 40 percent oxygen environment. Furthermore, as the pressure increases up to a point, OI values generally decrease, meaning that in typical scuba systems some of the best materials, like PTFE and PCTFE, may be considered flammable.

Though the frequency of nitrox fires, especially those in environments with less than 40 percent oxygen, is fewer than those in 100 percent oxygen, many have been reported. Perhaps the most common equipment experiencing nitrox fires in the recreational diving industry is fill

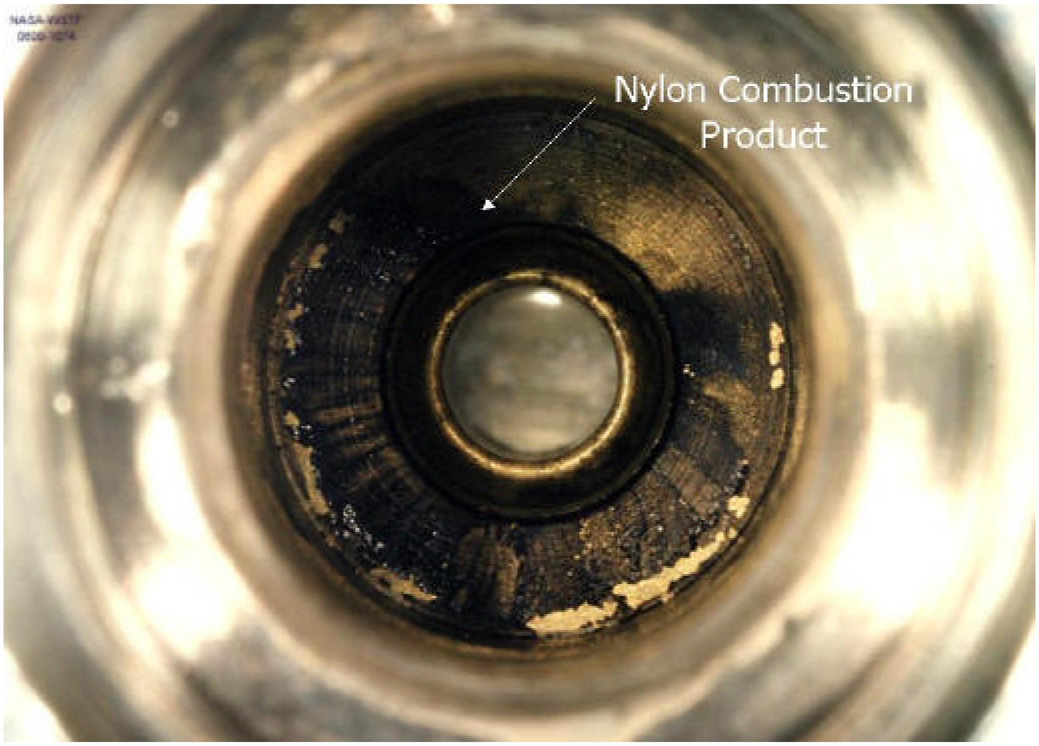


Figure 2 –Crown orifice from burned cylinder valve seat in 46 percent nitrox

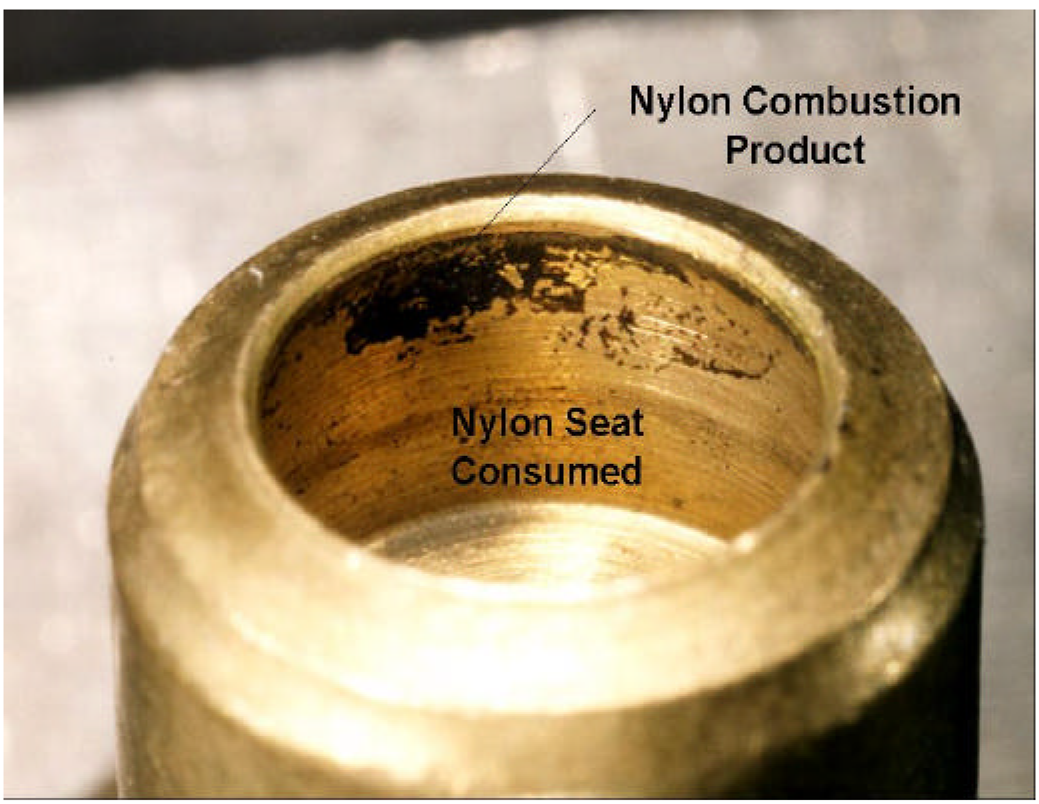


Figure 3 – Valve seat retainer with nylon seat consumed in 46 percent nitrox

Table 1 – Oxygen index values of selected polymeric materials per ASTM D2863

Material	Oxygen Index
EPR	21
EPDM	20-25
Nylon	21-38
Nitrile Rubber (Buna-N®)	22
Silicone Rubber	25-39
PVC	31
Neoprene®	32-35
PEEK	35
Vespel SP21®	53-61
FKM (Viton A®)	56
PCTFE (Kel-F 81®)	95-100
PTFE (Teflon®)	95-100

stations. Fire incidents in systems using less than 40 percent oxygen are known to have occurred in aluminum and carbon steel compressor blocks, aluminum-bodied filter towers, fill station panel valves and regulators, and some pre-compression nitrox generating equipment used for continuous blending. The cause of these fires varies, but many are related to hydrocarbon or particulate contamination, be it from poor maintenance or otherwise, that may have been avoided through proper cleaning. Hyperbaric chambers are other nitrox systems that have experienced fires. One of the most tragic chamber fires occurred in a 1.8-atmosphere air chamber (21 percent oxygen) in Milan, Italy, in 1997, killing 11 people.

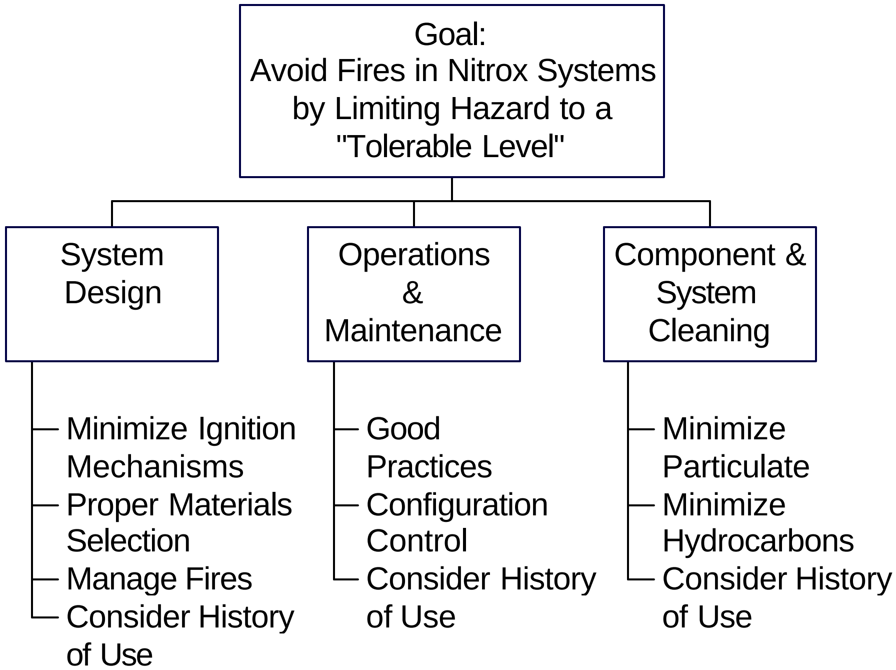
The Risk Defined

Thus, fire hazards are real, even in systems using less than 40 percent oxygen, and the reality of fires presents a risk to the user. But, managing the risk is possible, as has been shown by the many years of nitrox usage with relatively few incidents of fire. To manage the risk of fire effectively, though, requires a different approach than is typically employed for standard air. It also requires a systematic analysis of the hazards present, and above all, requires technical judgment.

Figure 4 is a flowchart that shows a risk management approach specific to nitrox and oxygen systems. The end goal is to avoid fires in nitrox systems by reducing the hazards to a tolerable level. The model is applicable because it allows those in a specific industry to define what "tolerable" means for them, understanding that risk tolerance is different for different industries. This may be especially true for the recreational diving industry.

The purpose in showing this chart is simply to convey that many factors are required to accomplish the goal. If any one of these factors is compromised, it can defeat the other two and, ultimately, lead to a fire. Our organization teaches entire courses on the details of this approach, based on ASTM standard and guidelines. The first box, system design, considers how systems and components need to be designed to avoid fires. This box is aimed primarily at equipment

Figure 4 – Model for fire hazard risk management in oxygen and nitrox systems



manufacturers and system engineers. It encompasses many things including minimizing active ignition mechanisms in a system, choosing proper materials, and designing a system to handle a potential fire. History of use is a consideration is each step of the risk management approach and is discussed below. The second box aims to stress the importance of operations and maintenance of oxygen or nitrox systems to avoid fires. Things like good practices and controlling the configuration of a system are imperative to avoiding fires. Both manufacturers and end users have a responsibility in understanding these principles. The third box shows where cleaning fits into the risk management approach. Through minimizing particulates and hydrocarbons, the hazard of igniting these contaminants is reduced. Again, responsibilities in this area lie with both the manufacturer and the end user. If a system is not well designed, or is improperly operated and maintained, the cleaning aspect of the risk management approach becomes critical. Cleaning may not completely prevent a fire, but it will certainly reduce the risk.

Is Cleaning Required?

To help evaluate the risk of fire and ultimately determine whether cleaning is required, it is beneficial to understand the oxygen-enrichment thresholds imposed by the professional organizations that routinely use oxygen-enriched gas systems. Table 2 gives a listing of some organizations and the oxygen-enrichment thresholds, with references, that have been established.

It is important to remember that oxygen-enrichment thresholds are simply used as a dividing line, identifying the point where these systems are treated differently to avoid fires, including system design, operations and maintenance, and cleaning. It is the point where industries define "tolerable risk" in their risk management approach. The values themselves are not "magic," whereby just above the threshold value spontaneous combustion is inevitable and below it nothing ever burns! They are simply limiting values for treating systems differently than standard air.

Table 2 – Oxygen-Enrichment Threshold Values from Various Organizations

Organization	Threshold Value	Reference
U.S. Navy	>25% oxygen	Mil-Std-1330D
CGA	>23.5% oxygen	CGA Pamphlet 4.4
NFPA	>21-25% oxygen	Various
ASTM	>25% oxygen	G 126, G 128, G 63, G 94
NASA	>21% oxygen, >100 psig air	Various KSC, JSC refs
OSHA	>23.5% oxygen	29 CFR1910.146, 29 CFR 1910.134
OSHA	>40% oxygen	29 CFR 1910.430

The faction of the recreational diving industry that holds fast to the "40 percent rule" for special-cleaning of nitrox systems references the OSHA document 29 CFR 1910.430 as its basis. Because this threshold is significantly higher than the others traditionally adopted by other industries and because it has such wide subscription in the recreational industry, it bares further study. First, all of 29 CFR 1910 subpart T applies to commercial diving operations. In section 1910.430, under "Equipment," and specifically under section (i) "Oxygen Safety," the standard states that equipment used with oxygen or mixtures over 40 percent shall be designed and cleaned for oxygen service. The validity of its application to the recreational diving industry can be debated, and has been debated for some time. This is because the standard contains much information not practiced by the recreational diving industry, does not directly address systems with equal to or less than 40 percent oxygen, and is considered such a "black sheep" compared to other oxygen-enrichment thresholds in other industries. Furthermore, the rationale behind the 40 percent value has been lost, though it is believed to be based on the commercial diving industry's *experience* with standard scuba equipment many years ago at the time the standard was written.

Despite these factors, the 40 percent oxygen-cleaning threshold *may not* be unreasonable for the recreational diving industry. It may be that the industry concludes that the risk of fire without cleaning systems up to a 40 percent oxygen threshold is "tolerable." This argument can only be supported, however, if individuals truly understand the level of risk that they deem "tolerable," and if the risk is properly communicated to others in the industry, including the fact that fires are still possible in this environment.

Is cleaning required? The unsatisfying but truthful answer to this question is a definite "maybe!" Because of the number of factors that contribute to a fire and the inherent risk of ignition in most nitrox systems, it is very difficult to specify a single value where special-cleaning is required for all scuba and fill systems, especially if the only factor considered is oxygen concentration. There may well exist systems that are well designed and are properly operated and maintained that can tolerate reasonable amounts of contamination without incident, even in a 40 percent oxygen environment. This must be true to some degree, in fact, or the number of fire incidents in the recreational diving industry would be higher. However, not all systems are this way.

More test data and scientific study are needed before we can ultimately predict when and where a fire will occur. Standard industry practice is to be conservative in applications where scientific data and understanding are limited. This explains why most industries set their oxygen-enrichment threshold values close to that of standard air. They have used technical understanding and judgment as a rationale for decisions, not just experience.

What About History of Use?

History of use is a credible part of the risk management approach shown above. It provides a starting point for hazards analyses and gives both designers and end-users a sense of comfort with equipment. The recreational diving industry relies heavily on a "successful" history of use as a rationale for decisions.

But, as the model shown above indicates, history of use is only a small part of the risk management approach. Though always considered, history of use is only used to support one or more of the main elements of risk management, not as a stand-alone. The reason for this is that history of use can often provide a false sense of comfort that a fire will not occur, especially if the system hasn't been effectively analyzed for hazards. Also, history of use is only applicable if all system conditions are comparable over time, including the application, operating environment, system design and materials selection, and type of contaminants the system is exposed to. For example, the commercial and scientific diving industries have built the bulk of their nitrox history with brass-bodied components operating in 2500-psi maximum systems. By contrast, today's recreational diver or nitrox blender may use components built from aluminum, titanium, or other exotic alloys at pressures up to 4500 psi. These systems may still be safe, but they have a limited history of use, which must be considered when evaluating risk level.

A "successful" history of use requires a large database of relevant applications. It also requires a low ignition probability and a low ignition consequence. Even then, for a history of use to be "successful," it is critical to understand *why* fires haven't occurred. Is it luck? Or is it because the risk of fire has been minimized through proper design, operation and maintenance, and cleaning?

Recommendations For Consideration

As an unbiased, objective "outsider" to the recreational diving industry, I am not in a position to mandate changes, nor do I have the intention of doing so. However, considering my background in oxygen system design and safety, I will propose some recommendations for consideration that may prove helpful concerning the topic of cleaning to avoid fires in nitrox scuba and fill systems.

1. *Allow diving equipment manufacturers to define oxygen or nitrox compatibility for, as well as set guidelines for, their own equipment.* This may already be the accepted practice as most training and certifying agencies refer to the manufacturer regarding specific compatibility issues with equipment. However, this point needs to be stressed more fully to ensure that end-users are not defining whether equipment can or can't be used in nitrox and whether specific concentrations of oxygen are acceptable. Guidelines for use also need to be supplied and emphasized by the manufacturer, such as maximum use conditions and environments, operation and maintenance, and cleaning processes and frequency. Only the manufacturer is in this position of authority, and understands their equipment sufficiently, to recommend compatibility of their equipment. Also, since the manufacturers design and test their own equipment, they understand the equipment limitations and are qualified to specify guidelines for use. This requires, however, that the manufacturer fully analyzes and understands the fire hazards in their equipment, and that they test their equipment for ignition mechanisms in the worst-case environment. Specific guidelines to aid manufacturers in this assessment could be established, as discussed below.
2. *Establish industry-specific guidelines or standards for nitrox use.* Though manufacturers' recommendations would still have final authority for a given product, the entire industry would benefit if common guidelines were established regarding the use of

nitrox equipment, system operation and maintenance, cleaning, gas blending, and other issues. Single definitions for oxygen-enrichment could be developed and substantiated based on a risk "tolerance" level acceptable to all. Similar to the medical oxygen industry, standard tests developed for nitrox scuba and fill system components would help validate them for nitrox or even 100 percent oxygen service. For these standards and guidelines to be most effective, they would have to be established by manufacturers, training agencies, and end-users alike, and be universally accepted and practiced. The recreational diving industry already has representation within the ASTM G-4 committee on "Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres," which could act as a vehicle to develop the guidelines and standards. The ASTM G-4 committee is open to anyone desiring membership and encourages participation from all industries with an interest in these issues.

3. *Implement oxygen and nitrox fire hazards training programs for nitrox users*. Most training agencies currently include a section on oxygen hazards as part of their nitrox certification. However, very few nitrox training manuals present accurate and thorough information regarding the risk of fire in nitrox systems. It is the nitrox blender's and diver's right to know the level of risk associated with their activity, not just the risk of physical harm from oxygen toxicity, but also the increased risk of fire in elevated oxygen concentrations. This information needs to come from a reliable source that understands oxygen fire hazards and be consistent from agency to agency. A multi-tiered system may be appropriate, similar to other diving courses, where courses could range from introductory to advanced and be specific for different audiences, including manufacturers, certifying agencies, instructors, and divers. Topics would depend on the target audience but could include design, testing, materials selection, operation and maintenance, and fire history.