Occupational Burns From Oxygen Resuscitator Fires: The Hazard of Aluminum Regulators

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Background *There have been over 30 incidents of oxygen resuscitator fires over the last 6 years, causing severe burns to a number of fire fighters, emergency medical service personnel, health care workers, and patients. The National Institute for Occupational Safety and Health (NIOSH) was requested to investigate three such incidents.*
Methods *NIOSH conducted site investigations of the incidents, and the requesters also sent the involved oxygen resuscitators to a forensic engineering company for a causal analysis.*
Results *The investigated fires were associated with aluminum regulators, all from one manufacturer, on compressed pure oxygen cylinders. The investigations indicated that the cause of the fires was an initial small ignition in the high-pressure area of the aluminum regulator, which then consumed itself in a massive burnout.*
Conclusions *Aluminum regulators used with high-pressure oxygen systems are subject to rare, but potentially catastrophic combustion in normal use. Replacement of such regulators with those made of more fire-resistant materials or designs, as well as education and improved safety practices are needed to reduce this hazard.* Am. J. Ind. Med. 42:63–69, 2002. *Published 2002 Wiley-Liss, Inc.*†

KEY WORDS: aluminum regulators; resuscitator fires; oxygen; compressed oxygen; aluminum flammability; hyperbaric oxygen

INTRODUCTION

The medical benefits of oxygen have been studied and applied since soon after its discovery by Priestley and Scheele in the 1770s [Jain and Fischer, 1989; Tiep, 1991], and it is one of the most effective and commonly used treatments in clinical medicine. The increased fire hazards associated with enriched-oxygen gases are also well known, as documented by reports of numerous fires and injuries to both patients and workers in various medical and other settings [National Fire Protection Association, 1994; Greco et al., 1995; Sheffield and Desautels, 1997; Gowardman and Moriarty, 1998; Thompson et al., 1998]. The reactivity of oxygen in combustion is increased by its temperature and by its partial pressure, the latter being determined by the gas mixture's pressure and the percentage of oxygen. Portable oxygen resuscitators commonly used by emergency medical technicians or fire department personnel usually include size D or E pressurized cylinders that contain pure ($>99.7\%$) medical grade oxygen and maximal pressures of 2,200 pounds per square inch (psi). This obviously represents a highly reactive oxygen condition with regard to potential combustion. The resuscitator regulator typically reduces the pressure to ~ 50 psi, with the oxygen flow to the patient then being regulated by a secondary control mechanism.

The use of aluminum in oxygen regulators has increased in recent years, partly due to the fact that aluminum has a distinct weight advantage over most other suitable

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Accepted 25 March 2002
DOI 10.1002/ajim.10085 Published online in Wiley InterScience (www.interscience.wiley.com)

Published 2002 Wiley-Liss, Inc.

materials. Although the exact numbers are not known, it is estimated that there are ~1½ million medical oxygen regulators in the United States [FDA, 2001], and that several hundred thousand aluminum oxygen regulators have been in use for the last 5–10 years. We present three cases of portable pressurized oxygen resuscitator fires associated with aluminum regulators, describing the investigations done and the fire mechanisms involved, and make recommendations to reduce this hazard.

MATERIALS AND METHODS

The NIOSH Fire Fighter Fatality Investigation and Prevention Program[1] was asked by the International Association of Fire Fighters to investigate three serious non-fatal incidents involving oxygen resuscitator fires causing injury to three fire fighters/emergency medical technicians. Injury field investigations included interviews with the injured workers and others at the scenes, evaluation of the oxygen resuscitators involved, and the associated fire fighter or ambulance equipment, and review of the local department's policies on resuscitator use, maintenance, and refilling practices. In addition, new (compressed oxygen) cylinders and regulators of the type involved were purchased and evaluated by NIOSH for the presence of contaminating particles. The resuscitator involved in each incident was also evaluated by one author (B.N.) employed by a private forensic engineering company with extensive experience in oxygen-related fires in medical devices. This evaluation consisted of detailed inspection, including microscopic examination for burn and erosion patterns, regulator disassembly, detailed photography, radiographic imaging, and analytic tests including scanning electron microscopy with energy dispersive spectroscopy (SEM/EDS) (performed at NASA White Sands Test Facility).

RESULTS

Case Reports

In 1998 and 1999, NIOSH investigated three separate cases of oxygen resuscitator fires which caused second and third degree burns to fire fighters [NIOSH, 1999a,b, 2000]. In each case, the equipment consisted of an aluminum compressed oxygen cylinder with an aluminum regulator (Fig. 1); and the fire fighter was performing a routine check of the cylinder pressure. On opening the cylinder valve, a large ball of fire shot out from the resuscitators and ignited clothing of the involved fire fighters. In Case no. 2, the fire also engulfed the (vacant) patient compartment of the ambulance, which was destroyed, and the cylinder as well as the regulator sustained extensive damage (Fig. 2). In Case no. 3, the cylinder valve was sheared off the oxygen cylinder. In none of the case investigations did there appear to be any significant element of excessive heat stress, rough handling, or external damage prior to use, inappropriate refilling techniques or over-pressurization to explain the resuscitator fires. However, all had been stored in the horizontal position, which is thought to increase the likelihood that contaminant particles may lodge near the neck of the oxygen cylinder and thus be subsequently entrained in the initial gas flow on opening the cylinder valve. All were also stored with the regulator attached to the oxygen cylinder to facilitate rapid use in medical emergencies. In Case no. 2 and 3, the cylinders were nearly full, with prior pressure measurements of 1,800 and 2,200 psi, respectively. In each case, the resuscitator had been either used or tested in the past 24 hr with no problems. It should also be noted that the regulators in Case no. 1 and 3 had been retrofitted with a bronze screen from the manufacturer instead of the original stainless steel screen in the regulator inlet, in an attempt to reduce the possibility of regulator ignitions.

After the third incident, the manufacturer has voluntarily recalled all regulators of this type, with the stated purpose to replace aluminum components in the high-pressure sections with brass components. The company also announced that they would stop the manufacture of aluminum-bodied regulators [Miller, 1999; Washenitz et al., 2001].

Laboratory Investigations

On removing the cylinder valves from newly purchased oxygen resuscitators of the type involved in the fire incidents, NIOSH was able to document small contaminant particles in the bottom of the aluminum cylinders. In addition, a few particles were also found in a new regulator, which may have been created when the pressure gauge was attached to the regulator body during initial assembly. Prior tests by Wendell Hull & Associates, Inc. found ~230 particles (96% in the 100–500 μm diameter-size range) emitted from similar fully-pressurized aluminum cylinders tested in the horizontal position during the first five valve cycles (open/close). SEM/EDS and Fourier Transform Infrared Spectroscopy studies indicated that approximately half of these particles were aluminum; the other half consisted of brass and plastic debris from the cylinder valve.

The severe damage to the devices in the three case investigations complicated the detailed regulator investigations performed by the private forensic engineering company, but several likely scenarios were proposed to explain the resuscitator fires based on the investigations and known flammability properties of aluminum and high-pressure

[1] This program, initially funded by Congress in 1998, is designed to investigate and report on line-of-duty United States fire fighter fatalities, and to develop appropriate prevention recommendations. Further information can be found on its web page: http://www.cdc.gov/niosh/firehome.html

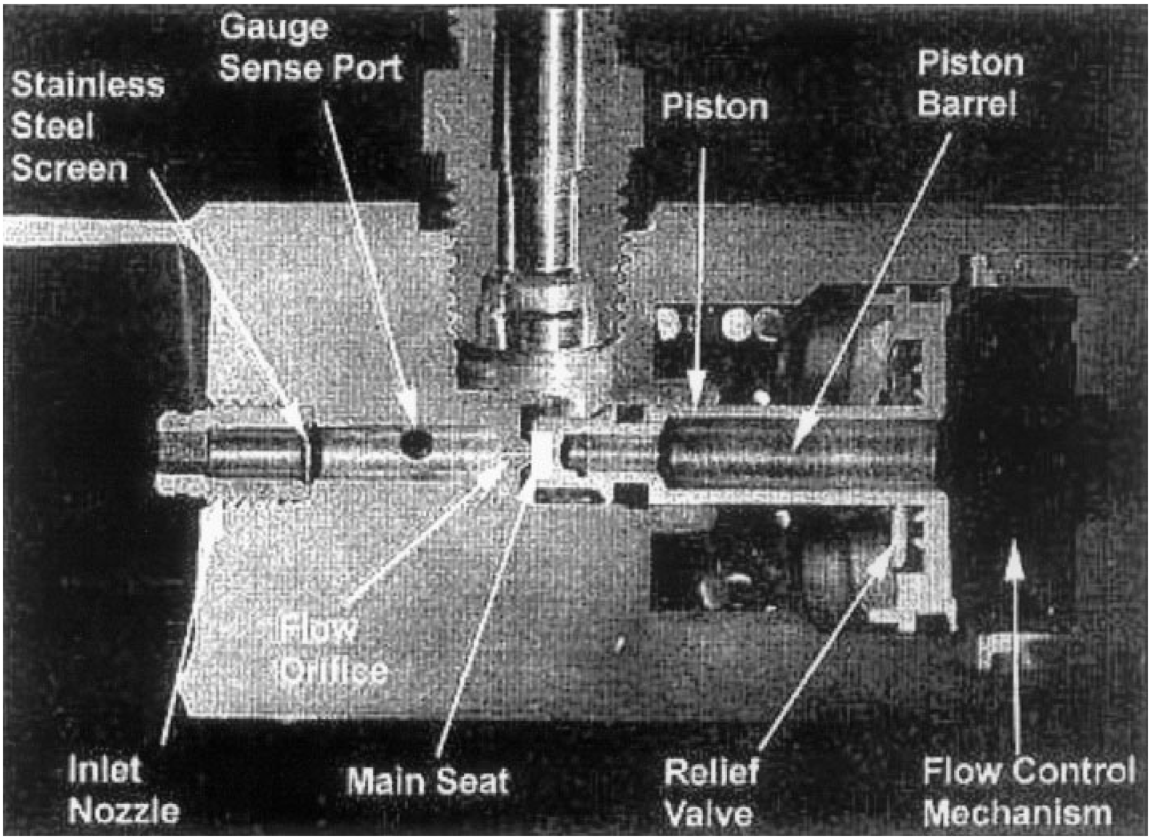

FIGURE 1. Cut-away view of the aluminum regulator. The inlet nozzle is brass. The stainless steel screen had been replaced (through a factory recall) with a sintered bronze screen in Case no. 1 and 3. The low-pressure components are to the right of the flow orifice.

oxygen systems. The full reports of these investigations are available.[2]

In Case no. 1, the fire erosion patterns were consistent with internal ignition in the proximity of the inlet filter with propagation radially outward and downstream (towards the low-pressure components). There were two burn holes in the regulator, which corresponded to the vent ports in the low-pressure cavity of the regulator, with evidence of lancing flow (fire, molten metal, and hot gases) passing through these vent paths (Fig. 3). This finding is consistent with the location of burn holes observed in prior research on oxygen regulator promoted combustion testing. [Newton et al., 1989, 1997]. There was no evidence of burn in the cylinder valve or its non-metallic valve seat. Based on these and related findings, the most probable ignition mechanism was particle impact on the regulator inlet screen during the initial flow transient after the operator opened the cylinder valve.

The resuscitator fire in Case no. 2 consumed more than 50% of the regulator's aluminum body. The cylinder damage (Fig. 2) was explained by burn patterns and SEM/EDS spectra data indicating a transient blowback (against the normal flow direction of gas from the pressurized cylinder through the regulator to the atmosphere) of combustion into the cylinder. Figure 4 demonstrates this by showing trace quantities of iron on the surface of the brass inlet nozzle, which are likely derived from the downstream stainless steel screen. The blowback condition in turn was due to the addition of a metal gauge guard to the regulator, which was attached such that it significantly blocked the vent ports. As noted in Case no. 1, these low-pressure escape routes were normally followed by the metal fire; their blockage led to significant burning and very high pressures in the cylinder, which led to the cracking of its wall. The initial ignition mechanism was thought to be located either at the cylinder valve seat, or in the high-pressure section of the regulator likely involving the inlet screen.

In Case no. 3, the combustion deposits observed in the cylinder neck and valve fracture area were consistent with burning of the regulator and not due to local combustion. Photographic and radiographic imaging of this regulator showed an expanding triangular burnout pattern, which was

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FIGURE 2. Compromised oxygen cylinder from Case no. 2.

consistent with fire origination at the regulator inlet screen with propagation downstream. The most likely ignition mechanism to explain these and the other findings was particle impact on the inlet screen.

It was also noted that the specific physical design of the involved regulator provided minimal protection of the aluminum to promoted ignition mechanisms. These features included gas flow tracks that could easily cause significant adiabatic compression temperature increases when the cylinder valve was opened and easy penetration (and thus propagation) of combustion from the high-pressure port to the low-pressure regulator components.

DISCUSSION

The combustibility of various materials in the presence of high-pressure pure oxygen has been studied by numerous groups over the years. As shown in Table I, commonly used brass alloys have good flammability characteristics, requiring a very high partial pressure of oxygen to burn, and releasing low amounts of heat when they do burn. Other alloys also have been developed with similar characteristics. In contrast, aluminum burns easily in the presence of high-pressure pure oxygen, and has a very high heat of combustion in this setting. Besides the oxygen threshold pressure test shown in Table I, several other test methods are used to assess a metal's flammability, including the burn propagation rate, ignition by frictional heating, and ignition by particle impact. In all of these tests, aluminum is the most flammable of all commonly tested metals [American Society for Testing and Materials, 1998]. For these reasons, several organizations have recommended that materials used in high-pressure pure oxygen systems (such as oxygen resuscitators) have the flammability characteristics of brass or bronze [National Aeronautics and Space Administration, 1983; Canadian Standards Association, 1987; National Aeronautics and Space Administration, 1996; American Society for Testing and Materials, 1997a].

Since 1996, the FDA has received 37 reports of oxygen regulator fires (Ann Graham, FDA unpublished communications, April 22, 2002). Most of these have involved aluminum regulators, and most have resulted in injuries to either workers or patients. It is thus clear that the use of aluminum regulators in oxygen resuscitators can result in rare, but unpredictable and potentially catastrophic fires.[3] The mechanism appears to involve two components: an initial ignition that may occur in several ways, followed by the burning of the aluminum regulator itself in the presence of pure oxygen under high pressure. There are several potential causes of the initial ignition, which requires heat as well as a combustion material in addition to the oxygen present to complete the "fire triangle." Heat occurs via adiabatic compression when the cylinder valve is initially opened, particularly if done quickly. This leads to a burst of oxygen flow, which then hits the small closed (by the secondary flow control mechanism) high-pressure area of the regulator, which can cause a rapid rise in temperature. The theoretical maximum temperature obtained when compressing oxygen adiabatically from 20°C and 1 atm to 2,000 psi is 920°C [American Society for Testing and Materials, 1997b]. This would be sufficient to ignite nearby contaminants.

Another potential source of heat for the initial ignition is the kinetic energy of any aluminum (or other) particles that might be entrained by the initial rapid oxygen flow. The moving particles can serve both as a heat source (when they impact) as well as the fuel for an initial ignition. As noted, particles were documented to exist in new aluminum cylinders, and in fact, are likely common. With regard to

[3] It should be recognized that any compressed oxygen system can cause a fire outside the resuscitator in which the regulator does not burn. These can be caused, for example, by a leaky gasket or seal between the cylinder and regulator. Often the gasket is an elastomeric material, which can then ignite through a variety of mechanisms and cause a brief flame that can, in turn, ignite flammable materials (resuscitator bag, clothing) in the immediate area.

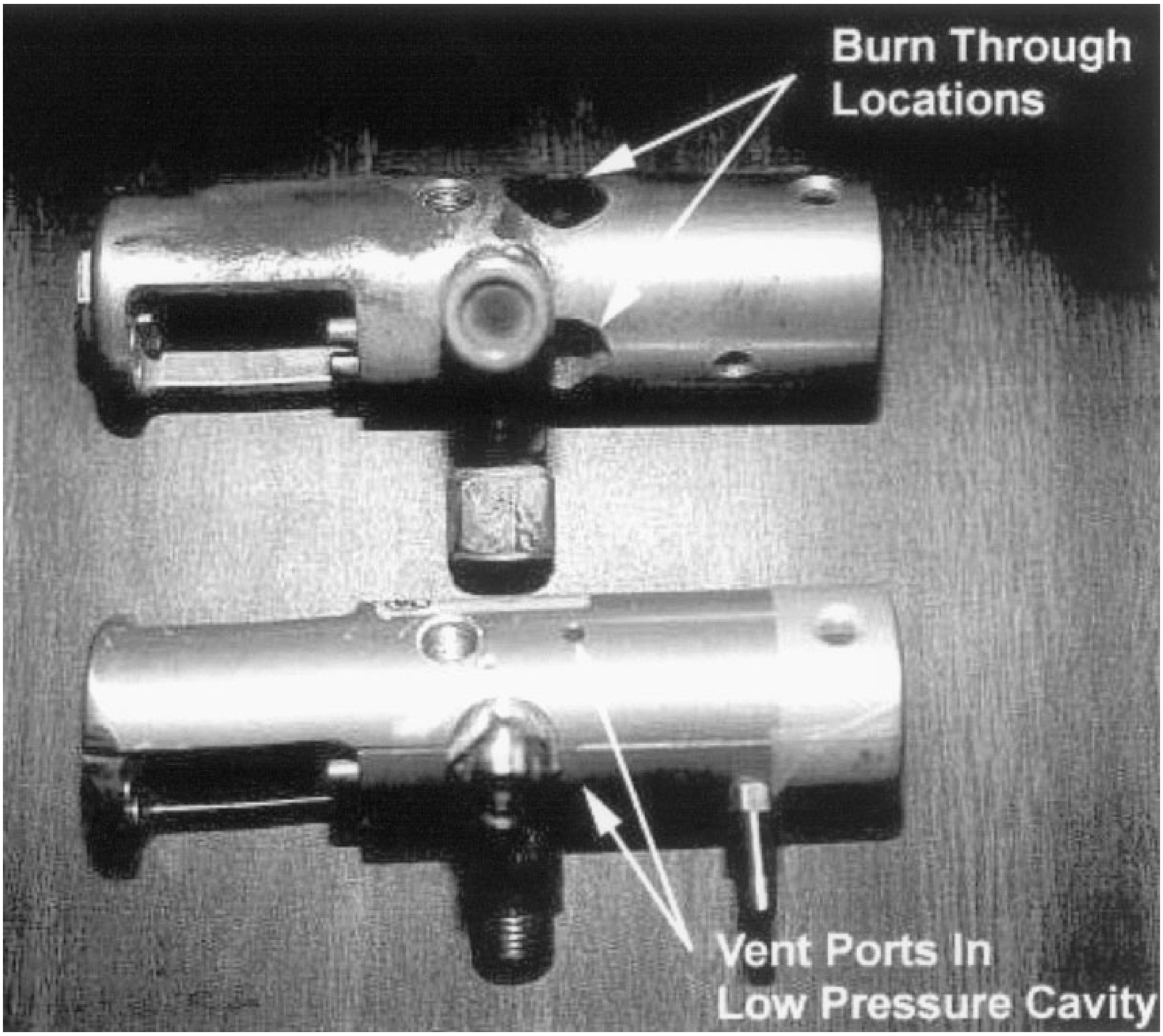

FIGURE 3. Burned regulator (top figure) from Case no. 1, and an undamaged regulator, showing the consistency of the vent ports and the burn-through holes in the incident regulator.

pressurized oxygen systems, the ASTM notes that: ‘‘Absolute removal of particles is not possible, and systems can self-regenerate particles’’ [American Society for Testing and Materials, 1997b (p 76)]. They can be created when the cylinder valve stem is screwed into the cylinder during initial assembly, and through the ‘‘wear and tear’’ of the valve opening and closing process. Additional fuel sources could be oil, grease, or dirt contamination in the regulator high-pressure area, or the often non-metallic valve seats and seals. There was no evidence to suggest that other sources of energy, such as acoustic oscillations or static electric discharges, played a role in the investigated fires.

Although the body of the aluminum regulator itself is not thought to be involved in the initial ignition, this ignition can raise the combustion threshold to the point where the regulator burns. Once this occurs, the very high heat of combustion of aluminum plus the high-pressure pure oxygen can combine to create an explosive fire. The apparent rare nature of these fires is not fully understood, although it seems likely that the intensity of the initial ignition may play a key role. The engineering design of the regulator may explain why most (but not all) of the resuscitator fires have occurred with just one brand and model. However, this model was also one of the more prevalent aluminum regulators in use; and accurate numbers could not be obtained to determine actual risk estimates. Of note, a second, unrelated oxygen resuscitator brand (also with an aluminum regulator) has recently been reported to the FDA in a similar fire; this emphasizes the generic risk of using aluminum in the high-pressure area of oxygen regulators. Although, all three cases involved aluminum compressed oxygen cylinders, there have been documented aluminum regulator fires used with

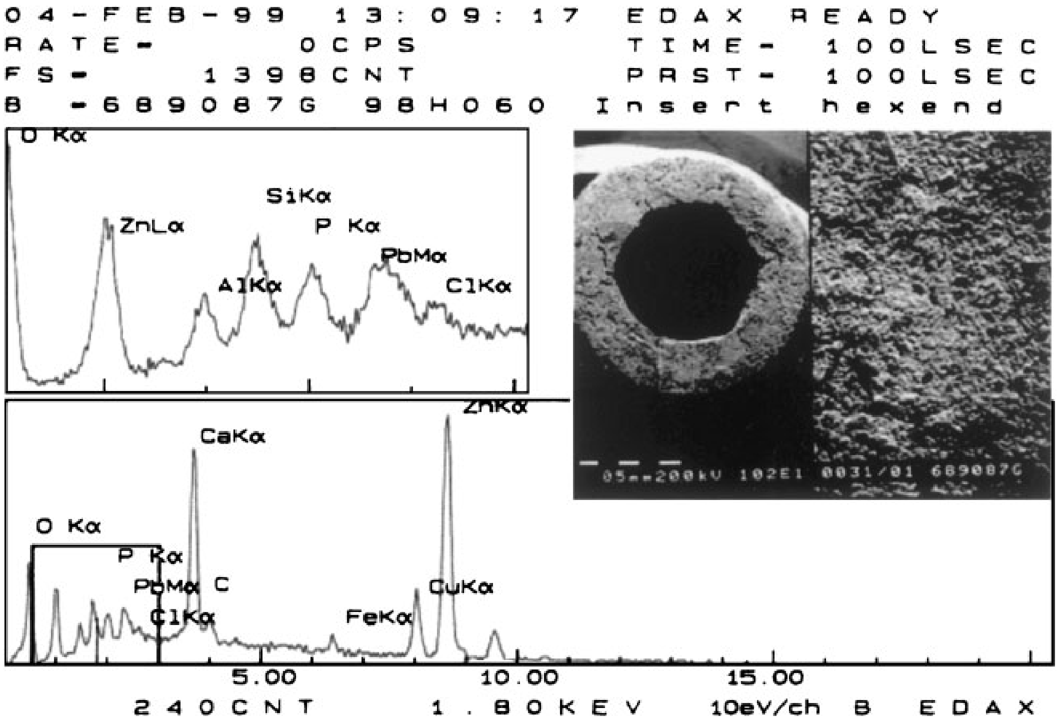

FIGURE 4. An example of SEM (with higher magnification photo on right) with EDS analysis on the inlet face of the brass inlet nozzle in the regulator in Case no. 2. EDS vertical axis is counts; horizontal axis is energy level. Data show aluminum deposits on this surface with trace quantities of iron (FeKα), which are likely derived from the downstream stainless steel screen.

TABLE I. Oxygen Threshold Pressures Required to Support Complete Combustion of 3.2-mm Diameter Rods Ignited at the Bottom, and Heats of Combustion for Selected Materials*

Material	Oxygen threshold pressure (psi)	Heat of combustion ($-\Delta H_c$, cal/g)
Monel®	$>$ 10,000	870
Brass 360 CDA	$>$ 10,000	825
Nickel 200	$>$ 8,000	980
Copper	$>$ 8,000	585
440C Stainless steel	1,000	$\sim$ 1,900
Aluminum 2,219	35	Not available
Aluminum 99.9%	25	$\sim$ 7,400

*Adapted from National Fire Protection Association [1994] and American Society for Testing and Materials [1997c]. Usually small differences exist in the values among different alloys of the same class, depending on their exact composition; aluminum alloys have oxygen threshold pressures ranging from 25 to approximately 100 psi. Typically, brasses have 60–90% copper and the rest zinc. Bronze alloys are predominantly copper, with 3–10% tin, and have similar oxygen threshold pressure values as brass alloys. As a class, Monels are essentially nickel alloys with 30% copper. Nickel 200 is 99.5% nickel. Aluminum 2219 is aluminum with the main other metals consisting of 6.3% copper and 0.3% manganese. Note that a full oxygen resuscitator cylinder has an oxygen partial pressure of $\sim$ 2,200 psi.

steel cylinders as well [Miller, 1999]. Thus, the use of non-aluminum cylinders would not remove the hazard of regulator fires, but by reducing the potential for impact ignition of the highly flammable aluminum particles, could reduce this hazard.

The Food and Drug Administration (FDA) has jurisdiction over these medical devices, and jointly with NIOSH released a Public Health Advisory in February 1999 calling attention to the problem of explosions and fires in aluminum oxygen regulators [Food and Drug Administration and National Institute for Occupational Safety and Health, 1999]. This Advisory, as well as the related NIOSH Firefighter Fatality Reports includes several safe handling recommendations in addition to the recommendation to avoid using aluminum exposed to high-pressure oxygen. These recommendations include meticulous filling, storage, maintenance, and training procedures to avoid contamination of the regulators and cylinders; vertical storage of cylinders to reduce the possible entrainment of particles; momentarily opening and closing the cylinder valve before attaching the regulator to flush out any particle contamination (which might not be feasible in medical emergency situations, but could be used during routine pressure checks); slow valve opening to reduce the heat of adiabatic compression; and pointing the cylinder and valve away from yourself and others when opening. Regulations and other guidelines on appropriate oxygen system operation are available from a number of sources [Canadian Standards Association, 1987; National Fire Protection Association, 1990, 1994; American Society for Testing and Materials, 1991, 1997a; Compressed Gas Association, Inc., 1996, 1998; National Aeronautics and Space Administration, 1996; Miller, 1999; Department of Transportation, 2000].

Informal discussions among emergency medical technicians, fire fighters, and health care workers suggest that the possibility of dangerous ‘‘metal’’ (aluminum) fires in oxygen resuscitators is not well appreciated. Education and improved safety practices and equipment are needed to reduce this rare, but potentially serious hazard.

ACKNOWLEDGMENTS

We thank Mike Sapko and Charles Lazzara, Herb Linn, and Norma Bolyard for their assistance in this project.

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