EVALUATION OF A MITIGATION PROCEDURE FOR SMALL LIQUID OXYGEN (LOX) SPILLS

COMMUNITY RISK REDUCTION

BY: Craig H. Kampmier
Swansea Fire Department
Swansea, MA

An applied research project submitted to the National Fire Academy
as part of the Executive Fire Officer Program

March 1995

ABSTRACT

The problem was the current procedure for mitigating small spills of liquid oxygen (LOX) inside a hospital building had not been tested to determine the procedure's effectiveness. The hypothesis being, if LOX on asphalt has been shown to be impact sensitive, then LOX on a floor tile surface will contact the tile's underlying petroleum-based adhesive through the seams or cracks of adjoining floor tiles, creating an impact-sensitive condition until mitigated. The absence in literature of a mitigation procedure for small LOX spills that could occur with portable LOX respiratory therapy equipment prompted the Kent County Memorial Hospital to develop a spill procedure.

The purpose of the research was to develop and conduct a controlled LOX spill test experiment to determine the procedure's effectiveness. The research sought answers to the following questions:

1. What experiment has to be developed?

2. What was the outcome of the experiment?

3. What is the outcome's relationship to the spill procedure?

The hazards and properties of LOX were reviewed, as were the spill procedures associated with transportation vehicles and stationary bulk systems. Actual incidents and testing mediums used to establish this information concerning LOX were used in determining and developing any experiment to evaluate the small LOX spill's mitigation procedure effectiveness.

The research results concluded that the perceived hazardous condition could not be achieved under test conditions. A procedure addressing mitigation of a small liquid spill of LOX from portable respiratory therapy equipment (Puritan-Bennett MARK 5 Walker) on a vinyl composition floor tile with a petroleum-based adhesive is not required.

Recommendations pursuant to the experiment's results provide for the further research of potential LOX incidents. LOX, in association with residential respiratory therapy, should be recognized in future reference materials written for safety professionals and emergency response organizations.

TABLE OF CONTENTS

LIST OF TABLES

INTRODUCTION

The problem was the current procedure for mitigating small spills of liquid oxygen (LOX) inside a hospital building had not been tested to determine the procedure's effectiveness. The hypothesis was that LOX spilled on asphalt outside of a building has been shown to be impact sensitive; therefore, LOX on a floor tile surface will contact the underlying tile adhesive through the adjourning floor tile's crack or seam, creating an impact-sensitive condition until mitigated. Following a literature search which determined a procedure did not exist, the Kent County Memorial Hospital, Warwick, Rhode Island, developed a spill procedure. LOX is used in portable respiratory therapy equipment in the hospital, and in residences protected by the Swansea, Massachusetts Fire Department, in lieu of compressed gas cylinders containing gaseous oxygen.

The purpose of this research was to develop and conduct a controlled LOX spill test to determine the procedure's effectiveness.

The study uses an experimental research methodology. The research questions to be answered are:

1. What experiment has to be developed?

2. What was the outcome of the experiment?

3. What is the outcome's relationship to the spill procedure?

BACKGROUND AND SIGNIFICANCE

The use of liquid oxygen (LOX) portable respiratory therapy equipment as an alternative to compressed gaseous oxygen portable respiratory equipment was introduced to Kent Count Memorial Hospital, Warwick, RI, in October 1993. The author, as Safety Coordinator for the Hospital, learned the Mark Oxygen Walker System (Puritan-Bennett, pp. 3-4) if laid on its side could release liquid oxygen, creating a fire or frostbite hazard. The author gave consideration to the materials that spilled LOX could contact within the community-based hospital, recalling the reactive nature and impact sensitivity of LOX, conveyed in a film (Naval Weapons Center) during a fire department training session in the early 1970s, and the National Fire Protection Association (NFPA) document, NFPA 50, *Standard for Bulk Oxygen Systems at Consumer Sites* (NFPA 50, 1990), requirements for the bulk systems used at five of the six hospitals of employment during the past 21 years. A spill procedure was sought to reduce the risk associated with a potential spill incident. Lincare of Clearwater, FL was the distributor of the Puritan-Bennett Mark Oxygen Walker System and LOX used at the hospital. The local Lincare distributor was located in Swansea, MA. DaPonte (personal communication, January 20, 1994) indicated Lincare was servicing some 500 Mark Oxygen Walker Systems in Swansea, an area served by the Swansea Fire Department, and surrounding communities. The Mark 5 Walker liquid oxygen system model used at the hospital could supply oxygen for approximately seven and a-half hours on a two-liter-per-minute flow setting (Puritan-Bennett, 1991). The Mark Oxygen Walker System units are refilled from a reservoir, which may be 40, 70 or 90 pounds of LOX capacity. The Mark 5 Walker is filled from the reservoir by the consumer, while a service representative periodically refills the reservoir at the consumer site from a service vehicle designed for such purposes. The Mark Oxygen Walker system is Underwriters Laboratories (UL) Listed, and the LOX is stored and used from vacuum-insulated containers (Puritan-Bennett).

The effects of a LOX spill on patient bedding, carpeting, clothing and other materials, or creation of an oxygen-enriched atmosphere (OEA) were considered. The most common floor surfacing, where patients were transported in the hospital with Mark 5 Walkers, was adhered to the concrete floor slab with a petroleum-based adhesive, Armstrong S-90 Adhesive. The adhesive material was 25 to 34 percent VM & P Naphtha and 64 to 73 percent petroleum grade asphalt (Armstrong, 1993). Aside from other risk considerations, should a liquid spill of LOX occur on a floor tile surface, would the LOX contact the underlying adhesive through the seams of adjoining floor tiles; if so, is an impact sensitive condition created, and when is it safe to walk on the floor surface.

Gayle, (1973, pp. 12-13) indicates that explosions resulting from spills of LOX on asphalt and subsequent initiation by mechanical impact have been reported by a number of authors, and the amounts of LOX involved in those and similar unpublished incidents were generally small. He noted small-scale impact tests on asphalt had confirmed violent explosions could readily be initiated by mechanical impact. Gayle proceeded to conduct a larger scale test to study propagation rather than ease of ignition because the small-scale impact tests and reports of incidents had indicated conclusively that an explosive reaction between LOX and asphalt could be initiated. Gayle reports (p. 13) that his tests were carried out during a period of damp weather with several gallons of water sponged off the test slab before each test, except for the last test conducted on a warm sunshiny day during which the test slab appeared dry. His results suggested a LOX asphalt reaction could propagate over the entire available interface area for a massive spill, once initiated.

The NFPA *Manual of Hazardous Chemical Reactions* (NFPA 491M, 1991, p. 150) notes LOX leaked from a coupling to the asphalt surface below during a product transfer to a tank truck. When the truck driver dropped a hammer on the surface, a 20-inch-square by 4-inch deep crater was formed by the violent explosion, which also broke nearby windows. The manual also states (p. 150) that LOX with hydrocarbons and many other organic compounds are powerful explosives.

Praxair (1992, p. 3) in referring to spilled LOX, said to allow spilled liquid to evaporate, and not to walk on or roll equipment over a spill because an explosion could occur, and that contact with flammable materials may cause a fire or explosion.

Fennelly (1993, p. 2) reports most fire departments are not aware of LOX respiratory therapy's presence in homes and multiple dwellings or the potential for explosions with hydrocarbons, and the many questions to be raised on safety and the possibility for disaster. Fennelly (personal communication, August 17, 1994) further indicated his community sustained a fire in a 12-story residential building from a person on respiratory therapy who was smoking in bed. The LOX contributed to the fire development and extension to several floors.

The author notes as Hospital Safety Coordinator, that a Mark 5 Walker tipped on its side while a patient was transported on a gurney in January 1994, freezing an intravenous line and saturating a portion of the gurney linen. The incident occurred without consequence.

These reports demonstrate that incidents involving LOX spills have occurred, and that a spill procedure was necessary. This led to the hypothesis regarding a liquid spill on a petroleum-oriented floor surface and the focus of a spill procedure concerning the floor surface. In the absence of a spill procedure, which the literature review will reflect, a procedure was developed. But the procedure's effectiveness was not known, presenting the problem to research: development of an experiment to evaluate the effectiveness of a mitigation procedure for small LOX spills.

These reports further demonstrate the past, current, and future significance to the fire service and in community risk reduction through a better understanding of LOX presence, properties, and emergency procedures.

The significance of this research is further exemplified by the effects that have resulted from the literature review process. Hall (personal communication, August 4, 1994) developed a recommended spill procedure for LOX at the University of Rochester, New York. McNamee (personal communication, January 10, 1995) investigated and recognized the presence of LOX respiratory therapy equipment within the community of Marshfield, MA, and has initiated awareness within his fire department. The National Aeronautics and Space Administration (NASA) Johnson Space Center Test Request No. 10512L (Janoff, October 13, 1994) seeks the White Sands Test Facility to perform a standard LOX mechanical impact test to assess the hazards of LOX spills on material not intended to be exposed to LOX, becoming impact sensitive, and which can react violently causing explosion and loud report. Materials could be foam insulation, floor tile, asphalt, carpet, cork, etc. The test program will determine how long after LOX soaking that these material are safe to walk on, or handle.

LITERATURE REVIEW

Several phases of literature review provided critical findings which culminated in the accomplishment of the research problem.

The lack of information on LOX and on spill mitigation, as well as crucial information on the properties of LOX and spill mitigation, contributed not only to the hypothesis and development of the mitigation procedure for small LOX spills, but were also influential in the pursuit and development of an experimental test to evaluate the procedure.

Oxygen

Earth's most abundant element is oxygen, comprising nearly 90 percent by weight in drinking water; rocks, and minerals are 50 percent oxygen, and the air we breathe is one-fifth oxygen (Linde, 1987). Medically, increased concentrations and volumes of oxygen are used to compensate for reduced pulmonary blood flow, to offset other biological chemical reactions, to increase physiological tension with increased tissue oxygen supply, and to permit patients an adequate influx of oxygen with minimal effort at breathing when they are compromised by cardiopulmonary disease or illness (Wintrobe *et al.*, 1970, pp. 1168, 1219, 1154-1155).

Oxygen which goes through a process of compression and distillation can be liquefied gas. As a liquid gas, the liquid oxygen (LOX) is considered a cryogenic liquid. The Compressed Gas Association (1993; 2.1.1, Table 1) notes a cryogenic liquid as a liquid with a normal boiling point below -130°F; the boiling point of LOX is -297°F. LOX has an expansion ratio of 1 volume to 860 volumes of gas at normal atmospheric pressure and room temperature (Compressed Gas Association, 1988).

Combustion and Explosion

Oxygen as an oxidizing agent causes a change within other elements or chemicals, such as rusting metals, the souring of wine, or the decay of vegetable matter (Haessler, 1974, p. 1). This chemical reaction is further illustrated by the combination of a solid carbon containing substance, oxygen and heat. Their reaction culminates in the reduction of the carbon-based fuel and oxygen with the generation of light and heat of combustion or fire.

As the oxygen molecules in air are consumed, incomplete combustion or smoldering occurs. Layman (1952, p. 7) points out that a decrease of oxygen in the surrounding atmosphere results in a corresponding decrease in the rate of fuel consumption and flame production, and that flame production ceases when the atmospheric oxygen content is reduced to approximately 15 percent. Without ventilation to replace the oxygen depletion, combustion is diminished. The sudden introduction of air into the heated fuel molecule environment provides the necessary oxygen for an eruption of flame, or "backdraft" (Drysdale, 1985, p. 287).

Oxygen will not burn, but strongly supports combustion. An atmosphere of oxygen will produce a more intense rate of combustion that an atmosphere of air (Tyron, 1962, p. 7-61). Linde (1987) states oxygen vigorously accelerates combustion. Substances which will burn do so much more vigorously in the presence of excess oxygen, and other substances which are not normally combustible in air may burn when excess oxygen is present (Union Carbide). Morton (1961, p. 385) explains that ignition will commence when the oxidizing molecule (oxygen in this research) collides with the fuel molecule with sufficient energy to cause a reaction and resulting propagation when the rate of energy release is greater than the rate of energy absorbed by the surrounding media. Sufficient energy must be subjected to a fuel media to drive the oxidizing molecule into contact with the fuel molecule. Royer (p. 11) notes that heat is the form of energy evidenced by the movement or vibration of molecules of a substance; the intensity of vibration is measured in degrees of heat.

An example involving compressed gaseous oxygen occurred when the oxygen was used to pressurize a hydraulic piston in an attempt to dislodge and push the ram out (Leo, 1993). The heat of friction created during the pressurization of the piston caused the oxygen and hydraulic oil to react. The three-eighths-inch-thick pieces of steel critically injured one person and dismembered another person, who later died. The hazards associated with oxygen under pressure and contact with oils, greases, and other materials of an organic nature were acknowledged in fire codes years ago (NFPA, No. 56, p. 431).

Linde (1988, p. 3) indicates LOX spills on asphalt or oil based flooring are especially dangerous and create a serious fire hazard. "Flammable Hazardous Materials" (Meidl, 1970, p. 152) notes a LOX explosion from a dropped fire department hose coupling on a LOX-soaked asphalt street.

On January 27, 1967, astronauts boarded the Apollo 1 space capsule at Cape Canaveral for a "full dress rehearsal." The capsule cabin was pressurized at 16.7 psi (normal atmospheric pressure is 14.7 pounds per square inch) with 100 percent oxygen. During the next five hours the oxygen permeated the cabin's equipment, wiring, plastic, Velcro, suits, instruments, paper checklists, aluminum and polyurethane foam cushions. Of the possible ignition sources, all were electrical. An ignition occurred, becoming a massive shock wave of flame feeding on the oxygen-soaked environment of the capsule interior, melting and burning metal pipes and transforming oxygen sources into screeching blowtorches of pure white fire (Shepard *et al.*, 1994, pp. 195, 199, 200, 202, 216). Shepard notes (p. 199) that pure oxygen had been used previously in the Mercury and Gemini spacecraft without incurring any problems. In 1969, Astronaut Neil Armstrong spoke from the Moon's surface, "That's one small step for man ...one giant leap for mankind." Burke (1978, p. 247) cites the attributes of the LOX and liquid hydrogen fuel which powered the Saturn V rocket carrying the astronauts on their moon landing voyage.

Coleman (personal communication, August 10, 1994) explains that LOX and asphalt create a gel which is shock sensitive because of the oxidant availability, and the oxygen is released very slowly. Stolzfus (personal communication, August 16, 1994) adds that the LOX combines with the petroleum asphalts, carbon, and hydrogen molecules to form a loose binding bond, which becomes a self-sustaining reaction once energy is introduced because of the oxygen and carbon molecules.

Ignition or explosion of LOX with petroleum and other organic materials by mechanical impact or compression and friction are noted by the Chemical Propulsion Information Agency (1984, 11-2.3), Linde (1987), Isman (*et al.*, 1980, pp. 91, 97-98), and the National Fire Academy (1983, CRY-14).

Mechanical Heat Energy

Heat is energy in a kinetic form, or energy of molecular motion (Kirk, 1969, p, 19). Frictional heat is the mechanical energy used in overcoming the resistance of friction, and friction generates heat; heat of compression is the heat released when a gas is compressed. The temperature of gas increases when compressed, and has application in the diesel engine where the heat of compression eliminates the need for a spark ignition system by relying on the heat released when the air (containing oxygen) is compressed and mixed with the petroleum fuel (Tyron, 1962, pp. 4-19, 4-20). When a piece of iron is struck with a hammer, the mass kinetic energy of the hammer disappears, and in its place the molecules of the hammer and the piece of iron are thrown into more violent agitation, or the hammer and iron are heated (Reed *et al.*, 1915, p. 185). An exothermic reaction occurs with heat being given off in the course of reaction.

This information provides an understanding of how walking on, or dropping or rolling an object on a liquid spill of LOX on a petroleum-based surface results in a violent reaction or explosion; the presence of fuel, high concentration of oxygen and heat source.

LOX Containers

The National Fire Protection Association (NFPA) document, *Standard for the Storage, Use and Handling of Compressed and Liquefied Gases in Portable Cylinders,* (NFPA 55, 1993, 1-1.2, A-1-1.2 (e)) does not apply to health care facilities, nor to portable containers or cryogenic liquids. NFPA 99 (1993, 4-6.2.1.6) indicates the transferring of LOX from one container to another, if permitted by the responsible authority of the health care facility, shall be accomplished in a location remote from patient care areas, and the use of the Compressed Gas Association Pamphlet P-2.6 on the "Transfilling of Low-Pressure Liquid Oxygen to Be Used for Respiration." Baudoin (1991) provided guidance to Puritan-Bennett liquid oxygen dealers on the use of LOX in health care facilities pursuant to a concern about the use of LOX in a hospital by a local fire authority. The primary concern was the storage and transfer of

LOX within the facility. Baudoin referred to the NFPA 99 text. Klein (personal communication, February 1, 1994) confirmed that concerns had been expressed by some fire marshals, that NFPA 99 was under review, open for comment, and suggested some other individuals that might be contacted regarding spill incidents and procedures. NFPA (1995, p. 74, 99-257, 99-258) contains a proposal to clarify the NFPA 99 text on transferring of LOX from one container to another, which was accepted by the NFPA Technical Committee responsible for the standard, and will be voted upon by membership at the NFPA 1995 Fall Meeting. The text did not add information regarding LOX spills.

A portable liquid oxygen unit warning label affixed to the hospital's Puritan-Bennett Mark 5 Walker, Lincare unit A 19155, says to read the patient operating instructions, and speaks to fire and health hazards, and the need to keep the unit upright.

Zawierucha (personal communication, August 10, 1994) indicated the design and testing of the portable LOX respiratory therapy equipment was probably done in the 1970s.

LOX Spills Mitigation Procedures and Risk Assessment

"Cryogenics: Know the Basics" (Union Carbide) notes that following a LOX spill on asphalt, the surface should not be walked on until the frost that formed has evaporated for at least 30 minutes. The Compressed Gas Association (*et al.*, 1988) indicates that in the event LOX is spilled over asphalt, or other surfaces contaminated with combustibles, such as oil-soaked concrete or gravel, do not walk on or roll equipment over the area for at least one-half hour after the frost has disappeared; in most spills an oxygen-enriched atmosphere will be indicated by a vapor cloud from moisture in the air that has been cooled by the LOX vapor.

Mullens (1990), Young (1978, p. 22), Varela (1990, p. 4-41), "Explosive and Toxic Hazardous Materials" (Meidl, 1970, p. 115), the Chemical Propulsion Information Agency (1984, 11-4), and Bahme (1972, p. 147) discuss the application of water on outdoor spills.

NFPA 53, *Guide on Fire Hazards in Oxygen-Enriched Atmospheres* (NFPA 53, 1994, Chapter 7), discusses the extinguishment of fires in oxygen-enriched atmospheres (OEA) at length. An OEA (NFPA 53, 1994, 1-2) is an atmosphere in which concentration exceeds 21 percent by volume or the partial pressure of oxygen exceeds 160 torr (millimeters of mercury) or both. The procedures do not, however, address fires or conditions involving oxygen which is partially in a liquid state.

Linde (1988, p. 3) and the Compressed Gas Association (*et al.*, 1988) reflect that clothing splashed with LOX or saturated with oxygen should be removed, allowed to ventilate, and not be worn for a least 30 minutes. The Compressed Gas Association (1993) states clothing splashed with LOX should be aired for at least one hour, while Young (1978, p. 21) says saturated clothing should be hung in open air for several hours.

Personal communications (Roy, February 1, 1994; Bender, February 1, 1994; Jaeger, February 1, 1994; Bush, February 2, 1994; Erickson, August 15, 1994; Murray, August 15, 1994) found no knowledge of incidents involving portable LOX respiratory therapy equipment, or knowledge of procedures for small LOX spills. Interviews (June 13-24, 1994) with the R310-94 Strategic Analysis of Community Risk Reduction class at the National Fire Academy in Emmitsburg, MD, found no one had experienced any incidents involving LOX, or knew of procedures for small spills. An inquiry for information on the ICHIEFS computer network (August 28, 1994), and literature search for LOX (MEDLINE, July 1994) did not discover any information.

A National Response Center (personal communication, February 27, 1995) data base search with an incident reporting information system (IRIS) from January 20, 1990 to February 27, 1995 found no LOX incidents had been reported. Weinberg (personal communication, July 5, 1994) indicated the Massachusetts General Hospital was not using portable LOX respiratory therapy equipment. Shouldis (personal communication, June 20, 1994) indicates the University of Pennsylvania Hospital in Philadelphia acknowledged the potential for a LOX incident exists.

The lack of information on LOX spill procedure becomes as significant as the information learned when considering the project's hypothesis and evolution of a procedure to the development of an experiment to test the procedure; followed by the evaluation of the experiment's results and relationship to the procedure and hypothesis. A bibliography provided as Appendix A further reflects information which did not support the focus of this research. A method of risk assessment used by the U.S. Navy (Chief of Naval Operations, 1986, p. 12-2) allows for the expression of risk by combining the elements of hazard severity and probability that a hazard will result in a mishap; an event or series of events that result in human death, injury, occupational illness, or equipment property damage or loss. Table 1 defines the system.

This system provided a medium to assess the literature findings, and lack thereof, to determine the worth of the research, potential outcomes and significance of the outcomes.

Table 1
Risk Assessment Matrix

Hazard Severity Category		**Definition**
I	Catastrophic:	The hazard may cause death or loss of a facility.
II	Critical:	May cause severe injury, severe occupational illness, or major property damage.
III	Marginal:	May cause minor injury, minor occupational illness, or minor property damage.
IV	Negligible:	Probably would not affect personal safety or health, but is nevertheless a violation of a safety standard.

Mishap Probability Subcategory	**Definition**
A	Likely to occur immediately or within a short period of time.
B	Probably will occur in time.
C	May occur in time.
D	Unlikely to occur.

Risk Assessment Code (RAC)

Hazard Severity	**Mishap Probability** A	B	C	D
I	1	1	2	3
II	1	2	3	4
III	2	3	4	5
IV	3	4	5	5

RAC	**Definition**
1	Critical
2	Serious
3	Moderate
4	Minor
5	Negligible

Test Procedure

Conducting an experimental test evaluation of the mitigation procedure was initially pursued with organizations that have experience conducting experimental tests. The inability to accomplish this was considered a limitation of the research procedure and was addressed as such.

To develop an experimental test, the American Society for Testing and Materials (ASTM) "Standard Test Method for Determining Ignition Sensitivity of Materials to Mechanical Impact in Pressurized Oxygen Environments, G86-89" (ASTM G86), and ASTM "Standard Test Method of Ignition of Materials by Hot Wire Sources, D3874-90a" (ASTM D3874) were reviewed.

Stoltzfus (personal communication, August 16, 1994) suggested developing a localized mechanical impact test that would fundamentally follow ASTM G86 principles. Create a scaled down version of the floor surface material and substrate, fabricate a means of holding a weight at an elevated height and method of releasing the weight from a remote distance. Pour LOX onto the floor surface test sample until it pools. Return to the release mechanism, approximately 100 feet away, releasing the weight, which will impart energy onto the floor surface test sample when it impacts. The test should be conducted 20 times, but at least 5 times for scientific merit. A baseline test should be conducted to demonstrate a violent reaction between the LOX, floor surface and energy release. The research hypothesis could then be evaluated by waiting 30 minutes and dropping the weight to establish that a reaction would occur. The final testing would evaluate the mitigation procedure by waiting 30 minutes, discharging water from a fire extinguisher onto the spill surface, wait 30 minutes, and drop the weight. If an explosion occurred in the second test, the hypothesis would have been proven; if no explosion occurred following the final test, the result would be that the procedure was effective.

Zawierucha (personal communication, August 17, 1994) offered an alternative, developing a hot wire test similar to ASTM D3874. The qualitative test was previously used by the military to determine flammability in an oxygen enriched atmosphere. Using Pyrex containers, Nichrome wire and a battery for an energy source, parameters for no reaction, smoldering, smoke, and flash flame could be set, and measured against time. An extended pole, e.g., broom handle, could be used to contact the LOX test surface with the energy source. The test could be conducted with the floor surface test sample on a cement block substrate. The amperage could be determined easily, and the test samples would be reasonably sized.

The mechanical impact test (ASTM G86, 1989; 3.1, 3.2, 4.1) describes a system designed to expose material test samples to mechanical impact in the presence of liquid or gaseous oxygen at pressures from 0 to 10,000 psig. The test unit consists of a pressurizable test chamber equipped with a striker pin, striker pin counter loader and necessary test chamber purge, pressurization and vent systems; a plummet and associated guide tracks, hold/release mechanism, rebound limiter; and controls and instrumentation necessary for performing the test and monitoring the test chamber for evidence of reaction. Materials for LOX testing are precooled, flowed by submerging the test sample in LOX. The sample holder is installed into the test chamber, which is pressurized with gaseous oxygen, and the plummet is dropped from a selected height onto the counter load pin, which transmits the energy to the test sample by means of the striker pin. This test method evaluates the relative sensitivity of materials to mechanical impact in pressurized liquid or gaseous oxygen. The suggested criteria (4.4) for discontinuing the tests are occurrence of 2 reactions in a maximum of 20 successive samples for a material that fails; or no reactions occurring in 20 successive samples for a material that passes, when tested at a specific chamber pressure and a specific impact energy (plummet drop height).

The hot wire test (ASTM D3874, 1990, 1.1-8.5) is intended to differentiate among materials with respect to their resistance to ignition because of their proximity to electrically heated wires and other heat sources. The method applies to molded and sheet materials available in thicknesses of 0.010 inches to 0.25 inches, which are rigid at normal room temperature. The standard is intended to measure and describe the properties of a material, product, or assembly in response to heat and flame under controlled laboratory conditions. Results may be used as elements of fire risk assessment. For a given material, the methodology determines the average time required for ignition of the specimen, in seconds. Subject to limitations, this index can be used to categorize materials. A Nichrome wire is used with a continuous linear power density, means of voltage adjustment, and ability to record the application of test power. Two posts are positioned 2-3/4 inches apart to support the specimen within the test chamber, with a fixture to uniformly position the wire. The center portion of the test specimen is wrapped with the test wire using a winding fixture. The circuit is energized until the test specimen ignites, or is discontinued if ignition does not occur within 120 seconds, or when the test specimen is no longer in intimate contact with the heater wire. A minimum of five specimen tests are conducted for each material.

Evaluation of personal protective equipment needs for handling LOX found the Compressed Gas Association (1993, 3.4), "Cryogenics: Know the Basics" (Union Carbide) and Chief of Naval Operations (1989, C1210d.) consistent in their recommendations. A face shield and/or protective goggles, leather gloves, cotton clothing with cuffless legs, and high-top safety shoes were prescribed.

Literature Review Summary

The literature review discovered, that while oxygen in and of itself is widely recognized and discussed, consideration of oxygen in a liquid state as a cryogenic is narrowly focused to recognition and discussion in a limited number of sources. The availability and application of LOX to society and the potential of incidents are not widely appreciated by the fire protection community. The exception to this is the relatively limited discussion on LOX spills involving transportation disciplines, and those significantly involved with LOX as a medium for their industry.

Although documented incidents involving LOX are sparse, those that were cited consistently occurred with significant consequence. Applying the risk assessment matrix to evaluate the critical severity and probability that an incident may occur in time, draws to conclusion a "serious" risk assessment code. Ultimately, the literature supports the research hypothesis.

The question of what experiment has to be developed was focused, by both the scientific community and the outcome to be evaluated. The hot wire test (ASTM D3874, 1990a) would evaluate flammability, but not the research hypothesis or mitigation procedure's effectiveness. Unable to find an organization conduct the experiment, the mechanical, impact test (ASTM G86, 1989) would be difficult to replicate, and requires test conditions which are an exaggeration of the spill mitigation condition to be evaluated. Developing the suggested experimental impact test (Stoltzfus, August 16, 1994) would be pragmatistic. The literature influenced the intent, where and how the experiment would be conducted, as well as other safety considerations employed for risk minimization and personal protection.

PROCEDURES

The experimental research was conducted to evaluate the effectiveness of a mitigation procedure for small LOX spills. A test methodology was developed that would represent a likely spill condition for which the mitigation procedure was written. The hypothesized hazardous condition would be validated by experimental testing, followed by subsequent re-creation of the hazardous condition and implementation of the mitigation procedure; testing would occur again, to determine the procedure's effectiveness.

Mitigation Procedure

A small puddle of LOX has formed on the surface of a vinyl asbestos or vinyl composition floor tile from a portable LOX respiratory therapy unit laying on its side.

1. Allow the spill to vaporize for 30 minutes, isolating the spill area from entry or passage.

2. From a distance of 20 feet, discharge a stream of water from a Class A (2-1/2 gallon) pressurized water fire extinguisher in a sweeping or layering motion. The water will fill the seams or cracks which separate the individual floor tiles. Should any of the LOX have gotten into these seams and bonded with the petroleum-based floor tile adhesive, the water will free up the oxygen. Spraying the water from a distance

minimizes the potential of striking the floor surface in a manner which could create impact or compression on the LOX and floor adhesive.

3. Allow the water to remain for 30 minutes.

4. After completion of these measures, the spill site will be safe for reentry and passage.

Test Procedure Materials

A means of creating the spill condition and creating compression from impact had to be developed. Environmental variables had to be monitored so that their influence on the test results, if any, could be assessed. Conditions considered were:

1. Floor tiles representative of those found in the hospital.

2. Floor tile adhesive representative of the type used in the hospital.

3. Subsurface floor material representative of the type found in the hospital.

4. A configuration of tubing to resemble a small swing set, allowing for triangular leg support at either end of a connecting crossbar, creating an open area on the floor surface for the spill and impact test to occur. A pulley mechanism needed to be attached at the center point of the crossbar for a weight and release device. The release device could not become tangled in the pulley during release of the weight, as sometimes occurs with pulleys and the sudden slack from the release of wire or fiber line going through the pulley.

5. Weight representative of a falling object. Rather than focus on what a representative human foot impact would be, or identifying a specific tool or instrument, five pounds was decided to be representative of a pocketbook or parcel one may carry at chest height.

6. Environmental factors: temperature, relative humidity, and wind. The test would be conducted outdoors on a day without precipitation.

7. A means of creating a LOX spill. The portable LOX respiratory therapy equipment creating this potential at the hospital would be used.

8. Sufficient floor surface test samples to conduct five tests per test phase for test result validity.

The materials used to create and implement these conditions are listed in Table 2.

Table 2
Experiment Test Materials

(4) 66-inch Single Clamp, Zimmer Straight Traction Bars (uprights).
(1) 66-inch Straight Zimmer Traction Bar (crossbar).
(1) Zimmer Single Clamp Pulley.
(1) 165-foot Zimmer Traction Cord, 1/4 inch.
(4) 10-pound Zimmer Sandbags.
(3) U.S. military surplus sandbags.
(1) 5-pound Dorey Anchor.
(2) 30-inch iron rods, 1/4 inch.
(1) 50-foot rope.
(1) 5-pound sledge hammer.
(1) 100-foot measuring tape.
(1) 10-foot tape measure.
(15) 18-inch x 18-inch x 2-inch cement patio blocks, 5, 000 psi test rating.
Armstrong S90 Adhesive for installation of Armstrong floor tiles.
Armstrong S515 Adhesive for installation of Armstrong floor tiles.
(3) Vinyl asbestos floor tiles, 1/8 inch thick.
(2) Vinyl (old type) floor tiles, 1/8 inch thick.
(6) Vinyl composition floor tiles, 1/8 inch thick, Armstrong 51858, Lot No. F230A.
(3) Vinyl composition floor tiles, 3/32 inch thick, Armstrong 51858, Lot No. G159A.
(1) Material Safety Data Sheet (MSDS) for Liquid Oxygen (LOX).
(3) Puritan-Bennett Mark 5 Walker, Liquid Oxygen System Unit, and accompanying Patient Instruction Manual.
(3) Nasal cannulas with oxygen tubing.
(1) Fischer Scientific Digital Temperature-Humidity Meter, Model 11-661-8, Serial No. L209850.
(1) Quest Electronics Permissible Sound Level Meter, Model 211A/FS.
(1) Wall clock.
(1) Outdoor (Fahrenheit) thermometer.
(3) Pressurized Class A water fire extinguishers, (2 1/2 gallons).
(1) Cemetery flag.
(1) Roll 3 mil vinyl barrier tape.
(1) 8 x 10-foot polyethylene tarpaulin.
(2) 2 x 4 x 60-inch pieces of wood.
(2) 18 x 24-inch pieces of plywood.
(1) Folding table.
(1) Shovel.
(2) Mattock.
(1) Toolbox of assorted tools, nails, and screws.
(1) Roll duct tape.
(1) Chalkboard and chalk.
(1) Clipboard.
(2) VHS video cameras.
(2) SLR 35 mm cameras with print and slide film .

Appropriate personal protective equipment and first aid materials were additional considerations for working with LOX. These items are listed in Table 3.

Table 3
Personal Protective Equipment and First Aid Materials

1. Safety (hard) hat, complying with American National Standards Institute (ANSI) Z89.1, Class A, B, C.
2. Full face shield, complying with ANSI Z87.1.
3. 100% cotton coveralls with cuffless legs.
4. Leather gloves.
5. Hightop safety shoes, complying with ANSI Z41.
6. First aid kit with extra gauze dressing and bandages.
7. One and a half gallons of water in containers suitable for warming frostbitten skin tissue.
8. Cellular telephone.

Floor tiles were cut into quarter sections and affixed to the cement patio blocks to create four representative tiles and seams with floor tile adhesive as noted in Table 2. The Armstrong S90 Adhesive was used by the hospital until approximately 1992-1993, when Armstrong S515 Adhesive began to be used. The vinyl asbestos floor tiles were installed before 1975. The older vinyl tiles were used from the late 1960s to the mid-1970s, when the Armstrong vinyl composition floor tiles were used. The hospital, constructed in 1951, incurred major building additions in 1961, 1972, 1980, and 1994.

The experiment was conducted in a field used for pasturing, but remote from humans, animals, structures, or environmental factors which could be affected by the potential effects of fire, explosion and noise, or pose a possible source of ignition.

The author was assisted by three people in conducting the experiment.

Instrumentation

The orthopedic traction bars were assembled in swing-set fashion. Each of the four legs was sandbagged for stability and to help protect them against damage from the test explosions. The iron rods were driven into the ground behind the orthopedic framing, and were used to tie off the framing with rope to counteract the drop weight (Dorey Anchor) being pulled up and dropped via traction cord from the other side.

A 150-foot distance was measured from the drop point to establish the safety zone. The traction cord, attached to the anchor, extended beyond the safety perimeter and was tied off on a tree. The cord would be untied to release and drop the anchor to conduct the impact test. Several safety trial drops were conducted before initiating the test phases.

Clearance between the bottom tip of the anchor and the floor tile surface was 37 inches, providing 15.5 foot pounds of impact.

A wooden post was driven into the ground at the safety zone to hold the clock and thermometer. The folding table served to hold instruments and allow for documentation. The chalkboard permitted the charting of test apparatus, environmental conditions, and test results. The nasal cannula and tubing were attached to the Mark 5 Walker to control the flow of gaseous oxygen which was set at the liter flow common at the hospital.

The cemetery flag was attached with duct tape to a fence post adjacent to the drop zone, and the barrier tape was tied to the orthopedic framing. Both items were used to detect wind movement and direction for purposes of test influence and safety.

The cement patio blocks were located near the drop zone for placement under the anchor. A plain patio block was placed adjacent to the test block so that there would be adequate surface area upon which to lay the Mark 5 Walker.

The noise meter would be used to determine loudness of the explosion when the anchor was dropped onto the cement block with floor tile and LOX spill.

Cameras were positioned to capture the testing from within the safety zone.

Table 4 illustrates the key aspects of the test site. Figure 2 illustrates the orthopedic framing, supports, protective features, and the drop weight in position. The cement block is positioned to provide adequate surface area of the Mark 5 Walker when a floor surface sample is placed adjacent to it. Figure 3 looks towards the drop zone from the vicinity of the safety zone. Figure 4 shows the floor surface test samples. Each cement block is marked to identify the floor tile type and adhesive type. Figure 6, taken after the LOX contents had been depleted, shows the side of the Mark 5 Walker that was placed so that it was face down upon the floor surface test samples. Figures 1 and 5 are documentary.

Test Procedure

Table 5 identifies the Test Phases, the number of drop tests to be completed per Phase, and with which materials.

The floor tile test sample was positioned within the drop zone; the drop weight would be secured at drop height.

Wearing the personal protective equipment listed in Table 3, the author would pick up a Mark 5 Walker which was stored in a LOX safety zone located away from the operational safety zone and test area, and proceed to the drop zone.

Fig. 1

Fig. 2

Fig. 3

Table 4
Photographs of Experiment Test Site

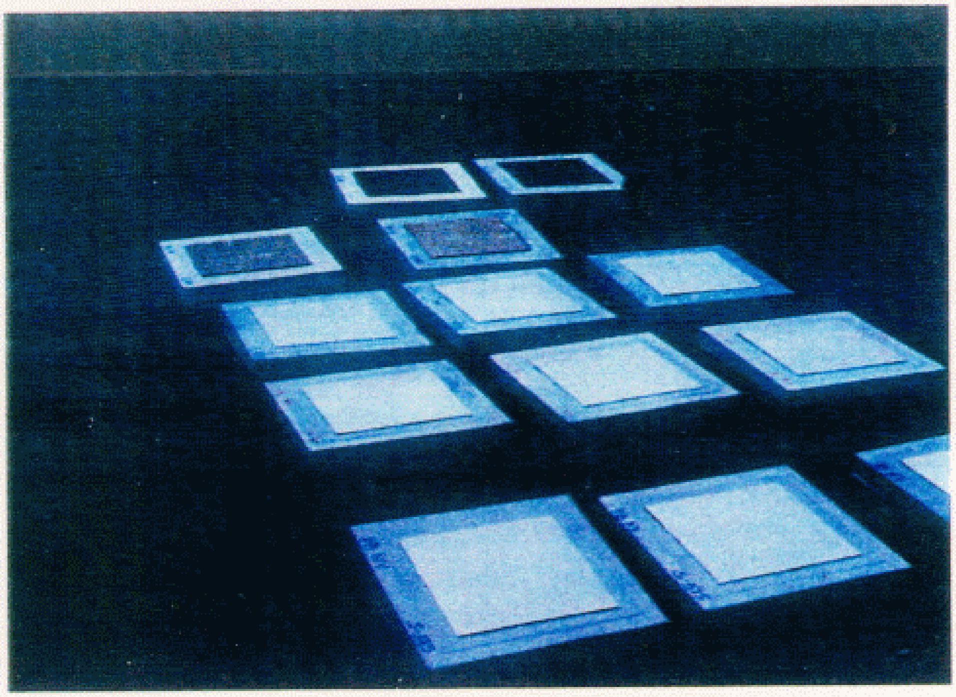

Fig. 4

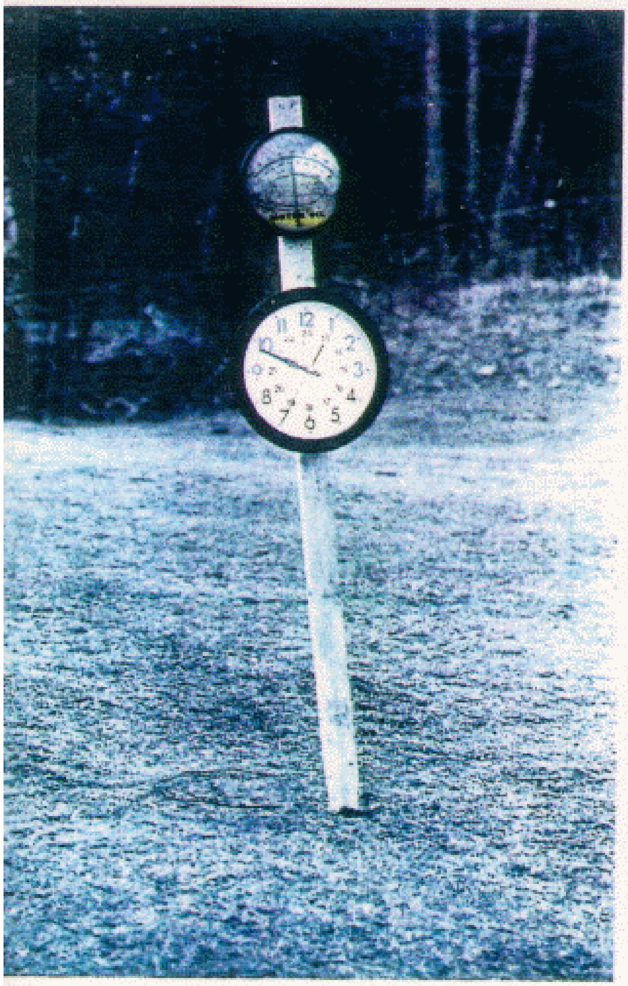

Fig. 5

Fig. 6

Verifying wind movement, the Mark 5 Walker flow valve was turned to a flow setting. The initial setting was ten liters. The Walker was placed upon the patio blocks with the flow valve against the block, and the backside that would customarily be against a patient, facing up or skyward.

Time and environmental conditions would be noted. When a puddle or pool of LOX became visible on the test sample, the Mark 5 would be cautiously removed. After the author exits into the safety zone, the weight would be dropped.

Phase No. 1 testing would be accomplished to establish that LOX will react violently when impacted by the dropped weight.

Phase No. 2 testing would permit the spilled LOX to remain for 30 minutes. The weight would be dropped at the end of 30 minutes to determine if a hazard existed with any of the floor surface test samples and adhesives.

Phase No. 3 Testing would permit the spilled LOX to remain for 30 minutes, at which time a pressurized water fire extinguisher brought from the operational safety zone by the author, would be discharged onto the drop site from a distance of 20 feet. Flowing another 30-minute period, the weight would be dropped to determine whether the spill had been mitigated.

If the dropped weight impact resulted in an explosion during Phase No. 2 testing, the experiment's hypothesis would be correct. Assuming this to be so, no explosion at the end of Phase No. 3 testing would prove the mitigation procedure for small LOX spills to be valid.

Table 5
Test Phases

Phase No. 1: Test for impact reaction immediately after leakage of LOX.

ADHESIVE

TILE TYPE	S90		S515
	(1) Vinyl Asbestos	1/8 Inch Thick	(1) New Vinyl 1/8 Inch Thick
	(1) Old Vinyl	1/8 Inch Thick	
	(1) New Vinyl	1/8 Inch Thick	
	(1) New Vinyl	3/32 Inch Thick	

Phase No. 2: Test for impact reaction 30 minutes after leakage of LOX.

(1) Vinyl Asbestos	1/8 Inch Thick	(1) New Vinyl 1/8 Inch Thick
(1) Old Vinyl	1/8 Inch Thick	
(1) New Vinyl	1/8 Inch Thick	
(1) New Vinyl	3/32 Inch Thick	

Phase No. 3: Test for impact reaction 60 minutes after leakage of LOX. After the first 30-minute period, water from a pressurized water fire extinguisher would be applied from a distance Following the second 30-minute period, the drop test would be conducted to evaluate impact reaction.

(1) Vinyl Asbestos	1/8 Inch Thick	(1) New Vinyl 1/8 Inch Thick
(1) New Vinyl	1/8 Inch Thick	
(1) New Vinyl	3/32 Inch Thick	

Assumptions

Through evaluation of the lecture review, the author could assume the initial tests of the experiment would result in an explosion, and that an explosion was probable 30 minutes following the LOX spill. This research only evaluates the effectiveness of a spill procedure for a small puddle of LOX on interior floor tile. Based upon interpretation of the literature review, the small puddle was assumed to constitute approximately one-quarter cup. The potential risk of increased reactivity or combustibility with other interior material and conditions must be assumed in consideration of the substance's properties.

Limitations

Given the considered risks associated with LOX and the demonstrated experiments (Compressed Gas Association, 1988; Linde, 1987; Mullen 1990; Naval Weapons Center; Union Carbide Corporation), assistance was sought from organizations familiar with laboratory testing to perform a mechanical impact test. Bryan Coleman, NASA (personal communication, July 6, 1994); Henry Febo, Factory Mutual Research Center (personal communication, July, 11, 1994); David Lucht, Worcester Polytechnical Institute (personal communication, August 23, 1994); James Milke, University of Maryland (personal communication, August 23, 1995); and Gerry Bassett, National Fire Academy (personal communication, September 1, 1994) indicated their organizations were unable to participate in the conducting of the experiment. Stoltzfus (personal communication, August 16, 1994) provided insight on how a mechanical impact test could be developed and conducted. Robert Zawierucha (personal communication, August 17, 1994) advised that a modification of a hot wire test might be a consideration for evaluating the reactivity of materials involved in a LOX spill, considering the cumbersomeness, time, and expense of an impact-sensitivity test. The American Society for Testing and Materials (ASTM) D3874 Hot Wire Test Standard and ASTM G86 Mechanical Impact Test Standard provided by Zawierucha were reviewed for their feasibility.

The ASTM D3874 and G86 tests would not allow for a true representation of a LOX spill on a floor tile surface with an underlying petroleum-based adhesive. A modification of the mechanical impact test was considered.

Assistance for a test site was sought from the Rhode Island State Fire Marshal's Office. Subsequently, a suitable test site was not available (Davies, personal communication, November 10, 1994).

The mechanical test materials were obtained and prepared; however, only two of the old vinyl floor tiles were available. A decision was made to include these floor surface test samples in Phases No. 1 and No. 2 of the experiment's testing, and delete it from Phase No. 3.

After a test site was located, the author learned LOX was not obtainable in a container which would permit the dispensing of LOX to accomplish the experiment as designed, due to regulations (Lavelle, personal communication, March 2, 1995).

After evaluating the potential risks associated with initiating a LOX spill from a portable LOX respiratory therapy unit, Mark 5 Walker, the decision was made to use the actual hospital equipment which was the premise for the spill procedure and evaluation of the procedure. The author's judgment was used to determine the feasibility of the experiment and achievability of safety parameters for the test materials, environmental conditions, and test site.

RESULTS

A tabulation of the experimental test results evaluating the procedure for mitigation of a small LOX spill are provided in Table 6.

The results reflect data which coincide with the experiment described within the procedures. All three of the Marker 5 Walker units were used to depletion of LOX in the experiment. The experiment was applied as developed, for Phase No. 1 testing. Phases No. 2 and No. 3 were not conducted. Nine drop tests were conducted during Phase No. 1 to initiate a LOX explosion by mechanical impact. Only two of the five floor surface test samples were used.

The experiment's outcome was that a puddle or pool of LOX was achieved in two out of nine tests; initiation of an explosion could not be accomplished when LOX puddled or pooled, or when there was no evidence of puddling or pooling. Because Phase No. 1 did not establish or verify that LOX would react violently when mechanically impacted by the dropped Dorey Anchor, Phases No. 2 and No. 3, which were the hypothesis and mitigation procedure, were not evaluated. The hazardous condition could not be created.

The outcome's relationship to the spill procedure is that the spill procedure is not necessary for the Mark 5 Walker on a vinyl asbestos or vinyl composition floor tile surface with an underlying petroleum-based adhesive.

Because the Mark 5 Walker manual (Puritan-Bennett, 1991) indicated LOX would escape and a liquid spill could occur if the unit was not kept upright, the lack of spillage during the experiment was unexpected. Information that was not intentionally sought, but was derived and is relevant to the problem being researched, is the Mark 5 Walker units used in the experiment did not create the hazardous condition for which the mitigation procedure was written, and the problem to evaluate the mitigation procedure researched. This suggests the Mark 5 Walker is effectively designed for spill risk minimization.

The hypothesis behind this research was that if LOX on petroleum-based asphalt was impact sensitive, then LOX pooling on a floor tile surface will contact the underlying petroleum-based adhesive through the seams or cracks of adjoining floor tiles, creating an impact-sensitive condition. The hypothesis was neither proved nor disproved because a liquid spill of oxygen could not be generated in seven of nine tests. The liquid spill generated in two of the nine tests vaporized before mechanical impact could be initiated.

Table 6
Experiment Test Results

11 MARCH 1995 LOX TEST RESULTS

TEST NO.	LINCARE MARK 5 WALKER UNIT NO.	OXYGEN FLOW LITERS/ MINUTE		FLOOR TILE SAMPLE, TYPE	FLOOR TILE ADHESIVE, TYPE	TEMP. DEGREES FAHRENHEIT	PERCENT (%) RELATIVE HUMIDITY	WIND SPEED (MPH)	TIME	CRACK-LING NOISE	VAPOR PRESEN-TATION	LIQUID PRESEN-TATION	WEIGHT DROPPED
01	A19155	10	Y	Asbestos	Armstrong 590	36.1°	8	3-10	00.00	02.00	02.58	03.45	10.00
02	A19155	10	Y	Asbestos	Armstrong 590	42.8°	8.9	3-10	00.00	-	02.30	03.30	09.00
03	A19154	10	N	Asbestos	Armstrong 590	41.0°	6	3-10	00.00	-	02.05	-	09.00
04	A14822	10	Y	Asbestos	Armstrong 590	42.5°	8.3	3-10	00.00	-	-	-	09.00
05	A14822	1	Y	Old Vinyl	Armstrong 590	46°	6.4	None	00.00	-	-	-	10.00
06	A14822	10	Y	Old Vinyl	Armstrong 590	43°	6.3	0-5	00.00	-	-	-	10.00
07	A14822	15	Y	Old Vinyl	Armstrong 590	43.3°	6.8	0-5	00.00	-	-	-	08.00
08	A14822	15	Y	Old Vinyl	Armstrong 590	50.7°	6.5	7-15	00.00	-	-	-	02.00
09	A19155	15	Y	Old Vinyl	Armstrong 590	48°	7.4	5-10	00.00	03.00	04.45	-	08.00

DISCUSSION

The project results demonstrate the hazardous condition supported by the research hypothesis was not achieved.

Linde (1988, p. 3) supports the precautions noted by Puritan-Bennett (1991), but the implications of effective safe design technology by Zawierucha (August 10, 1994) are supported by the lack of documented incidents involving portable LOX respiratory therapy units. The potential, however, remains evident by fire code recognition (NFPA 50, 1990; NFPA 53, 1994; NFPA 99, 1993; NFPA 419M, 1991).

The interpretation of these results is that the studied medium of oxygen therapy is prudently safe from the relative focus that was studied. While the research was focused, the potential risks associated with other scenarios were not diminished. Once these potentials are realized, understood and planned for, however, will the potential be any worse than that associated with other hazardous materials which sustain society on a daily basis, but have the potential to do harm under abnormal conditions?

The research results do not absolve the hospital or Swansea Fire Department from considering the ramifications of an OEA from the application of LOX respiratory therapy, considerations given by NFPA 99 (1993) to the transfer of LOX from a Reservoir to a portable unit, or the potential contribution of LOX to a fire scenario similar to the one experienced by Fennelly (August 17, 1994).

RECOMMENDATIONS

The research focused on the release of a small liquid spill of LOX from a Puritan-Bennett Mark 5 Walker, distributed by Lincare, onto a vinyl composition floor tile with an underlying petroleum-based floor tile adhesive.

The study did not consider other aspects of LOX respiratory therapy equipment, leaving future research to address:

a. What hazards may be associated with a physically damaged portable LOX respiratory therapy unit?

b. The home use and transfer of LOX from a reservoir to a portable respiratory therapy unit.

c. A structure fire with the presence of a LOX reservoir and portable respiratory equipment, and their potential outcomes.

d. Potential outcomes associated with portable LOX and respiratory therapy equipment, and a motor vehicle accident or motor vehicle fire.

e. A comparative risk analysis between portable LOX and compressed gaseous oxygen cylinders and their real or potential behavior in mishaps or abnormal conditions.

Recognition of LOX portable respiratory therapy equipment also is recommended for authors of future hazardous material reference publications intended for health care safety professionals and emergency response organizations.

REFERENCES

American Society for Testing and Materials. ASTM G86 Standard Test Method for Determining Ignition Sensitivity of Materials to Mechanical Impact in Pressurized Oxygen Environments (1989). Philadelphia, PA: American Society for Testing and Materials.

______. ASTM D3874 Standard Test Method for Ignition of Materials by Hot Wire Sources (1990). Philadelphia, PA: American Society for Testing and Materials.

Armstrong (October 1, 1993). S-90 Adhesive: Material safety data sheet. Lancaster, PA: Armstrong World Industries, Inc.

Bahme, C.W. (1972). Fire officer's guide to dangerous chemicals. Boston: National Fire Protection Association.

Bassett, G. Hazardous Materials: Interview, National Fire Academy, September 1, 1994.

Baudoin, C. Home care bulletin no. 19, Puritan-Bennett, January 31, 1991.

Bender, J Interview, Maryland State Fire Marshal's Office, February 2, 1994.

Burke, J. (1978). Connections. Boston: Little, Brown and Company.

Bush, K. Interview, Maryland State Fire Marshal's Office, February 2, 1994.

Chemical Propulsion Information Agency (1984). Hazards of rockets and propellants: Vol. III liquid propellants (CPIA Publication 394). Laurel, MD: Johns Hopkins University, Applied Physics Laboratory.

Chief of Naval Operations (1989). OPNAV Instruction 5100.19B: Navy occupational safety and health (NAVOSH) program manual for forces afloat. Washington, DC: Department of the Navy.

______. (1986.) OPNAV Instruction 5100.23B: Navy occupational safety and health (NAVOSH) program manual, Change 4. Washington, DC: Department of the Navy.

Coleman, B.J. Chief, Failure Analysis & Materials Evaluation Branch: Interview, National Aeronautics and Space Administration, Kennedy Space Center, July 6, 1994 & August 10, 1994.

Compressed Gas Association, National Welding Supply Association, & WESCAP Insurance Company (1988). Characteristics and safe handling of cryogenic liquid and gaseous oxygen, AV-8 (Videotape). Arlington, VA: Compressed Gas Association.

______. (1993). Safe handling of cryogenic liquids: CGA P-12-1993 (3rd Ed.). Arlington, VA: Compressed Gas Association.

DaPonte, D. Homecare Specialist: Interview, Lincare, Inc., Swansea, MA, January 20, 1994.

Davies, S. Interview, Rhode Island State Fire Marshal's Office, November 10, 1994.

Drysdale, D. (1985). An introduction to fire dynamics. New York: John Wiley & Sons.

Erickson, D.S. Interview, American Hospital Association, August 15, 1994.

Febo, H. Standards Division: Interview, Factory Mutual Research Center, July 11, 1994.

Fennelly, K. (1993, September). Liquid oxygen therapy used in residential settings. Fire Marshals Quarterly.

Gayle, J.B. (1973). Explosions involving liquid oxygen and asphalt. Fire Journal, 67 (3).

Haessler, W.M. (1974). The extinguishment of fire. Boston: National Fire Protection Association.

Hall, J. University Fire Marshal: Letter, University of Rochester, NY, August 4, 1994.

ICHIEFS, Fire service computer network (1994, August 28). Inquiry for LOX incidents. Fairfax, VA: International Association of Fire Chiefs.

Isman, W.E. & Carlson, G.P. (1980). Hazardous materials. New York: Macmillan Publishing Company.

Jaeger, T.W. Interview, Gage-Babcock & Associates, February 1, 1994.

Janoff, D. Lockheed-ESC/B22. National Aeronautics and Space Administration, Johnson Space Center, Test Facility No. 94-28635, Request No. 10512L, October 13, 1994.

Klein, B. Chief Health Care Fire Protection Engineer: Interview, National Fire Protection Association, February 1, 1994.

Lavelle, R. Operations Manager: Interview, BOC Gases, Warwick, RI, January 1995.

Layman, L. (1952). Attacking and extinguishing interior fires. Boston: National Fire Protection Association.

Leo, J. (1993). Emergency response report (Report No. 93-65). Providence, RI: Rhode Island Department of Environmental Management.

Linde, Union Carbide Industrial Gases (1987). Pipeline supplied (Videotape). Union Carbide Corporation.

Linde, Union Carbide (December 1988). Safety precautions: Oxygen, nitrogen, argon, helium, carbon dioxide, hydrogen, fuel gases L-3499H. Union Carbide Corporation.

Lucht, D. Interview, Worcester Polytechnical Institute, August 23, 1994.

McNamee, R.B. Fire Chief, Marshfield, MA: Interview, January 10, 1995.

MEDLINE, Bibliographic computer database (1994, July). Literature search for LOX 1985 July-1994 July. Bethesda, MD: National Library of Medicine.

Meidl, J.H. (1970). Explosive and toxic hazardous materials. Encino, CA: Glencoe Press.

______. (1970). Flammable hazardous materials. Encino, CA: Glencoe Press.

Milke, J. Department of Fire Protection Engineering: Interview, University of Maryland, College Park, August 23, 1994.

Morton, H.S. (1961). Ignition concepts applied to industrial explosions. Fire Engineering, 114 (5).

Mullens, J.A. (Producer), & Hartman, D. (Director) (1990). Surviving the hazardous materials incident: Understanding cryogenics (Videotape). Fort Collins, CO: Emergency Resource, Inc.

Murray, D. Consultant to American Hospital Association: Interview, August 15, 1994.

National Fire Academy (1983). The chemistry of hazardous materials: Readings and references. Emmitsburg, MD: National Emergency Training Center.

National Fire Protection Association. NFPA 50, Standard for Bulk Oxygen Systems at Consumer Sites (1990). Quincy, MA: National Fire Protection Association.

______. NFPA 53, Guide on Fire Hazards in Oxygen-Enriched Atmospheres (1994). Quincy, MA: National Fire Protection Association.

______. NFPA No. 56, Recommended Safe Practice for Hospital Operating Rooms (1951). Boston: National Fire Protection Association.

______. NFPA 99, Standard for Health Care Facilities (1993). Quincy, MA: National Fire Protection Association.

______. NFPA 491M, Manual of Hazardous Chemical Reactions (1991). Quincy, MA: National Fire Protection Association.

______. (1995). 1995 Fall meeting report on proposals. Quincy, MA: National Fire Protection Association.

National Response Center. Interview, U.S. Coast Guard, February 27, 1995.

Naval Weapons Center. Man from LOX (Film). China Lake, CA: Department of the Navy.

Praxair (1992, December). Oxygen (cryogenic liquid) material safety data sheet, L-4637-D. Danbury, CT: Praxair, Inc.

Puritan-Bennett (1991). Mark 5 liquid oxygen system: Patient instruction manual part no. 77009. Indianapolis: Puritan-Bennett.

______. Mark oxygen walker system: Patient operating instructions part no, 776425 (rev. a). Puritan-Bennett.

Reed, J.O. & Guthe, K.E. (1915). College physics. New York: Macmillan Company.

Roy, B. Executive Secretary, Fire Marshals Association of North America: Interview, February 1, 1994.

Royer, K., & Nelson, F.W. Water for fire fighting. Iowa State University Bulletin No. 18. Ames, IA: Fire Service Extension, Iowa State University.

Shephard, A., Slayton, D., Barbee, J., & Benedict, H. (1994). Moonshot: The inside story of America's race to the Moon. Atlanta, GA: Turner Publishing, Inc.

Shouldis, W.J. Battalion Chief, City of Philadelphia Fire Department: Letter, June 29, 1994.

Stoltzfus, J.M. Interview, National Aeronautics and Space Administration, Johnson Space Center, White Sands Test Facility, August 16, 1994 & September 1, 1994.

Tyron, G.H., ed. (1962). Fire protection handbook (12th ed.). Boston: National Fire Protection Association.

Union Carbide Corporation, Linde Division, Safety, Health and Environmental Affairs. Cryogenics: Know the basics (Videotape). Tarrytown, NY: Union Carbide Corporation.

Varela, J., ed. (1990). Surviving the hazardous materials incident: Student workbook, series 1. Fort Collins, CO: Emergency Resource, Inc.

Weinburg, K. Safety Director: Interview, Massachusetts General Hospital, July 5, 1994.

Wintrobe, M.M., Thorn, G.W., Adams, R.D., Bennett, I.L., Jr, Brawnwald, E., Isselbacher, K.J., & Petersdorf, R.G. (eds.) (1970). Harrison's principles of internal medicine (6th Ed.). New York: The Blakiston Company, McGraw-Hill.

Young, M.S. (1978). Handling emergencies involving cryogenic materials. Fire Command, 45 (5).

Zawierucha, R. Research and Development: Interview, Praxair, Inc., August 10, 1994 & August 17, 1994.

APPENDIX A

BIBLIOGRAPHY

BIBLIOGRAPHY

Bowen, J.E. (1982). Unique hazard posed by oxygen-enriched atmosphere. Fire Engineering, 135 (3).

Brooks, R., Project Manager (1986). Hazardous materials tactical considerations: Student manual. Emmitsburg, MD: National Fire Academy, National Emergency Training Center.

Carlson, G.P., ed. (1988). Hazardous materials for first responders. Stillwater, OK: Fire Protection Publications, Oklahoma State University.

Compressed Gas Association (1983). Transfilling of liquid oxygen to be used for respiration: CGA P-2.6-1983. Arlington, VA: Compressed Gas Association.

Fire, F.L. (1986). The common sense approach to hazardous materials. New York: Fire Engineering.

Hosty, J.W. & Foster, P. (1992). A practical guide to chemical spill response. New York: Van Nostrand Reinhold.

Isman, W.E. & Carlson, G.P. (1983). Hazardous materials: Cryogenics. American Fire Journal, 37 (9).

Kramp, R.T. (1982). Use of cryogens at Fermi Lab could pose rescue problems. Fire Engineering, 32 (12).

Mozinog, A. (1980). Hazardous materials: Cryogenic materials. Western Fire Journal, 32 (12).

Murphy, J.J. Jr., & Grasso, J. (1993). Upgrading cryogenic oxygen systems. Industrial Fire Safety, 2 (3).

Staff (1988). Focus on hazardous materials: Liquid oxygen (LOX). Industrial Fire World, 3 (2).

Stutz, D. (1994, February-March). Hazmat primer. Firefighter News.

U.S. Coast Guard (1985). Chemical hazard response information system (CHRIS) manual II. Washington, DC: U.S. Coast Guard.

Woodward, F.P., Hansen, L.E., & Melton, D.A. (1994). Cryogenic liquid oxygen container explosion: An investigation. Fire Engineering, 147 (1).

APPENDIX B

ACKNOWLEDGMENTS

Many individuals were most gracious in their assistance to provide answers, guidance, and understanding in the accomplishment of this research.

However, some individuals supported these efforts beyond the usual and customary approach, and, without their help, this research program would not have been accomplished.

Joel M. Stoltzfus
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
White Sands Test Facility
Les Cruces, NM

Robert Zawierucha
Research and Development
Praxair, Inc.
Tonawanda, NY

Conducting the experiment:

Michael Fay, Chairperson
Local Emergency Planning Committee
Rhode Island District No. 3

John Leo
Hazardous Materials Response
Division of Site Remediation
Rhode Island Department of Environmental Management

Rebecca M. Lukowicz
Kent County Memorial Hospital
Warwick, RI

Respiratory Care Section
Kent County Memorial Hospital
Warwick, RI