Hyperbaric and hypobaric chamber fires: a 73-year analysis

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Sheffield PJ, Desautels DA. Hyperbaric and hypobaric chamber fires: a 73-year analysis. Undersea Hyper Med 1997; 24(3):153–164.—Fire can be catastrophic in the confined space of a hyperbaric chamber. From 1923 to1996, 77 human fatalities occurred in 35 hyperbaric chamber fires, three human fatalities in a pressurized Apollo Command Module, and two human fatalities in three hypobaric chamber fires reported in Asia, Europe, and North America. Two fires occurred in diving bells, eight occurred in recompression (or decompression) chambers, and 25 occurred in clinical hyperbaric chambers. No fire fatalities were reported in the clinical hyperbaric chambers of North America. Chamber fires before 1980 were principally caused by electrical ignition. Since 1980, chamber fires have been primarily caused by prohibited sources of ignition that an occupant carried inside the chamber. Each fatal chamber fire has occurred in an enriched oxygen atmosphere (>28% oxygen) and in the presence of abundant burnable material. Chambers pressurized with air (<23.5% oxygen) had the only survivors. Information in this report was obtained from the literature and from the Undersea and Hyperbaric Medical Society's Chamber Experience and Mishap Database. This epidemiologic review focuses on information learned from critical analyses of chamber fires and how it can be applied to safe operation of hypobaric and hyperbaric chambers.

hyperbaric oxygen therapy, hyperbaric chamber fires, National Fire Prevention Association chamber fire codes, chamber fire safety, chamber accident

Modern hyperbaric oxygen (HBO_2) therapy originated with the clinical trials of Dr. I. Churchill-Davidson of London in 1955 (1) and the first reports on the use of HBO_2 by Professor I. Boerema of Amsterdam in 1956 (2). In 1960, Professor Boerema and associates published an article, *Life Without Blood* (3), that provided the rationale for HBO_2, and ushered in the practice of administering oxygen to patients under hyperbaric conditions. In the 1960s, several large clinical chambers were constructed to support surgical operations, and a few diving decompression chambers were adapted for clinical use (4). Oxygen was administered to the patient while pressurized inside the air-filled chamber. In 1964, a "monoplace" hyperbaric chamber, the Vickers Hyperbaric Oxygen Bed, was introduced in which a single patient could be totally immersed in the pure-oxygen environment (5). It was also a time of expanded exploration of the deep sea and outer space. Research chambers were fabricated for the use of pure O_2 and special gas mixes. Before 1970, there were no national fire safety standards for clinical hyperbaric chambers in the United States, so fire prevention was a matter left to common sense of the operators.

This paper is an analysis of fires in human-occupied chambers reported in Asia, Europe, and North America from 1923 to 1996. Data were obtained from reports in the literature and from the Undersea and Hyperbaric Medical Society (UHMS) Chamber Experience and Mishap Database (6). The UHMS Safety Committee Chairperson maintains the UHMS database, which contains reports of fire, structural failure, and other operator experience. Individuals who contribute to the database are promised anonymity as well as confidentiality of location. Thus, cases described in this report that were obtained from the UHMS database have the source and location omitted. When the UHMS database is referenced as the source in this report, it is because there were no published accounts of the mishap available to be cited.

Table 1 shows fires that occurred in diving and hypobaric (altitude) systems. Pure-oxygen fires in the Apollo Command Module and hypobaric chambers served as initiating events to develop strong fire safety codes that now govern hyperbaric facilities in the United States. Table 2 lists fires that occurred in clinical hyperbaric chambers. Of the 39 fires reported, 10 occurred in dive chambers (2 bells, 8 decompression chambers), 3 occurred in altitude chambers, 1 occurred in a spacecraft, and 25 occurred in clinical hyperbaric chambers.

Table 1: Fires Inside Diving and Hypobaric Systems

Mishap	Date/ Nation	Chamber	O_2, %	Casualties Fatal	Casualties Injury	Probable Cause (Reference)
Diving Bells						
16	1974/JA	multi-bell	unk He-O_2	2		Short in vinyl wiring caused toxic fumes and consumed O_2, killing 2 divers; designer committed suicide (6)
18	1976/unk	multi-bell	unk He-O_2	2		Defective welding device (6)
	Subtotal			4	0	
Decompression Chambers						
2	1939/US	multi-dec	unk air	0	4	Cigar of outside attendant ignited chamber interior when door was opened (13)
3	1945/US	multi- dec	unk air	2	1	Sparks from electric fan ignited wood floor (12–15)
4	1953/UK	multi- dec	unk air	5		Light bulb imploded igniting canvas floor cover (12)
7	1965/US	multi- dec	28	2		Scrubber motor ignited filter element (4,12–15)
13	1969/US	multi- dec	20–28	1		150-W lamp ignited cotton shirt draped over it (4,12,13)
14	1970/JA	multi- dec	unk	1		300-W lamp ignited mattress and blanket (12)
17	1975/CA	multi- dec	40	1		Suspected electrostatic charge when diver separated wood and synthetic sweaters; first reported as spontaneous ignition of oil-impregnated muffler (6)
22	1979/US	multi- rec	unk air	1		Welding sparks ignited student's clothing (13,16)
	Subtotal			13	5	
Hypobaric Systems						
5	1962/US	res	100	0	1	Electrical short ignited wiring insulation (7,12)
6	1962/US	res	100	0	4	Electric lamp short ignited wiring insulation (7,12)
8	1967/US	Apollo CM	100	3		Electrical short ignited wiring insulation (7,12,15)
9	1967/US	res	100	2		Electrical arc at extension cord ignited clothing (7,12,15)
	Subtotal			5	5	

Key: CA = Canada; JA = Japan; US = United States; UK = United Kingdom; dec = decompression; res = research; unk = unknown; tr = treatment.

FIRE POTENTIAL IN HYPERBARIC CHAMBERS

Three components must be present for a fire to occur: ignition, oxygen, and fuel (burnable material). Fire behaves differently with varying oxygen concentration. Combustion cannot occur if oxygen is less than 6%, but complete combustion can occur if O_2 is above 12% (7,8). Burn rates increase in oxygen-enriched atmospheres (7,8). The National Fire Prevention Association (NFPA) 53-1994 defines an oxygen-enriched atmosphere as "an atmosphere in which the concentration of oxygen exceeds 21 percent by volume or the partial pressure of oxygen exceeds 160 torr (millimeters of mercury), or both" (7). However, the fire safety standard for hyperbaric chambers, NFPA 99 Chapter 19, defines an oxygen-enriched atmosphere as, "For the purpose of this standard, and only for the purpose of this standard, an atmosphere in which the concentration of oxygen exceeds 23.5 percent by volume" (9). Within an oxygen-enriched hyperbaric chamber, fire behavior is modified by the following: a) the energy required for ignition is lower; b) the flame spread rate is faster; c) the rise in temperature causes a rapid rise in chamber pressure; and d) there are problems of escape from the confined area (7). Thus, fire prevention is especially important. Fire prevention techniques are aimed at eliminating ignition sources, limiting oxygen concentration, reducing the amount of fuel, and providing a method of fire

Table 2: Fires Inside Clinical Hyperbaric Chambers

Mishap No.	Year/ Country	Type Chamber	O_2, %	Casualties Fatal	Casualties Injury	Probable Cause
1	1923US	multi- tr	21% air	0		External gas burner caused interior insulation to smolder, necessitating evacuation of chamber (10)
10	1967/JA	mono- tr	50	1		Butane hand-warmer ignited clothing (6,12)
11	1967/CH	multi- tr	100	2		*Smoking (6)
12	1969/JA	multi- res	73	4		Sparks from camera cord ignited newspapers (12,13)
15	1973/FR	mono- tr	100	1		Unreported (21)
19	1976/US	mono- tr	100	0		Electrostatic spark in fiberglass tray ignited unoccupied mattress (5,13,16,22)
20	1978/UK	mono- tr	100	0		Electrostatic spark in fiberglass tray ignited unoccupied mattress (22)
21	1979/JA	mono- tr	100	1	6	Patient tried to light a cigarette (5,6)
23	1983/CH	mono- tr	100	1		*Static electricity (6)
24	1984/CH	mono- tr	100	1		*Static electricity (6)
25	1986/CH	mono- tr	100	1		*Static electricity (6)
26	1986/CH	mono- tr	100	1		*Electrical short in phone (6)
27	1987/CH	mono- tr	100	1		*Static electricity (6)
28	1987/CH	multi- tr	100	8		*Spark from child's electrical toy (6)
29	1987/IT	mono- tr	100	1		Spark-generating friction toy ignited bedding (5)
30	1989/JA	mono- tr	60–90	1		Butane hand-warmer ignited clothing (5)
31	1989/US	multi- tr	23.5% air	0		Microwave-heated blanket began to burn (4,23)
32	1989/CH	mono- tr	100	1		*Static electricity (6)
33	1993/JA	mono- tr	100	1		Butane hand-warmer ignited clothing (6)
34	1993/CH	multi-tr	100	5		*Smoking (6)
35	1993/CH	multi- tr	unk air	8		*Electrical short in air conditioner (6)
36	1994/CH	multi- tr	unk air	7		*Electrical short in air conditioner (6)
37	1994/CH	multi- tr	unk air	11		*Electrical short in air conditioner (6)
38	1995/RU	mono- tr	unk O_2	1		Unreported (20)
39	1996/JA	mono- tr	100	2	2	Chemical hand-warmer ignited blanket (6,19)
	Subtotal			60	8	

Key: CA - Canada; CH = China; FR = France; IT = Italy; JA = Japan; RU = Russia; US = United States; UK = United Kingdom; tr = treatment; res = research; unk = unknown % O_2. * = Unconfirmed.

extinguishment and escape. Medical and technical personnel who operate clinical hyperbaric facilities should know the potential for fire in the chamber and must be especially vigilant to prevent its occurrence.

A HISTORIC FIRE

The first hyperbaric chamber fire that is known to the authors occurred in the winter of 1923 at the Cunningham Sanitarium in Kansas City. The chamber was outside the building, and was heavily insulated to protect occupants from extreme temperature. A documented report of the mishap is described below (10).

Mishap 1: " The tank's on fire!" An anguished cry over the intercom from the inside nurse brought Cunningham on the run. He couldn't believe it; patients had been warned not to smoke, every precaution taken. The doctor plunged into the entry lock, saw hazy smoke in the left compartment and quickly herded out all the patients, and then emptied the other end of the t ank. There seemed to be nothing on fire, but part of the floor was charred. . . .He had installed open gas burners under the tank to keep it warm in winter. Somebody had turned the flame a little too high and scorched the interior insulation.

FIRES IN DIVING BELLS

Divers may enter a diving bell (or personnel transfer capsule) at sea level pressure and then be lowered to the work site with the bell still pressurized at atmospheric pressure. When they are ready to go to work, they pressurize the bell (usually with a premixed helium-oxygen mixture) until the bell is at the same pressure as ambient water pressure and the hatches can be opened. The working diver exits the bell, usually by an umbilical tether, while one or two divers remain in the bell to tend the working

diver and act as standby (11).

From 1974 to 1976, two fires were reported in the helium–oxygen environment of submerged diving bells, resulting in five fatalities. It is unclear whether the bells were pressurized with helium–oxygen, or with air in which the divers were breathing helium–oxygen. One fire was caused by an electric short in vinyl wiring that produced toxic fumes and consumed the O_2 from the bell that was submerged at a depth of 33 fsw (10 msw, 2 atm abs). Two divers died and the designer committed suicide (6). A faulty welding device caused the second fire in a submerged bell at a depth of 400 fsw (121 msw, 13 atm abs), resulting in the death of both divers (6).

FIRES IN DECOMPRESSION CHAMBERS

At the completion of a dive, the diver is often brought to the surface to complete the decompression schedule in the more comfortable surroundings of a decompression chamber. When the same chamber is used to treat divers stricken with decompression illness, it is considered a recompression chamber. The chamber is usually pressurized with air, but may be equipped for pressurization with mixed gases. Oxygen is often used as the breathing gas during surface decompression and/or during the latter phases of decompression (11).

From 1939 to 1979, eight fires were reported in air-pressurized decompression chambers, producing 11 fatalities and 5 survivors. Mishap analyses reveal that before the late 1950s, decompression chambers were equipped differently from modern chambers (12). They contained wooden seats and floor grates that were sometimes covered by canvas. Lighting was by open incandescent lamps. Exhaled gases from the occupants were dumped directly into the chamber, causing the O_2 percentage to rise during O_2 decompression. Pressurization was by oil-lubricated air compressors that sometimes left an oil film on the chamber interior. Fire suppression equipment usually consisted of a bucket of sand or water, or nothing at all.

Electrical sources (light bulbs, motors, temporary electrical extension cords) ignited five fires in oxygen-enriched air chambers, causing 11 fatalities. Unprotected incandescent light bulbs caused three of the fires, one due to implosion and two due to over-heating of adjacent bedding or clothing that was draped over the light bulb. In one of the chamber fires, the occupant had been provided with a bucket of water for extinguishment, but the flame spread too rapidly for him to use it. Following is a synopsis of Mishap 4 (12).

Mishap 4: In 1953, within 2 min after the air-filled chamber dive commenced, an unprotected 100-W light bulb imploded between 5–6 atm abs (134–170 fsw, 511–621 kPa) and incandescent pieces of the filament ignited the canvas floor covering. The five occupants unsuccessfully tried to stamp out several small fires in the canvas, which rapidly spread to the wooden floor and benches. Within 1 min, flames engulfed the chamber and the heat caused pressure to rise to above 9.2 atm abs (265 fsw, 929 kPa). When the chamber surfaced 5 min into the dive, flames came out through the open doorway, requiring extinguishment by fire hose. Within 6 h, all five occupants had expired from their 90–100% total body surface area (TBSA) burns.

Overheating and arcing of electrical motors caused two fires in decompression chambers that produced four fatalities. One of the fires is described in the following mishap report (12–15).

Mishap 7: In 1965, two divers were fire casualties in a US Navy research recompression chamber that contained about 28% oxygen, 36% helium, and 36% nitrogen at 3.8 atm abs (91 fsw, 380 kPa). Most probable cause of the fire was attributed to an overheated electrical motor in the carbon dioxide scrubber. Downstream of the motor was a filter element of the type that was normally used to filter jet fuel. Following manufacture, it had been tested in a kerosene mixture, leaving residual kerosene as the probable primary fuel in the fire (15). An occupant called over the intercom, "We have got a fire in here!" Two outside observers noted a flame coming from the carbon dioxide scrubber. Immediately thereafter a flash fire engulfed the compartment and smoke obscured vision. The occupants did not have time to use the bucket of water provided for fire extinguishment. Temperature rose to about 800°F and pressure jumped from 3.8 to 8.9 atm abs (91–260 fsw, 380 – 897 kPa). Rescue was attempted, but was impossible due to the intense heat.

Mishap 22 was due to deviation from acceptable welding practices while undergoing training in the recompression chamber that was pressurized with air. The subsequent fire resulted in one fatality (13,16).

Mishap 22: In 1979, while practice welding in a chamber at 6.8 atm abs (190 fsw, 683 kPa), a student diver was fatally burned when his polyester clothes ignited from welding sparks. He had violated the established safety procedure that required him to stand waist deep in water while welding. The only thing consumed by the fire was the student's clothing.

Both spontaneous combustion and electrostatic charge were suggested in separate reports as the initiating event of a decompression chamber fire that caused one fatality in Mishap 17. The initial report of the mishap suggested that spontaneous combustion might have caused a fire in the air

muffler. "It was suspected that the muffler filter element absorbed a sufficient quantity of oil vapor to ignite when the oxygen level inadvertently built up to above normal limits." The filter element was completely consumed during the chamber fire (memorandum from D.M. Hughes, Oceaneering International to all ADC members, Subject: Fatal Diving Accident, 1975. Available from UHMS.) Further investigation revealed that the compressor had not been discharging oil, thus the muffler was an unlikely source of spontaneous combustion. A second report from the investigating team stated that no conclusion could be reached about the source of ignition, but the most likely source was electrostatic discharge generated by separation of sweaters of dissimilar fabrics (G.H. Koch, personal communication). The mishap report below describes in detail the ensuing events (6).

Mishap 17: In 1975, a diver was completing his surface O_2 decompression at 1.6 atm abs (20 fsw, 162 kPa) following a routine helium–oxygen dive to 275 fsw (9.3 atm abs, 943 kPa). The diver had a respirator mask with an overboard discharge that was not working properly. He donned a second mask that was "Y connected" to the first, and placed it on free-flow. This deactivated the overboard discharge and allowed O_2 to build up inside the chamber to an estimated 40%. The diver wore two sweaters for warmth. As the chamber was being vented, the diver removed his wool sweater from over a synthetic one. There was a flash in the chamber and smoke poured out of the vents and the outside built-in breathing system (BIBS) mask. The diver died as a result of the explosion, carbon monoxide poisoning, and asphyxia. The reporter indicated that subsequent studies showed that synthetic fabric and wool could generate 50,000 V upon separation; and that a 1-inch static discharge is equivalent to 10,000 V (no amperage), which was reported as sufficient for ignition.

In response to Mishap 17, synthetic and wool fabrics were prohibited inside the chamber, leaving 100% cotton as the preferred fabric. Even though it burns readily, cotton does not cause static sparks. Also at the author's (P.J.S.) facility, a procedure was established for periodic checks of the air muffler with ultraviolet light to ensure that the compressor oil had not accumulated in the filter. Additionally, stainless steel filings that were contained in the air inlet mufflers were replaced with more fire-resistant brass filings.

In 1939, an outside attendant unwittingly ignited the chamber interior with his cigar as he opened the door at the surface. A synopsis of this mishap is described below (13).

Mishap 2: A shipboard chamber interior was ignited at the surface by an outside attendant's cigar when he opened the door to the oxygen-enriched environment. Four occupants had completed O_2 decompression by mask and exhaled O_2 had accumulated inside the chamber. The oil-lubricated compressor had left a thin film of oil on the chamber interior. Fortunately, the open door made escape possible and the four divers survived.

FIRES IN HYPOBARIC FACILITIES

On 20 July 1969, Neil A. Armstrong and Edwin E. Aldrin, Jr, walked on the moon as their colleague, Michael Collins, and the world watched in admiration. In preparation for this historic event, numerous hypobaric (altitude) chamber studies were conducted in pure-oxygen environments. During a 5-yr period (1962–1967), there were four fires in hypobaric facilities (three altitude chambers, one Apollo Command Module), all of which were attributed to electrical ignition in pure O_2. Three fatalities occurred in the Apollo Command Module fire that contained pure O_2 at a hyperbaric pressure of 1.1 atm abs (16.2 psia, 111 kPa). There were two fatalities in one altitude chamber fire, but no fatalities in two other fires.

In 1962, two nonfatal fires occurred in research altitude chambers that contained pure O_2 at 0.34 atm abs (5 psia, 34 kPa) or less. Two survived the first fire (7) and four survived the second (7,12), as described in Mishaps 5 and 6, respectively.

Mishap 5: Two subjects dressed in pressure suits were evaluating temperature control factors in pressure suits and cabins at 0.26 atm abs (3.8 psia, 26 kPa). One subject saw a glow behind the instrument panel, which was ablaze within several seconds, filling the chamber with black smoke. The second subject was awakened by the fire alarm, opened his pressure suit visor, and subsequently suffered respiratory tract damage. The flames propagated slowly enough that the operator could "dump the chamber" and extract the two pressure-suited occupants without fatality. Neither subject experienced clothing or body burns. The fire was extinguished with difficulty by means of a carbon dioxide device. Although the exact cause of the fire was not determined, it occurred within the wiring of the enclosed instrument panel. The same chamber had previously experienced a mission abort when a power tube in the cabin TV monitor overheated.

Mishap 6: Another altitude chamber fire occurred at 0.34 atm abs (5 psia, 34 kPa) when a light bulb was replaced, causing a short that ignited the electrical insulation. An occupant requested water, but was told to snuff the fire out with a towel. The towel caught on fire and blazed so vigorously that it set the man's clothing on fire. Flames rapidly spread to bedding and pajamas of the four occupants, causing second-degree, 15–20% TBSA burns. An asbestos fire blanket was used to snuff out a clothing

fire, but it too burst into flames. When burning insulation dripped onto the bunk, a crewmember tried to beat it out with his hands and "his skin caught on fire". All four occupants survived because escape was possible through a second chamber compartment.

In 1967, two fatal pure-oxygen fires occurred within a 3-day period. One resulted in the death of three astronauts (Mishap 8) (7, 12, 15) and the other resulted in two technician fatalities (Mishap 9) (7, 12).

Mishap 8: Three astronauts died when a flash fire spread through Apollo Command Module 204 at the Cape Canaveral launch pad. The Command Module contained pure O_2 at 1.1 atm abs (16.2 psia, 111 kPa). Although the cause of the fire was not specifically determined, investigators thought it to be initiated by an electrical arc. Within seconds, the spacecraft temperature reached 1,000°F, and pressure increased to 1.9 atm abs (27.7 psia, 192 kPa), causing the cabin to rupture within 14.7 s. Extinguishment was due to fire-induced O_2 starvation since there was no fire-extinguishing capability.

Mishap 9: Two U.S. Air Force technicians were killed in a US Air Force research altitude chamber fire, which contained pure O_2 at 0.5 atm abs (7.4 psia, 51 kPa). Apparently, one of the occupants stepped on an electric cord, abrading it against the nonskid aluminum floor, thus causing an arc that ignited his pants. Flame spread rapidly, like a "fireball". Although the chamber was pressurized to ground level and the occupants removed within 1.5 min after ignition, it was too late. Fire extinguishment equipment in the chamber consisted of two portable carbon dioxide extinguishers, neither of which was used, although one overheated and discharged through its pressure relief valve.

Because of these hypobaric fires, pure O_2 was abandoned as a spacecraft environment, and nitrogen gas was added to the cabin atmosphere. In response to the catastrophic hypobaric fires (Mishaps 8 and 9), as well as the U.S. Navy research recompression chamber fire (Mishap 7), the aerospace industry and medical operators sought the assistance of the NFPA to create a single source of data on the hazards of oxygen-enriched atmospheres. This prompted creation of a manual on fire hazards in oxygen-enriched atmosphere (7) and the first national fire safety standard for hyperbaric and hypobaric facilities in the United States (17,18). Current standards for clinical hyperbaric facilities are contained in NFPA 99, Standard for Health Care Facilities, Ch 19, Hyperbaric Facilities (9).

FIRES IN CLINICAL HYPERBARIC CHAMBERS

Clinical hyperbaric chambers are defined by the NFPA as Class A (multiplace) and Class B (monoplace). In multiplace chambers, one or more patients receive O_2 by mask, hood, or endotracheal tube while pressurized in the air-filled chamber (4). In monoplace chambers, a single patient may be pressurized with air, or with pure O_2 (5). NFPA 99 wisely forbids pressurization with pure O_2 in multiplace chambers. However, this practice does not seem to be universal, since three fires in China reportedly occurred in multiplace, pure-oxygen chambers, resulting in 15 fatalities (6).

During the period 1967–1996, there were 60 fatalities in 21 of the 24 clinical hyperbaric chamber fires (Table 2). Ten fires were caused by ignition sources that occupants carried into the chamber (hand warmer, lit cigarette, spark-generating toy), seven fires were suspected to be caused by electrostatic sparks, five were caused by electrical ignition, and two had unreported causes (Table 3).

In 1967, the first clinical chamber fire was reported in a pure-oxygen, monoplace chamber (Mishap 10) (6,12). It would be the first of four single-fatality fires in Japan to be initiated by hand warmers (three butane and one chemical). In 1989, a patient was fatally burned 73 min into the first HBO_2 treatment at 2 atm abs (33 fsw, 202 kPa) with O_2 between 60 and 90% (Mishap 30) (5,6). In 1993, black smoke was seen inside the chamber 15 min into the treatment at 2 atm abs (33 fsw, 202 kPa). As the operator turned off the O_2, an orange flame was seen at the front of the chamber, which resulted in fatal burns of the patient (Mishap 33) (6). In 1996, a chemical hand warmer was responsible for fatal burns of the patient and fatal trauma to the nearby spouse (Mishap 39) (19).

Mishap 10: The patient was 20 min into the third HBO_2 treatment at 1.7 atm abs (25 fsw, 178 kPa) with about 50% O_2 in the chamber. The nurse saw a flame start at the abdomen before it engulfed the entire chamber. The fatal fire occurred when the patient ignited a butane hand warmer.

Mishap 39: A patient was in his second treatment in a monoplace chamber for "inadequate blood flow to the brain". After 1 h at 2.7 atm abs (56 fsw, 272 kPa) in the pure-oxygen environment, fire erupted in the patient's synthetic blanket. Flames spread rapidly with intense heat of about 1,260°C, causing a rise in pressure to about 10.9 atm abs (327 fsw, 1.1 mPa), which caused a tie rod to shear off. The fire was contained within the chamber, but both ends of the chamber exploded outward, one of which killed the patient's wife who was nearby. Two passers by were injured from flying debris. The burned patient died within 12 h. The patient had been put into the chamber in his own clothes, wrapped in a heavy acrylic blanket in which he had been brought from another hospital (D. Bush, Presentation at Technical Aspects of Hyperbaric Chamber Safety

Table 3: Chamber Fire Characteristics

	Type of Chamber				
	Clinical	Dive	Altitude	Spacecraft	Total
Ignition sources					
Electric arc/spark	5 (4)[a]	6	3	1	15
Electrostatic	7 (5)	1	–		8
Hand warmer	4	–	–		4
Smoking	3 (2)	1	–		4
External source	2	–	–		2
Child's toy	2 (1)	–	–		2
Welding	–	2	–		2
Unknown	2	–	–	1	2
Total	25 (12)	10	3		39
Oxygen percentage					
21–23.5	2	–	–		2
≥28	19 (9)	3	4		26
Unknown	4 (3)	7	–		11
Total	25 (12)	10	4		39

[a]Numbers in parentheses are unconfirmed.

Course, San Antonio, Texas, March 1996). Apparently, there had been no body check or belongings check before admittance into the chamber. Ignition source was a chemical hand warmer that the patient had taken into the chamber (19). It is commendable that the chamber manufacturer, Sechrist Industries, initiated a worldwide stand-down of all chambers of this model until the fire was investigated and the cause determined to be no fault of the chamber.

In 1967, attempting to smoke in a pure-oxygen monoplace chamber resulted in one fatality and injury to six bystanders (Mishap 21) (6). Attempting to smoke also caused two pure-oxygen multiplace chamber fires that resulted in seven fatalities (Mishaps 11 and 34) from occurrences in 1979 and 1993, respectively (5,6).

Mishap 21: An unconscious patient was placed inside the pure-oxygen monoplace chamber when the operator was convinced by anxious buddies to proceed quickly. When the patient regained consciousness, he attempted to light a cigarette, causing a fire and explosion that killed him and severely burned six bystanders (6). How the fire escaped from the chamber was not reported.

In 1987, children playing with spark-generating toys in a pure-oxygen chamber caused two fires on separate continents. In Italy, a 4-yr-old child was incinerated when sparks generated from a rolling toy automobile caused a flash fire in the 2–3 atm abs (33–66 fsw, 202–303 kPa) environment of a steel monoplace chamber (Mishap 29) (5). In China, eight fatalities reportedly occurred when a child played with an electric toy inside a pure-oxygen multiplace chamber (Mishap 28) (6). According to newspaper reports, one pediatric fatality occurred in a pure-oxygen monoplace chamber fire in Russia during 1996 (Mishap 38), but no probable cause was identified (20).

Electrical shorts and sparks were suspected to have ignited five clinical hyperbaric chamber fires. A phone short was responsible for one fatality in a pure-oxygen monoplace chamber (6). Electrical shorts in the air conditioning system reportedly caused three multiplace chamber fires, with 7, 8, and 11 fatalities, respectively (6) In Mishap 12, an electrical spark caused a fire in a medical research chamber, resulting in four fatalities (12,13).

Mishap 12: In 1969, two doctors and two patients were fire fatalities in a medical research chamber that contained 74–80% O_2 at 2.9 atm abs (63 fsw, 297 kPa). A spark from an extension cord that provided temporary power to a fluorescent lamp and camera produced ignition of papers and clothing. There was no fire extinguishing system and the doctors' attempts to stamp out the rapidly spreading flames with their feet were unsuccessful. About 10 s after the cry of "Fire! Turn off the electricity!" an explosion opened the exhaust valve and blew out the windows of the room housing the chamber.

Severe burns caused most fatalities. Carbon monoxide poisoning was reported as the cause of death in Mishap 15 (21). However, a combination of factors should be considered: severe hypoxia as O_2 was consumed by the fire, toxic gases from burning plastics, and carbon monoxide poisoning.

Mishap 15: In 1973, 5 min into the treatment, a fire

occurred in a Vickers chamber at about 1.3 atm abs (10 fsw, 131 kPa) while it was being compressed on pure O_2. Flames started around the head of the patient where the "material of transmission to the exterior" was located. The ignition source is not clear but the fire consumed electrical wires, the plastic mattress cover, and the patient's hair and pajamas. The fire rapidly consumed the available O_2 within the chamber and, just before decompression, appeared to extinguish itself, with incomplete combustion producing carbon monoxide inside the chamber. The chamber was immediately brought to the surface and opened, where the fire reignited. Autopsy findings indicated that the severity of patient's burns were insufficient to cause death, and attributed the cause of death to carbon monoxide poisoning.

From 1976 to 1989, static electricity was the suspected cause of seven fires resulting in five fatalities in pure-oxygen monoplace chambers. Within a 15-mo. period, on separate continents, two nonfatal fires occurred at the surface after the HBO_2 treatment was completed and the patient had been removed (Mishaps 19 and 20). A review of maintenance records isolated the incident to inadequate earthing connections. It is believed that the resulting static charge stored in the fiberglass tray was sufficient to ignite the oxygen-saturated mattress as described in Mishap 19 below (5,13,16,22). Another suggestion was that uncured fiberglass in the tray could have generated the heat needed to ignite the mattress. These mishaps resulted in replacement of fiberglass trays with stainless steel and publication of strict guidelines in NFPA 99, Ch 19 for ensuring continuity of grounding.

Mishap 19: Electrostatic charge or spontaneous combustion caused a fire at the foot of the fiberglass stretcher tray within minutes of completing treatment with pure O_2. After removing the infant patient from the chamber area, the attendant returned (about 4 min) and heard a "crackling sound". On lifting the sheets from the gurney, flames were noted on the mattress. Fiberglass and black smoke filled the area. The operator pulled the gurney out and extinguished the fire with a CO_2 extinguisher. There were no injuries in the unoccupied chamber fire.

In 1989, a unique nonfatal fire occurred as a microwave-warmed blanket was sent inside the air-filled multiplace chamber. The blanket was extinguished by water deluge without fatality. A hand-held hose was readily available, but was not used because the inside attendant was busy trying to eliminate the burning blanket from the chamber (4,23).

Mishap 31: A multiplace chamber with four patients and two inside attendants was completing the HBO_2 treatment at 2.0 atm abs (33 fsw, 202 kPa) in a chamber atmosphere of about 21% O_2. Responding to a request for a warm blanket for an infant patient, a cotton blanket was heated in the microwave for 2.5 min on the high setting. Upon removal from the microwave, a scorched odor was noted, but no fire was detected when the blanket was examined, so it was locked into the chamber. Upon removal from the entry lock into the chamber, the blanket ignited. The inside attendant unsuccessfully tried to reinsert the flaming blanket into the entry lock, but dropped it on the steel floor. The chamber operator activated the water deluge fire extinguishing system (FES) which rapidly extinguished the fire. Because of poor visibility and suspected continued smoldering, the FES was activated a second time. There were no injuries, but the occupants were very wet.

Thus, four clinical hyperbaric chamber fires occurred without fatalities (10,22,23). However, one had only smoke from fire that was outside the chamber (Mishap 1), and two were unoccupied at the time of the fire (Mishaps 19 and 20). The single nonfatal fire that occurred inside an occupied chamber (Mishap 31) was in an air environment with less than 23.5% oxygen (23).

FIRES OUTSIDE HYPERBARIC CHAMBERS

Fires that occur outside the chamber may also threaten patients while undergoing HBO_2. Table 4 lists systems fires contained in the UHMS Chamber Experience and Mishap Database that occurred outside the hyperbaric chamber. Seven fires occurred in clinical chamber systems, four fires were in dive systems and two were in unidentified systems. The majority of system fires occurred in a high-pressure oxygen system, often when a quick opening ball valve was used (24–27). Both authors (PJS, 1977; DAD, 1990) have personal experience in dealing with separate fires produced by quick-opening ball valves in high-pressure oxygen lines (6,24–26).

DISCUSSION OF LESSONS LEARNED

Scope of the Problem: This 73-yr analysis of clinical HBO_2 experience has revealed no fatalities in clinical hyperbaric chamber fires in North America. Two fires without fatalities occurred in North American clinical hyperbaric chambers in 1976 and 1989 (Mishaps 19 and 31). European clinical hyperbaric facilities reported two fatalities in three fires (Mishaps 15, 20, 28). Nineteen of the 25 clinical hyperbaric chamber fires occurred in Asia, resulting in 58 fatalities.

Fire Prevention: This review confirms previous reports (4,12,28–30) that fatal hyperbaric chamber fires were caused by a combination of factors: abundance of burnables, elevated oxygen concentration, faulty electrical components, inadequate extinguishment, and lack of

Table 4: System Fires Outside Hyperbaric Chambers

Mishap	Date	Probable Source	Fire Damage
0–1	1968	bunk room, unknown	Fire burned through compressed air line which fanned flames to burn through metal wall and damage nearby hyperbaric chamber
0–2	1968	high pressure O_2 line ball valve	Trash and hydrocarbons in oxygen line caused explosion and fire that knocked down the technician and ignited his clothing
0–3	1969	oxygen check valve	Heat of compression ignited oxygen check valve
0–4	1970	welding equipment	Fire in adjacent repair shop filled bulding with smoke, causing abort of chamber treatment
0–5	1974	electrical transformer	Attempt to extinguish electrical fire with CO_2 caused technician to get electrical shock as the charge traveled up CO_2 extinguisher discharge
0–6	1977	high pressure O_2 3-way valve	Fire shot out of the end of the oxygen line when the 3-way valve was opened on the high pressure line
0–7	1979	soldering torch	Explosion of oxygen line occurred during soldering on a line that was not purged with nitrogen
0–8	1986	restriction in line	Explosion and fire in oxygen line attributed to restriction at elbow
0–9	1987	oxygen line separation	Fire in high pressure oxygen line when line separated from valve
0–10	1988	water separator	Chilled water to compressor was turned off resulting in overheating of plastic water separator components
0–11	1989	reducing-valve failure	When reducing-valve failed, the quarter-turn valve in high pressure oxygen caused explosion of low pressure copper line
0–12	1990	gas-mixing spider	Improperly installed gas-mixing spider caused fire due to heat of compression
0–13	1990	high pressure oxygen gauge	Oxygen gauge failed as 2,500-psi cylinder was connected to analyzer
0–14	1990	HP O_2 3-way valve	Fire ignited by heat of compression when quick-opening valve was opening
0–15	1990	HP O_2 3-way valve	Heat of compresion and friction caused by high velocity particles in O_2 line ignited fire when the quick-opening valve was opened
0–16	1991	compressor fire	Electric fire in back-up generator causes exhaust fumes to be introduced into the compressor air intake
0–17	1991	HP oxygen regulator	Grease was thought to have been put on the interior surface during repair
0–18	1995	HP oxygen valve	Heat of compression caused high pressure O_2 fire when opening O_2 cylinder
0–19	1996	overheated battery	Fire caused when communication system batteries were exchanged, causing overheated audio-type wires

vigilance to exclude ignition sources from being carried into the chamber.

Ignition sources: Ignition sources of principal concern in oxygen-enriched environments are defined by NFPA 53-94 and are placed in four categories: electrostatic and break (arc) sparks, exothermic chemical reactions, heated gases, and hot surfaces (7). One might successfully argue that electrostatic sparks and electrical arcs should be separate categories since they are different ignition sources with regard to cause and level of risk. Electrostatic spark is considerably less fire risk than electrical arc and is currently a source of controversy.

Table 3 shows the characteristics of the 35 hyperbaric chamber fires. Ignition sources for the 10 dive-chamber fires included one suspected electrostatic spark, two break sparks, four hot surfaces (three lamps, one motor), and three items already burning (one lit cigar, two welding devices). Ignition sources for the 25 clinical hyperbaric chamber fires included seven suspected electrostatic sparks, seven arcs or break sparks, two hot surface (one external burner, one heated blanket), six items already burning (three lit cigarettes, three butane hand warmers), one exothermic chemical reaction (chemical hand warmer), and two unknown.

Smoking near or inside the chamber caused four fires with 10 injuries and eight fatalities. These chamber fires make it abundantly clear that smoking and open flames must be prohibited in or near a chamber where O_2 is present. In 1975, the author (PJS) personally experienced a nonfatal fire outside the chamber when a patient dropped his lit cigarette into an ashtray in which other patients had deposited trash and an alcohol-impregnated cotton ball.

Before 1980, 56% (10 of 18) of fires had an electrical ignition source. Analysis of the 17 fires occurring since 1980 reveals that electrical ignition sources have been virtually eliminated from hyperbaric chambers, with the exception of China, where 83% (9 of 11) of fires were reported as ignited by electrical components or static electricity. Since little is known about the mishaps in China, the degree to which static electricity contributed to the fire cannot be confirmed. Elsewhere, static electricity did not seem to be a big fire hazard. In contrast, the

remaining eight fires that have occurred since 1980 were all ignited by items that an occupant carried into the chamber. The items consisted of three hand warmers (Japan), two spark-producing toys (China, Italy), one lit cigarette (China), one microwave-heated blanket (USA), and one unknown (Russia).

Electrical components have vastly expanded since Dr. J.L. Corning, a New York anesthesiologist, first described the use of electrical air compressors for his chamber in 1891 (31). Electrical ignition sources have been a continual concern. Necessary wiring is insulated with Teflon or mineral insulation and enclosed in metal conduit. Instrument housings are purged with inert gas to achieve below 6% O_2, where fire is impossible. Telephones and intercoms must be intrinsically safe. Battery operated devices should contain fully enclosed, sealed batteries that do not off-gas. Batteries should be neither charged not changed while the chamber is pressurized (32).

Although the matter of electrostatic spark as an ignition source is controversial, reasonable precautions to prevent it makes good sense. Synthetics and wool fibers that can build up static charges should not be permitted inside the chamber. Maintaining humidity above 50–60% will reduce static sparks in the chamber. Humidifying the O_2 before it reaches the patient will reduce the amount of static electricity in the BIBS used for O_2 delivery.

Oxygen concentration: An oxygen-enriched atmosphere does not, by definition, produce an increased fire risk (7). Oxygen does not burn, nor does it increase the potential for having a fire. However, when O_2 is present, items that can burn will ignite more readily and burn more quickly.

Fire risk (both ease of ignition and burning rate) is increased when the hyperbaric chamber is pressurized. Fire risk increases in two ways: with increased oxygen partial pressure (i.e., compressed air) and with increased oxygen concentration (i.e., pure oxygen). Cook and associates (8) published the burning rates of filter paper strips with varying nitrogen/oxygen percentages. An inert gas, such as nitrogen, can provide a physical obstacle to the interaction of fuel and O_2 molecules, so that no combustion occurs when O_2 is below 6%, and combustion is incomplete when O_2 is below 12%. Complete combustion can occur when the O_2 is above 12%, and burning rates increase exponentially with increased O_2 percentage.

Burning rates increase dramatically if O_2 percentage rises above 25% (7,8,15,33). In pure-oxygen environments, the burning rate is so rapid that a "fireball" occurs, making survival unlikely. The two hypobaric pure-oxygen fires with survivors contained an oxygen partial pressure of only one third of an atmosphere. In the 35 hyperbaric chamber fires, there were survivors only from air-filled chambers. Mishap 1 had an unknown number of survivors of a smoke-filled chamber in which there was no flame.There were 11survivors of hyperbaric chamber fires where there were open flames. Four survived a fire that occurred at the surface (Mishap 2), one survived a fire of unknown O_2 content that occurred at 2.2 atm abs (40 fsw, 223 kPa) (Mishap 3), and six survived one fire that contained less than 23.5% O_2 (Mishap 31). Two pure-oxygen chambers were unoccupied when the fire occurred (Mishaps 19 and 20). There were no survivors in the remaining 30 fires where chamber O_2 content was either $\geq 28\%$, or unknown. The industry standard for maximum allowable O_2 in air-filled chambers is 23.5% (9). This is achieved by exhausting exhaled gases outside the chamber and periodically ventilating the chamber.

Because of inherent fire and explosion hazards, it is imperative that all potential ignition sources be eliminated from pure-oxygen hyperbaric chambers. No one has ever survived such a fire.

Fuel: Anything that will burn serves as fuel for the fire. In the confined space of a chamber, combustion of a small quantity of fuel can result in rapid generation of high temperature and elevated pressure. High temperature causes rapid spread of the fire. High temperature and inhalation of toxic combustion products can be lethal to the occupants, even if they are not engulfed in flame (7,21).

In this series, fatal chamber fires were fueled by an abundance of flammable materials, such as canvas, wood, newspapers, books, hydrocarbon fumes, clothing, bedding, blankets, and plastics. Laboratory experiments suggest that human skin is difficult to ignite in low-pressure oxygen. However, skin burned readily in the presence of combustibles that acted as localized ignition sources, such as, oil, grease, nylon, and molten plastic (7).

Burnable materials inside the chamber should be restricted to the bare essentials. Medical supplies and paper products required for patient therapy should be stored in flameproof or metal boxes when not in use. Clothing that is chosen for its fire retardant or antistatic properties includes Durette Gold or equivalent, cotton, or an antistatic blend of cotton and polyester (9). Volatile, flammable liquids such as ether and alcohol should never be used inside the chamber. Most importantly, chamber occupants should change into clean clothing provided at the hyperbaric facility for exclusive use while inside the chamber. This improves vigilance for fire prevention in two ways. It is easier to prevent soiled clothing and unwanted products from entering the chamber. But, of greater significance, it creates a mental attitude that promotes fire safety among both patients and staff while the chamber is in operation.

Extinguishment and escape: In addition to having an effective fire prevention program, each facility should also have a means of extinguishing a fire should it occur. There should always be breathable gas in the BIBS and a mask for each occupant. It is advisable to develop an escape plan and to practice it periodically.

In this series of 35 hyperbaric chamber fires, extinguishment methods included slapping with the hands, stamping with the feet, asbestos fire blankets, buckets of sand or water, carbon dioxide fire extinguishers, water-filled fire extinguishers, hand-held water hoses, and water deluge FES. Within the past 40 yr of clinical experience that included 24 clinical hyperbaric chamber fires, there were survivors in only one fire that occurred in a pressurized hyperbaric chamber. That fire occurred in an air environment and was extinguished by a water deluge FES that was activated by an alert outside attendant. Some of the other compressed-air fires might have been survivable, but the occupant(s) either had no means of extinguishment, or the flames spread too rapidly for the occupant(s) to use the fire blanket, carbon dioxide extinguisher, bucket of sand, or bucket of water that was provided. Fire blankets are of little value in an oxygen-rich environment because the fire continues to burn beneath the blanket.

Once the flames spread, the intensity of the fire enclosed within the chamber made rescue from the outside difficult to impossible. In most cases the fire was contained within the chamber. Injuries to persons outside the chamber occurred in Mishaps 20 and 39 either from structural failure or from fire being removed from the chamber.

NFPA 99, Chapter 19, has specific guidance for fire extinguishing systems in Class A (multiplace) chambers (9). Fire extinguishing systems must be capable of activation from either inside or outside the chamber. Water is the extinguishment agent of choice. Each member of the hyperbaric medicine team should have personal experience on how to activate his or her chamber FES. If O_2 is limited to below 23.5%, a fire should be survivable. Recognizing that fires in pure-oxygen hyperbaric atmospheres are not survivable, the NFPA offers no guidance for extinguishment or escape in Class B (monoplace) pure-oxygen chambers (9).

FIRE SAFETY STANDARDS IN THE UNITED STATES

The NFPA was organized in 1896 to promote the science and improve the methods of fire protection. Because of fatal hypobaric and hyperbaric fires of the 1960s, and a lack of appreciation of the fire hazard, the NFPA was compelled to develop strict fire safety codes. Characteristics of chamber fires of the time included: high oxygen concentrations, a plethora of burnables, ignition sources that were principally electrical, and the absence of fire extinguishing systems. In 1965, the aerospace industry and medical operators expressed to NFPA a need for a single source of general data on the hazards of oxygen-enriched atmospheres. In response, the NFPA developed NFPA 53M, *Manual on Fire Hazards in Oxygen-Enriched Atmospheres* (7), which was first published in 1969 and recently revised. In 1968, NFPA 56D-T, *Tentative Standard for Hyperbaric Facilities*, was published and circulated for public review (17). The resulting national standard was implemented in 1970 as NFPA 56D, *Standard for Hyperbaric Facilities* (18), and NFPA 56E, *Standard for Hypobaric Facilities* (NFPA 56E is currently designated NFPA 99B). The 1970 standard was a monumental effort based on rules governing operating rooms where volatile flammable anesthetics were used. It was so strict that no chambers could fully comply, so many simply ignored it. In 1984, under the leadership of Dr. W. H. L. Dornette, a more acceptable hyperbaric standard was published as NFPA 99, *Standard for Health Care Facilities*, Chapter 10, *Hyperbaric Facilities*. UHMS members who operated hyperbaric facilities were attempting to comply. In 1987, the contents of Chapter 10 were moved to NFPA 99, *Standard for Health Care Facilities*, Chapter 19, *Hyperbaric Facilities* (9), where it remains as of this writing. It is a product of the untiring efforts of the aerospace industry, certifying agencies, regulators, chamber manufacturers, and hyperbaric facility operators, all of whom were trying to make a fire-safe environment for patients and staff. Some of the operating room rules have survived to this day even though they may not be entirely appropriate for clinical hyperbaric chambers. W. T. Workman has replaced Dr. Dornette as Chairman of the NFPA Subcommittee on Hypobaric and Hyperbaric Chambers, and is working diligently toward refining the standards. The NFPA fire safety standard for hyperbaric facilities has become a code with which hyperbaric systems operators can and should comply. However, enforcement of compliance is usually left up to local fire marshals and local chamber operators.

REPORTING CHAMBER ACCIDENTS

These chamber fires were known by the authors at the time this report was prepared. Readers that know of additional cases are encouraged to report them to the UHMS Chamber Experience and Mishap Database. The database is maintained under the auspices of the UHMS Safety Committee, which developed it to help reinforce safety standards and provide guidance for future standards. To report an accident or for further information, contact David Desautels: telephone 1 813 870 4869; fax 1 813 870 4862; e-mail davidd6858@aol.com.

This chamber fire analysis is dedicated in the memory of the 82 known fatalities reported in 39 accidental fires in worldwide hypobaric and hyperbaric chamber environments since 1923. The authors thank the investigators, reporters, and governments who were kind enough to release the information so that operators of other hyperbaric chambers could learn from it. The initiative to set up a hyperbaric facility database in 1990 by the staff of the United States Air Force Davis Hyperbaric Laboratory is gratefully acknowledged. We are indebted to the members of the Undersea and Hyperbaric Medical Society who provided documentation for the UHMS Chamber Experience and Mishap Database.—*Manuscript received February 1997; accepted July 1997.*

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