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TECHNICAL NOTES

Safe Quantity of Open Medical Gas Storage in Healthcare Facility Smoke Compartments

Final Report by:

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Foreword

Medical gases are gases that are manufactured, packaged, and intended to support various healthcare operations, such as surgeries, calibration of medical equipment, and breathing support for patients. While the storage and use of medical gases are essential to healthcare facilities, they have the potential to create hazardous conditions when not handled, stored, or refilled properly, which increases the probability of injuries and accidents occurring in these facilities. NFPA 99, the Health Care Facilities Code, allows a volume of up to 300 ft³ of medical gases (normally oxygen) to be stored outside of a dedicated storage enclosure, however, the technical substantiation for this requirement was unknown. Therefore, this report addresses the hazards associated with medical gases through a review of incident case studies, relevant literature and a hazard assessment to evaluate the current code requirement in NFPA 99.

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Safe quantity of open medical gas storage in healthcare facilities

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Executive Summary

NFPA 99 (2018) allows medical gases to be stored outside of a storage enclosure as long as the volume is less than or equal to 300 ft³ for a smoke compartment in healthcare facilities. Medical gases are required for various operations such as surgeries, calibration of medical equipment, and breathing supports for patients. Hence, storing enough volume of medical gases in the healthcare facility is critical. These gases, however, may pose a serious threat to occupants if they are not stored or handled properly. For example, failure of oxygen cylinders can increase oxygen concentration in ambient air, which can increase the reactivity of ignition and fire of materials that may not burn in normal air in case of fire. Therefore, regulating the number of the medical gas cylinder that can be stored outside a storage enclosure can reduce this fire risk. In this context, the current study aims to identify hazards associated with medical gas storage in healthcare facilities and assess whether this requirement is reasonable.

Statistics on the medical gas industry provide evidence of increasing demand for medical gases and a decreasing trend for fire incidents in health care facilities in the US. Cooking equipment has been known to be the major cause of healthcare facility fires. Based on the statistics, it is not clear that medical gas volume and associated fire risk are closely related.

The oxygen concentration of 23.5 Vol % is considered an Oxygen Enriched Atmosphere (OEA) in which fire risk is deemed to increase significantly. Quantitative analysis on oxygen concentration for various oxygen release amounts is conducted for an average patient room (320 ft² large and 9 ft high) with the ventilation of eight-air changes per hour. It is shown that an entire release of three fully charged E-sized oxygen cylinders is required to reach 23.5 Vol % and with a more probable scenario of one-cylinder failure, OEA is not formed.

In addition, the floor plan trend moving from multiple occupancy rooms to single-patient rooms along with the increase of smoke compartments size from 25,000 ft² to 40,000 ft² is deemed to help decrease the number of people exposed to fire, which ultimately reduces fire risk.

Despite relatively low fire concerns associated with medical gas storage, the current study recommends a wide range of surveys to be conducted to better understand the typical storage location of medical gases up to 300 ft³, from which other fire concerns such as fuel load, the number of occupants likely to be exposed to fire, if any, and potential ignition sources around the medical gas storage could be further assessed.

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1 Introduction

NFPA 99 (2018): Health Care Facilities Code specifies three different storage requirements of medical gases depending on its volume. For example, a volume of medical gases up to 300 ft³ can be stored outside of a storage enclosure, i.e., in the corridor or behind a nurse station. A volume of gases between 300 ft³ and 3000 ft³ shall be stored outdoors or in an interior enclosure made of non-combustible or limited-combustible construction. A volume more than 3000 ft³ shall be also stored outdoors or in an interior enclosure with increased restrictions such as lockable doors, gates, or fire-rated construction. Note that more stringent fire protection requirements are specified for a larger volume of medical gases, which indicates that medical gases are considered hazardous from the perspective of fire safety.

However, it has been argued that the volume of gases specified in NFPA 99 (2018) lacks scientific validation. This argument is further supported by the fact that the medical gases that are “in-use” or “for immediate use” are not required to be included in the calculation of the gas volume per NFPA 99 (2018). For example, a total volume of medical gases not stored in an enclosure may be up to 450 ft³, if gas cylinders up to 100 ft³ are currently “in-use” and other gas cylinders of 50 ft³ are indicated “for immediate use.” Therefore, the actual volume of medical gases not stored in a storage enclosure can be larger than 300 ft³ in reality.

In this context, the current research aims to;

- identify hazards associated with medical gases from literature,
- assess the hazards identified from the perspective of fire safety,
- establish guidance on allowable volume of medical gases out of enclosed storage, i.e., with a focus on the volume of medical gases up to 300 ft³.

in health care facilities.

2 Background and literature review

2.1 Medical gases

The gases that are used on a human or any live being, who is considered a patient, in the form of anesthesia, therapy or diagnosis of the disease are considered to be medical gases (Bennington, 2019). Oxygen (O₂), nitrous oxide (N₂O), medical air, nitrogen (N₂), carbon dioxide (CO₂), and other gases that are manufactured and enclosed for medical purposes fall under the category of medical gases (Gómez-Chaparro et al., 2018). Medical oxygen is generally used for the prevention and treatment of respiratory diseases. Medical air is used in the intensive care units for the people who are supported with mechanical ventilation to reduce the risk of excessive oxygen supply to the lungs or any other corporal tissues. Medical nitrogen in the hospital environment is used as a cryopreservative of biological specimens. Apart from that, nitrous oxide can also be administered in combination with other anesthetic gases in surgical conditions. Furthermore, nitrogen is utilized as a pneumatic gas to pressurize the medical equipment and to prevent combustion and chemical

reactions which can occur due to other gases and equipment. Carbon dioxide is used to inflate body areas especially in keyhole surgeries and it works as a breathing stimulator when mixed with oxygen. Another use of CO₂ is to test tooth sensitivity in the dentistry (Bennington, 2019; Gómez-Chaparro et al., 2018). Depending on its characteristics and use, they may be stored in high-pressure cylinders or cryogenic containers. Different color codes for different types of medical gases are used for gas cylinders; it should be noted that the attached cylinder labels should be read to identify the gases, not the color of cylinders; the color code is recommended as a secondary check of the contents. For example, the E or D size cylinder for oxygen has a green color body and medical air has a yellow color body. Further details regarding the color code and cylinder size are easily found in section 5.1.11.1.1 NFPA 99 (2018). Note that the color code for the medical gas cylinders in the US is different from that in other countries where the ISO color code is used.

2.2 NFPA 99 (2018): Health Care Facilities Code

NFPA 99 (2018) prescribes minimum requirements for installation, inspection, testing, maintenance, performance, and safe practices for medical gas systems in health care settings. Some of the key requirements from NFPA 99 (2018) are excerpted below followed by reviews.

2.2.1 The volume of medical gas cylinders in an enclosure storage

11.3.4 Storage for non-flammable gases equal to or greater than 85 m³ (3000 ft³) at STP shall comply with 5.1.3.3.2 and 5.1.3.3.3 unless such installations are approved existing installations, which shall be permitted to be continued in service.*

11.3.5 Storage for non-flammable gases greater than 8.5 m³ (300 ft³), but less than 85 m³ (3000 ft³), at STP shall comply with the requirements in 11.3.5.1 through 11.3.5.7.*

11.3.6 Storage for non-flammable gases with a total volume equal to or less than 8.5 m³ (300 ft³) shall comply with the requirements in 11.3.6.1 and 11.3.6.2.

11.3.6.1 Individual cylinder storage associated with a smoke compartment in accordance with NFPA 101 shall not be required to be stored in enclosures.

11.3.6.2 Precautions in handling cylinders specified in 11.3.6.1 shall be in accordance with 11.6.2.

The storage requirement differs depending on the volume of gas. Such key requirements are compiled in Table 1 per the publication by NFPA (Medical Gas Cylinder Storage, 2018).

Table 1: Gas cylinder storage requirement per NFPA 99 (2018) (Medical Gas Cylinder Storage, 2018)

The volume of medical gases	Recommendations
< 300 ft ³	<ul style="list-style-type: none"> - Not required to be stored in an enclosure being associated with a smoke compartment - Precautions for handling the cylinders must still be observed
Between 300 ft ³ and 3000 ft ³	<ul style="list-style-type: none"> - Outdoors or in an interior enclosure of noncombustible or limited combustible construction - Indoor locations must include the following: <ul style="list-style-type: none"> o Restriction of oxidizing gases such as oxygen and nitrous oxide from being stored with any flammable gas, liquid, or vapor o Separation of oxidizing gases from combustibles or flammables (more than 20 ft separation distance in an un-sprinklered building or 5ft in a sprinklered building, or gas cabinet in a sprinklered building) o Cylinder temperatures less than 52°C (125°F) o Appropriate restraints per NFPA 99 (2018), 11.6.2.3. o Cylinder valve protection caps o Smoking, open flames, electric heating elements and other sources of ignitions prohibited from storage locations and within 20ft of outside storage locations
> 3000 ft ³	<ul style="list-style-type: none"> - Access to move cylinders on hand trucks - Availability of lockable doors or gates - Availability of minimum two entries/exits (if outdoors and >200ft²) - Interior finishes, racks, shelves, and supports with noncombustible or limited combustible material (if indoors) - Walls and floors made with 1-hour fire-resistance rating & other openings with ¾-hour fire protection rating (if indoors) - Racks, chains or other fastenings to secure cylinders from falling - Access for delivery vehicles and management of cylinders - Regulation of temperature - Prohibition of motor-driven machinery - Additional ventilation requirements

Here, the volume of medical gases to determine the storage requirement excludes the gases “in use” or “for immediate use” as stated below in NFPA 99 (2018). Despite the ambiguity of calculation, this may be justifiable from a practical point of view since the gas cylinders in use or for immediate use are indispensable for the patients and it is inconvenient to know the exact amount of leftover gases in the cylinders in use.

*A.11.3.5 When determining the volume of storage, do not consider cylinders and containers that are **in use**. Only the volume of stored gas that is **in excess of 300 ft³** is **required to be located in an enclosure**, since 11.3.6 already permits up to 300 ft³ without any special storage requirements.*

11.3.8 Individual small-size (A, B, D, or E) cylinders available for immediate use in patient care spaces shall not be considered to be in storage.

Storage of gas cylinders outside an enclosure is also associated with the smoke compartment as defined per NFPA 101; each smoke compartment can have medical gas cylinders up to 300 ft³ out of enclosure storage. For example, if a single floor of a medical facility has two smoke compartments per NFPA 101, medical gas cylinders up to 600 ft³ can be out of an enclosure on the floor with a maximum of 300 ft³ in each smoke compartment. The storage requirements associated with the smoke compartment is further discussed in section 2.2.3.

2.2.2 Storage requirement difference between (< 300 ft³) and (300 ft³< and < 3000 ft³)

To understand the perspective of NFPA 99 (2018) on the storage requirements of medical gases up to 300 ft³, it may be useful to see the storage requirements of cylinders between 300 ft³ and 3000 ft³ which is the next level gas volume. This is because any distinctive difference in storage requirements between these two groups can represent the concerns of an increased volume of medical gases.

Based on the requirements specified in Table 1, for volumes larger than 300 ft³ and up to 3000 ft³, the three primary differences may be categorized as follows:

- Separation of oxidizing gases from combustibles/flammables
- Protection of cylinders from temperature and physical impact
- Removal of nearby ignition sources

Among these, the protection of cylinders from temperature and physical impact is generally required for the gas volumes up to 300 ft³ as well per NFPA 99 (2018), 11.3.6.2; typical ambient temperature in health care facilities is less than 52°C. Therefore, the requirements for the increased medical gas volumes are related to controlling ignitions sources and combustible/ flammable materials or gases near the medical gases. Based on this, one may argue that the storage requirements per NFPA 99 (2018) may need to be revisited if nearby ignition sources and additional combustibles do not increase the fire risk associated with medical gases in health care facilities.

2.2.3 Health care facilities

Per NFPA 99 (2018), A.3.3.71, Health care facilities are defined as below.

*A.3.3.71 Health Care Facilities. Health care facilities include, but are not limited to, hospitals, nursing homes, limited care facilities, clinics, medical and dental offices, and ambulatory health care centers, whether permanent or movable. This definition applies to normal, regular operations and does not pertain to facilities during declared local or national disasters. A **health care facility is not a type of occupancy classification as defined by NFPA 101. Therefore, the term health care facility should not be confused with the term health care occupancy.** All health care occupancies (and ambulatory health care occupancies) are considered health care facilities; however, not all health care facilities are considered health care occupancies, as **health care facilities also include ambulatory health care occupancies and business occupancies.***

Therefore, in addition to health care occupancy, relevant facilities to health care in ambulatory health care occupancies and business occupancies are also included in the health care facilities. Per NFPA 101 (2018): Life Safety Code, these occupancies are defined as below;

3.3.196.7 Health Care Occupancy. An occupancy used to provide medical or other treatment or care simultaneously to four or more patients on an inpatient basis, where such patients are mostly incapable of self-preservation due to age, physical or mental disability, or because of security measures not under the occupants' control.*

3.3.196.1 Ambulatory Health Care Occupancy. An occupancy used to provide services or treatment simultaneously to four or more patients that provide, on an outpatient basis, one or more of the following: (1) treatment for patients that renders the patients incapable of taking action for self-preservation under emergency conditions without the assistance of others; (2) anesthesia that renders the patients incapable of taking action for self-preservation under emergency conditions without the assistance of others; (3) treatment for patients who, due to the nature of their injury or illness, are incapable of taking action for self-preservation under emergency conditions without the assistance of others.*

3.3.196.3 Business Occupancy. An occupancy used for the transaction of business other than mercantile.*

Among these, the definition of business occupancy can be applied to multiple facilities as it has a broader definition. When it comes to health care facilities, it refers to a facility where no one will be present overnight but there would be three or fewer people who are not capable of self-preservation at any given time (*The New "Life Safety" Chapter-What It Applies to and How Organizations Can Comply with It.*, 2009). Common examples may include doctor's office, dentist office, physical therapy and rehabilitation centers, and outpatient clinics (*Fire Codes for Business*, 2019). Based on this, it is found that the storage requirements of medical gas cylinders in NFPA 99 (2018) are intended to be applied to the places where occupants may not be able to take action for self-preservation in case of fire. In this case, occupants might need assistance for evacuation

or to reach a safe place and therefore, NFPA 101, Life Safety Code, utilizes horizontal exits, which influences the building structure in such a way that each story would be divided into at least two separate compartments bounded by a smoke barrier. This protected compartment is called a smoke compartment (Hart, 2019).

2.2.4 Smoke compartment

The storage requirement of medical gas cylinders up to 300 ft³ in the context of the smoke compartment is found in NFPA 99 (2018), 11.3.6.1.

11.3.6 Storage for non-flammable gases with a total volume equal to or less than 8.5 m³ (300 ft³) shall comply with the requirements in 11.3.6.1 and 11.3.6.2.”

*11.3.6.1 Individual cylinder storage associated with **a smoke compartment in accordance with NFPA 101** shall not be required to be stored in enclosures.*

This requirement is only applied to a single smoke compartment. In a large floor area where multiple smoke compartments exist, the total medical gas volumes out of an enclosure on the floor can be larger than 300 ft³. Despite the increased medical gas volume, it should be noted that the fire risk from the medical gases up to 300 ft³ is assumed to be accepted for a single compartment,

Per the NFPA 101 (2018), the smoke compartment size is defined in detail. In this document, general requirements are excerpted below for each occupancy.

- For new health care occupancy,

18.3.7.1 Buildings containing health care facilities shall be subdivided by smoke barriers (see 18.2.4.3), unless otherwise permitted by 18.3.7.2, as follows:

(1) To divide every story used by inpatients for sleeping or treatment into not less than two smoke compartments

(2) To divide every story having an occupant load of 50 or more persons, regardless of use, into not less than two smoke compartments

(3) To limit the size of each smoke compartment required by 18.3.7.1(1) and 18.3.7.1(2) to an area not exceeding one of the following:

(a) 22,500 ft² (2100 m²), in hospital smoke compartments where any patient sleeping room is configured for two or more patients

(b) 40,000 ft² (3720 m²) in hospital smoke compartments where all patient sleeping rooms are configured for only one patient, in which case suites in accordance with 18.2.5.7 shall be permitted where every occupiable sleeping room within the suite is configured for only one patient

(c) 40,000 ft² (3720 m²) in hospital smoke compartments that contain no patient sleeping rooms

(d) 22,500 ft² (2100 m²) in nursing homes and limited care facilities

For existing health care occupancy, the specifications of the smoke compartment are not different, but the smoke compartment is required for the story having an occupant load of 30 or more.

- For ambulatory health care occupancy,

20.3.7.2 Every story of an ambulatory health care occupancy shall be divided into not less than two smoke compartments unless otherwise permitted by one of the following:

(1) This requirement shall not apply where the area of the ambulatory health care occupancy is less than 5000 ft² (465 m²) per story and that area is protected by an approved automatic smoke detection system.

(2) This requirement shall not apply where the area of the ambulatory health care occupancy is less than 10,000 ft² (929 m²) per story and the building is protected throughout by an approved, supervised automatic sprinkler system installed in accordance with Section 9.7.

(3) An area in an adjoining occupancy shall be permitted to serve as a smoke compartment for an ambulatory health care occupancy if all of the following criteria are met:

(a) The separating wall and both compartments meet the requirements of 20.3.7.

(b) The ambulatory health care occupancy does not exceed one of the following:

(i) 22,500 ft² (2100 m²)

(ii) 40,000 ft² (3720 m²) in buildings protected throughout by an approved, supervised automatic sprinkler system in accordance with Section 9.7

(c) Access from the ambulatory health care occupancy to the other occupancy is unrestricted.

Specifications for the smoke compartment size are identical to health care occupancy. However, some differences are identified in terms of the size of the occupancy that requires smoke compartments. For existing ambulatory health care occupancy, the general requirements and specifications are not different from the above.

- For business occupancy,

There is no requirement of smoke compartments in new and existing business occupancies per NFPA 101 (2018). This may be fine as most business occupancy for health care purposes is relatively small buildings and no sleeping occupants are typically assumed.

The maximum floor area of a single smoke compartment is generally 22,500 ft² but can be up to 40,000 ft² with additional requirements satisfied. Note that the medical gas volumes up to 300 ft³ do not have to be stored in an enclosure in a single smoke compartment.

2.2.5 Separation of gas cylinders

NFPA 99 (2018) requires a separation between oxidizing gases and combustibles or flammable materials as below.

11.3.5.3 Oxidizing gases such as oxygen and nitrous oxide shall be separated from combustibles or flammable materials by one of the following:

(1) Minimum distance of 6.1 m (20 ft)

(2) Minimum distance of 1.5 m (5 ft) if the entire storage location is protected by an automatic sprinkler system designed in accordance with NFPA 13

(3) A gas cabinet constructed per NFPA 30 or NFPA 55, if the entire storage location is protected by an automatic sprinkler system designed in accordance with NFPA 13

This separation requirement is due to the concern of increased burning rate in the oxygen-enriched environment. Per NFPA 99 (2018), A.3.3.12.2,

A.3.3.12.2 Atmosphere of Increased Burning Rate. The degree of the fire hazard of an oxygen-enriched atmosphere varies with the concentration of oxygen and diluent gas and the total pressure. The definition contained in the current edition of NFPA 53 and editions of NFPA 56D before 1982 did not necessarily reflect the increased fire hazard of hyperbaric and hypobaric atmospheres.

The definition of the atmosphere of the increased burning rate used in Chapter 14 and NFPA 99B defines an oxygen-enriched atmosphere with an increased fire hazard as it relates to the increased burning rate of material in the atmosphere. It is based on a 1.2 cm/sec (0.47 in./sec) burning rate (at 23.5 percent oxygen at 1 atmosphere absolute) as described in Figure A.3.3.12.2.

Besides, it also requires separation of ignition sources in or near the storage as below. The reason for this is quite obvious to reduce the probability of a potential fire.

11.3.5.6 Smoking, open flames, electric heating elements, and other sources of ignition shall be prohibited within storage locations and 6.1 m (20 ft) of outside storage locations.

Therefore, one of the key concerns in the case of the unintended release of oxidizing gases is to keep the oxygen concentration below 23.5 Vol%. The calculation for oxygen concentration is further discussed in section 4.2.

3 Hazard identification

3.1 Generic hazards associated with medical gas storage

The objective of this section is to identify generic hazards due to gas leakage and accumulation of gases in the smoke compartment. Definition of hazard as stated in a publication by the British Compressed Gases Association (BCGA) is “any substance, condition or equipment that has the potential to cause harm to an individual or the environment” (*The Management of Risk When Using*

Gases in Enclosed Workplaces, 2018). The hazards in an enclosure such as a smoke compartment containing pressurized medical gases are listed below.

Table 2: Potential hazards from pressurized medical gases

Hazard	Medical gases
Oxidizing	Boost materials to burn robustly Ex: O ₂ , N ₂ O
Pressure	Permissible stored pressure of the medical gas cylinders up to 300 bar. Ex: for all gases
Asphyxiation	Gases listed below can cause oxygen deficiencies in the environment. Ex: N ₂ , CO ₂ , N ₂ O

3.1.1 Oxidizing hazards

Oxidizing gases such as oxygen or nitrous oxide can leak out of cylinders and increase oxygen concentration of the surrounding environment. Since oxygen has a high affinity with free radicals, it can accelerate combustion phenomena by rapidly reacting with free radicals generated from combustible materials in the fire. Note that oxygen is not a flammable gas but necessary gas for fire, and as a result, supports the combustion of normal materials. Nitrous oxide is a nonflammable and weak oxidizing agent but it breaks down to oxygen and nitrogen around 300°C (572 F) supporting combustion (PubChem, 2020). In a health care facility, flammable material is profusely available such as bed linens, mattresses, gowns, etc. Those materials, when saturated, can burn readily, releasing a higher amount of heat. Oxidizing gases other than oxygen can be toxic to inhaling individuals and can result in pulmonary edema (*Oxidizers Chemical Hazards and Risk Minimization*, 2019).

3.1.2 Pressure hazard

Medical gases are usually stored in cylinders and the pressure inside a full cylinder can range from 51 bar (745 psig) - 172 bar (2500 psig) according to A.11.3.4, NFPA 99 (2018). Individuals handling the cylinders have to be extremely cautious because of this high pressure. If improperly handled, a severe and deleterious incident may occur due to the high escaping velocity of the gas; the cylinder can be projected in the opposite direction. A damaged cylinder can lead to cylinder projectile incidents with the cylinder rocketing a distance of around 300 meters (*Scottish Health Technical Memorandum*, 2015).

3.1.3 Asphyxiation hazard

Oxygen is the only gaseous component of air that sustains life and should be present in a concentration of 20.9%. In enclosures such as smoke compartments, if the ventilation is faulty, a leakage of other medical gases such as nitrogen, nitrous oxide, helium, and carbon dioxide can replace the atmospheric oxygen. This can lead to oxygen-deficient atmospheres resulting in the risk of asphyxiation. The deleterious health effects of inhaling reduced oxygen concentrations are explained in Table 3 (McManus, 2009).

Table 3: Health outcomes of getting exposed to oxygen-deficient atmospheres.

Atmospheric O ₂ %	Health outcomes
16.0 - 20.9	No significant symptoms can be identified.
14.1 – 16.0	Increased heart/ breath rate and breathing volume, loss of coordination, impaired attention, and thinking
12.1 - 14.0	Abnormal fatigue upon exertion, impaired judgment, faulty coordination
10.1 - 12.0	Very poor judgment/ coordination, permanent heart damage, nausea, vomiting
< 10	Nausea, vomiting, perhaps unconsciousness, the inability to perform movements, death
< 6	Convulsions, difficulty breathing cardiac standstill, spasmodic breathing, death in minutes
< 4	Unconsciousness after one or two breaths

3.2 Previous incidents related to medical gas cylinders

Previous incidents related to the storage of medical gas cylinders are reviewed below. The type of incidents may be largely categorized into four groups: mechanical failure of cylinders, fire with the medical gas release, misuse and mislabeling of gas contents, and other miscellaneous incidents. For each category, a brief description of the incident is included.

a. Explosion generating projectiles

- In October 2006, an oxygen medical gas cylinder exploded in a refilling facility, claiming three lives and leaving one injured who worked 25 feet away from the others. The incident occurred when the oxygen cylinder was placed on the floor after being lifted. The cause was not found. The remains of the ruptured cylinders were found 40 ft away from the

facility. All the walls and the roof of the medical gas refilling area were severely damaged due to the explosion (Gupta & Jani, 2009).

- The pressure valve was detached from a 4.5 ft tall compressed oxygen cylinder while it was rolled by a lorry driver in an oxygen manufacturing facility. The compressed oxygen burst out of the cylinder's valve hole after the valve was disengaged and hit the driver's abdomen, killing him after being projected about 25 ft. In this incident, it was evident that proper procedures for handling the cylinders were not followed. No fire or explosion was recorded (Tabin & Sharma, 2013).

b. Fire with oxidizing gas release

- In 1993, a respirator supplying oxygen to a patient exploded in a medical center, Brooklyn, NY. It led to a fire, killing 3 in-house patients; two of them died of burns and the other due to inhalation of smoke. Several hours before the explosion occurred, the hospital engineers tried to fix the respirators based on the complaints of the nurses that the respirator was giving electrical shocks. The respirator which could not be fixed properly led to a fierce fireball in an oxygen-rich environment. (Chao & Henshaw, 2002; Wolff, 1993).
- A fire incident occurred in 2012 at the Royal United Hospital, Bath, the UK, when an ICU patient was being transferred to another hospital. The temporary oxygen supply was connected from a CD-size oxygen cylinder placed close to the feet of the patient and connected properly to the patient's respiratory system. According to the statement of the officer, he heard an abnormal hissing sound when he tried to manipulate the valve. Followed by the large hiss, a spark from the O₂ cylinder outlet was created. This generated a four-foot-long flame resulting in a fire over the bed linen and the rest of the compartment. The medical officer was able to extinguish the fire using fire extinguishers (Kelly et al., 2013).
- In September 2008, a fire and explosion occurred in the ICU at the Great Ormond street hospital, London, UK. This ICU could accommodate 4 patients, but no one was present at the time of the incident. Allegedly, an electrical fault in the ICU television started the fire. Plenty of used and abandoned high-pressure oxygen cylinders, separate oxygen supply lines, and an ample amount of combustible materials such as toys were in the ICU. The fire, spread by the combustible materials, heated the oxygen cylinders in the room, eventually causing the oxygen tanks to explode and initiated a massive fire (Ralph, 2012)

c. Misuse or mislabeling

- In 2000, four patients died and six were injured due to asphyxiation in a nursing home in Ohio; a nitrogen cylinder was mislabeled as an oxygen cylinder. The nursing home supposedly received four new oxygen cylinders, however, one of them was nitrogen; the nitrogen label was covered by the oxygen label (Food and Drug Administration, 2006).
- In 1997, a hospital in Nebraska received a portable oxygen cylinder shipment, with additional argon cylinders in it. An employee connected argon cylinders to the oxygen system by mistake. A patient who was undergoing surgery died as a result of this (Food and Drug Administration, 2006).

d. Others

- In November 2011, an oxygen cylinder exploded in the Intensive Care Unit of Bath Royal United Hospital, UK. The reason for the explosion is unknown. A patient got burnt from this explosion and several staff members inhaled smoke (Nelson, 2011).
- In 1987, a magnetic resonance projectile accident occurred in a Magnetic Resonance Imaging (MRI) room. A patient was undergoing imaging on the MR table while receiving oxygen through an oxygen cylinder. The cylinder was kept in an MR protected area. The medical officer on duty noticed that the cylinder was short of oxygen and asked another staff to bring in a new oxygen cylinder. With the hope of replacing the cylinder soon, he kept the cylinder in a place where the MR protection was not available. The magnetic power dragged the cylinder from the cart towards the MR machine. The cylinder hit the MR table, the front panel. Luckily, the patient survived the collision (Chaljub et al., 2001).

Based on these previous incidents, there is certain fire risk associated with medical gas release, especially with oxygen cylinders. However, available incident records are not abundant. Assuming most critical fires have been reported for the past several decades, it is conjectured that the actual number of fire incidents involved with medical gas release may not be significant. Other supporting data for this may be found in Table 4 which includes a list of reasons for the medical gas cylinder disasters from 1972 to 1994. It is identified that most of the cases had been the result of careless handling and inappropriate usages of medical gas cylinders. Disasters directly related to the excess storage or leakage of medical gas cylinders are rare in recorded history.

Table 4: Medical gas cylinder near hits at healthcare sites in the US and other countries from 1972-1994 (Petty, 1995).

Problem	Number of incidents	
	United States	Other countries
Wrong gas in the cylinder	2	4
Foreign substances in gas cylinder	3	2
Mislabeled gas cylinder	1	3
Overfilled nitrous oxide cylinders	1	2
Yoke modified	2	-
Pin altered or missing from oxygen pin index safety system York	-	2
Mislabeled or switched diameter index safety system connectors	1	1
Leak at nitrous oxide gasket	1	-
Washers used to bypass pin index safety system	1	-
Nitrogen cylinders with the same thread as oxygen	-	1
Oxygen pin index safety system used for nitrous oxide cylinder	-	1
Refilling oxygen cylinders at hospital site without any pin index safety system safeguards	-	1
No reducing valve used for oxygen flowmeter	-	1

4 Hazard assessment

Although hazards associated with stored medical gases are identified above in Section 3, how to assess the hazards with regards to the storage quantity was unclear. Generally, as the quantity of medical gas cylinders stored outside of an enclosure increases, the risk presented by the medical gas storage increases as well. This is because of associated risks, including mishandling and mislabeling of the cylinders, malfunctioning or inherent defects of the cylinders, and their probability of being exposed to fire (even with its low probability of occurrence), increases as the storage amount increases. Therefore, the focus of assessing the risk is not about quantification of existing hazards, but about assessing whether 300 ft³ requirement is appropriate, too stringent, or too conservative.

In addition, it is not known how the number of 300 ft³ was initially determined. In some cases, the values specified in codes are supported with a concrete scientific background such as experimental results. But in other cases, they are determined based on a consensus agreement among the relevant code's technical committee members. In the latter case, the specified values often lack scientific validation but are still well accepted until a tragic incident occurs or a new technical justification is found. Since the 300 ft³ medical gas volume seems to be the latter case, it is necessary to look into the level of risk that this requirement has imposed through relevant statistical data. In addition to this, the current study also investigates mathematical correlations to better understand how much oxygen should be released to reach a critical point and how long it would take to dilute it to reach a safe condition. This calculation does not give any absolute values of allowable storage amount but provides an estimated amount that we may need to start to be concerned about.

4.1 Fire data related to healthcare facilities

Every fire requires three main elements; fuel, ignition source/ heat, and oxygen/ oxidizer (*Hospital Fire Prevention and Evacuation Guide*, 2018). These three elements are often readily available in healthcare facilities, which puts these facilities at risk of having an incident. This section provides details on fuel, ignition, and oxidants available in the healthcare facilities and the analysis of previous fire incidents occurred in recent history.

4.1.1 Fuel sources available in healthcare facilities

Healthcare facilities use various types of materials for their day-to-day works. Basic materials to be used in healthcare facilities are listed below (*Medical Device Safety Report (MDSR)*, 1992)

- Linen: gowns, masks, shoe covers, blankets, mattresses, and pillows, etc.
- Dressings: sponges, bandages, etc.
- Equipment/ supplies: flexible endoscopes, gloves, stethoscope tubes, etc.
- Paper: documents, patient's reports, and stationery, etc.
- Wood: bed: nurses' stations, furniture, etc.
- Liquids: white wax, alcohol-based skin preparations, alcohol-based antiseptic, other combustible liquids, etc.
- Gases: flammable gases, natural gases, gasoline, etc.
- Rubber/ plastic: suction tubes, drug packaging, etc.
- Other: GI gas, polystyrene and polyurethane (emits toxic gases when burning)

The majority of the above substances are combustible material although some alcohol-based liquids are highly volatile and flammable. Apart from this, the basic structures already built within the healthcare facility such as lightweight wooden frames, wooden floorings, plastic partitions are also valid fire fuels.

In BS EN 1991-1-1-2:2002 (or EN 1991-1-2:2002), estimated fire loads are presented per occupancy. Note that this is based on European cases, therefore, it may be different from those in the US, but it is meaningful to see what the relative fuel loads in healthcare-related facilities present

in comparison to other occupancies. The fire load density shown in Table 5 is excerpted from the BS code and represents the total energy of fuel per unit floor area.

Table 5: Fire load densities (Table E.4 from BS EN 1991-1-1-2:2002)

Occupancy	Average [MJ/m ²]	80% fractile [MJ/m ²]
Dwelling	780	948
Hospital (room)	230	280
Hotel (room)	310	377
Library	1500	1824
Office	420	511
Classroom of a school	285	347
Shopping center	600	730
Theater (cinema)	300	365
Transport (public space)	100	122

It is found that the fuel load density of the hospital(room) is relatively low when compared with other occupancies. For other spaces in hospitals such as nurses stations, the fuel load density is not informed, but it may be considered equivalent to office occupancy taking into account the characteristics of the space's use.

4.1.2 Ignition sources available in healthcare facilities

Ignition sources play a critical role in initiating a fire. Even though the combustible materials are readily available, fire rarely occurs without the presence of the ignition source. Healthcare facility uses a variety of medical and non-medical equipment that may generate sparks or heat to initiate fire. Major causes for the structure fires in healthcare facilities are presented in Table 6 for three-difference periods: 1999-2001, 2006-2010, and 2011-2015.

Table 6: Structure fires in health care facilities by leading cause (Campbell, 2017; Kampmier, 2005; Statistics On Main Causes Of Fire, 2015).

Cause	1999-2001	2006-2010	2011-2015
Cooking /cooking equipment in kitchen	33.9 %	61 %	66.0 %
Smoking materials	8.2 %		5.0 %
Intentional	12.0 %	6 %	6.0 %
Electrical appliances/ Electrical	9.4 %		6.0 %
Other known causes	9.2 %	7 %	7.0 %
Open flame	14.9 %		
Other Appliances	12.4 %		

Cooking/cooking equipment in the kitchen is responsible for most recent fire incidents in healthcare facilities and its percentage has been increasing over time. Considering other main causes presented in Table 6, there are no other particular locations identified with high vulnerability. This may mean that fire risk associated with the stored oxygen cylinders may not be significantly influenced as long as they are not stored in the kitchen area or anywhere else that cooking equipment are used in the healthcare facilities.

4.1.3 Oxygen/ oxidized sources available in healthcare facilities

Oxygen or nitrous oxide can exacerbate fire when both combustible material (fuel) and an ignition source are present. Healthcare facilities use several methods to store oxygen such as compressed gas cylinders, oxygen concentrators, liquid oxygen, or manifold cylinder bank (Gardner, 2013; Hardavella et al., 2019). Nitrous oxide is often stored in a compressed gas cylinder (Gardner, 2013). It can be classified as anesthesia, cryosurgery, respiratory and medical imaging by its application and it is an essential substance for surgeries. The market size for some of the medical gases is presented in Figure 1. For oxygen, it has increased by about 24% from \$275 Million to \$340 Million over the three years, 2012 – 2015. The demand of those gases is expected to increase further with the increasing trend on the surgeries (*Medical Gas and Equipment Market Trends and Forecast to 2026 – TMR*, 2018).

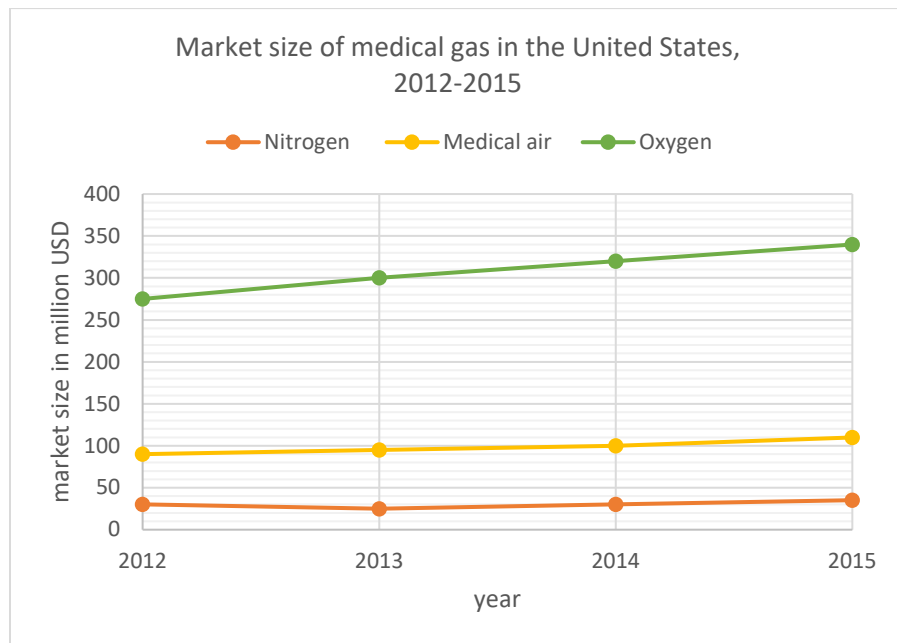


Figure 1: Medical gas market size, 2012-2015

4.1.4 Detail on fire disasters and deaths in the healthcare facilities in recent history

The statistics on the structure fires in facilities caring for the sick between 1980 to 2001 and in healthcare facilities are shown in Figure 2 and Figure 3 (Campbell, 2017; Kampmier, 2005). The

incidents in nursing homes and residential board and care facilities are not included in the data from 1980 to 2001, which is why the number of fires in 2001 from Figure 2(A) is larger than the number of fires in 2003 in Figure 2(B). It is, however, clearly shown that the number of fires has been continuously decreasing since 1980. The period from 2003 to 2015 shows a relatively consistent number of fires in healthcare facilities.

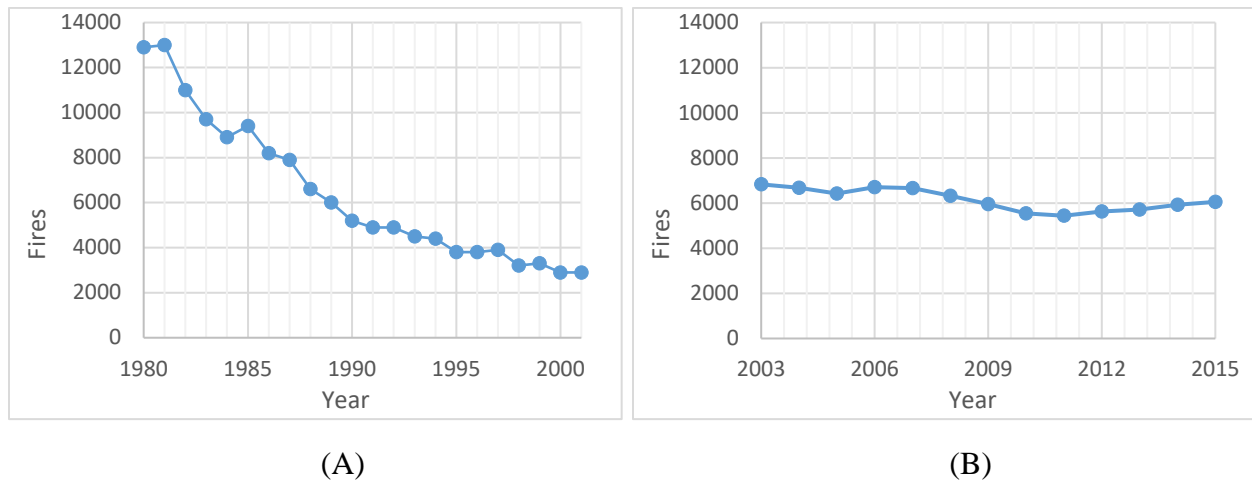


Figure 2: (A) Number of structure fires in facilities that care for the sick excluding nursing homes and residential care facilities 1980–2001 (Kampmier, 2005), (B) number of structure fires in healthcare facilities 2003–2015 (Campbell, 2017)

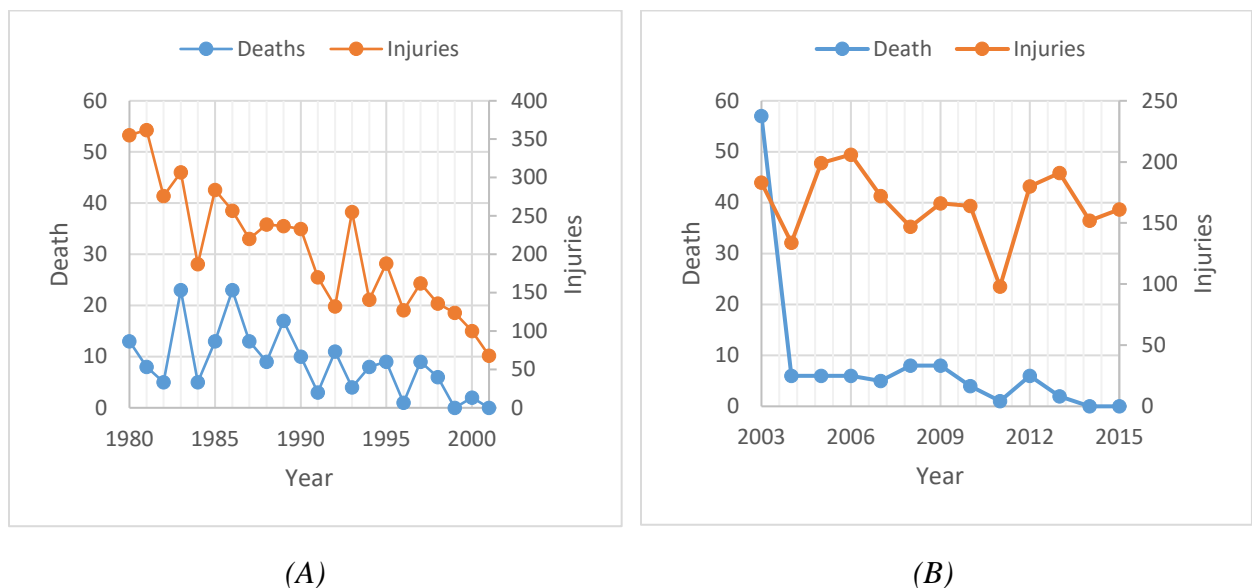


Figure 3: Number of deaths and injuries in facilities that care for the sick excluding nursing homes and residential care facilities 1980–2001 (Kampmier, 2005), (b) number of deaths and injuries in health care facilities 2003–2015 (Campbell, 2017)

The trend of decreasing the number of fires is also reflected in the number of deaths and injuries of civilians as shown in Figure 3. From Figure 3(B), except for 2003 which is an exception

compared to other years, the number of death is less than 10 per year. Besides, in some years such as 1999, 2001, 2014, and 2015, no deaths were recorded in health care facilities.

4.1.5 Summary

Based on the fire statistics and other data sources for healthcare facilities, the fire hazards associated with medical gases seem to be relatively low;

- Fuel load is lower than most other occupancies.
- The most probable fire cause in healthcare facilities is related to cooking equipment in the kitchen area where oxygen cylinders are not expected to be stored. Further, no literature provides concrete data that medical gas has significantly contributed as a cause of healthcare facility fires.
- An oxygen-enriched condition is certainly a major concern and medical gases such as oxygen or nitrous oxide can contribute to this. However, there is no clear relationship between the amount of oxygen used and the number of fires or deaths/injuries based on Figure 1, Figure 2(B), and Figure 3(B). Note that oxygen usage shows an increasing trend while the number of fire incidents and corresponding death/injury rate is relatively constant.

4.2 Quantitative hazard assessment focusing on oxygen concentration

The following ventilation calculation estimates the oxygen concentration overtime after a failure of oxygen cylinder which results in a sudden release of oxygen in the compartment. Oxygen is naturally present in the air at a concentration of 20.95%. Per NFPA 99 (2018), 3.3.129, atmospheres where the oxygen concentration exceeds 23.5% are considered Oxygen Enriched Atmospheres (OEA) which significantly increases the burning rate of materials or combustibility. Factors that determine the oxygen concentration in a compartment include:

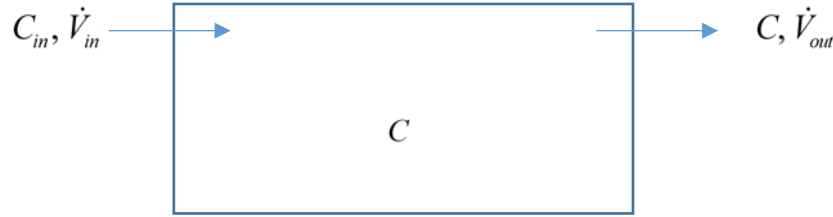
- The amount of oxygen released [g]
- The duration of oxygen release [s]
- The volume flow rate of ventilation or fresh air [m^3/s]
- The volume of the compartment where oxygen is released [m^3]

The worst-case scenario for the first two items would be a sudden failure of oxygen cylinders, i.e., a large amount of oxygen released in a very short period. The third item is related to the air change rate, often denoted as ACH (air change rate per hour). In healthcare facilities, ACH varies with space usage, but typically ranges from 6 – 20 (ASHRAE 170, 2008; Ninomura, 2001). The last item, the compartment size, may be a single patient room or an entire smoke compartment, which can be up to 40,000 ft^2 . The average single patient room size in the US is 320 ft^2 , which forms the compartment volume of 2880 ft^3 (or approximately 85 m^3) assuming a 9 ft (2.7m) high ceiling (*Best of 2014: Increasing Patient Satisfaction by Decreasing Patient Room Size*, 2014; *Space Standards & Dimensions*, 2015).

Based on this, the following oxygen release and dilution scenario is investigated;

A sudden oxygen release from only one fully charged E-sized cylinder to a room that has a volume of 2880 ft³ (320 ft² large and 9 ft high) with 8 air changes per hour (ACH).

The typical air changes per hour in hospitals is at a minimum of 6 ACH, but “normal stable unoccupied control can be found with 8 ACH” which is used for the calculation. Based on these parameters, the oxygen concentration is calculated as below (Doyle & Villani, 2015; Villani, 2014)



Where,

C_{in} = oxygen concentration in the air flow into the compartment [$\approx 280 \text{ g/m}^3$]

C = oxygen concentration within the compartment [g/m³]

\dot{V}_{in} = air flow rate into the compartment [m³/s]

=8 ACH corresponds to the flow rate of $\frac{8V}{3600}$ [m³/s]

\dot{V}_{out} = air flow rate out of the compartment [m³/s] = \dot{V}_{in}

V = compartment volume [m³]

K_{mix} = mixing factor

For perfect mixing condition, $K_{mix} = 1$

For 50% mixing efficiency, $K_{mix} = 2$

Assuming that the sudden oxygen release within the compartment, the governing equation becomes as below.

$$G.E.: \frac{d}{dt}(CVK_{mix}) = C_{in}\dot{V}_{in} - C\dot{V}_{out}$$

$$I.C.: C = C_{init}$$

Solving for compartment oxygen concentration, C , at time t [s],

$$C = C_{in} + (C_{init} - C_{in})\exp\left(-\frac{\dot{V}_{in}}{K_{mix}V}t\right)$$

Table 7: Type E medical Gas Cylinder Technical Information (Technical Information/Medical Gas Cylinders, 2010)

Contents	Medical Air	Carbon Dioxide	Helium	Nitrogen	Nitrous Oxide	Oxygen
Cubic Feet	23.5	56.2	22	23	56.2	24.9
Cubic Meters	0.65	1.56	0.61	0.64	1.56	0.69
Liters (L)	650	1,560	610	640	1,560	690
Gallons (gal)	172	412	161	169	412	182
Pounds (lb)	1.76	6.44	0.23	1.67	6.44	2.06
Kilograms (kg)	0.8	2.92	0.1	0.76	2.92	0.93

Assuming that one E size cylinder contains approximately 930 g of oxygen from Table 7 above and well-mixed condition ($K_{mix}=1$), the initial condition is as below.

$$C_{in} \approx \frac{(0.233)(1191 \text{ g/m}^3)(85 \text{ m}^3)}{85 \text{ m}^3} = 278 \text{ g/m}^3$$

$$C_{init} \approx \frac{(0.233)(1191 \text{ g/m}^3)(85 \text{ m}^3) + (930 \text{ g/cylinder})(1 \text{ cylinder})}{(85 + 0.7) \text{ m}^3} = 286 \text{ g/m}^3$$

Assuming that air consists of only oxygen (MW=32 g/mole) and nitrogen (MW=28 g/mole), i.e., $xO_2 + (1-x)N_2$ for 1 mole of air and behaves ideally, the oxygen concentration [g/m³] can be converted to volume percent based on the following correlation.

$$O_2 \text{ Vol \%} = 100 x, \text{ and } C [\text{g/m}^3] = \frac{P(32x)}{8.314T}$$

$$\Rightarrow \text{Vol \%} = \frac{100(8.314T)C}{32P} = 25.98 \frac{TC}{P}$$

Assuming 1 atm(=101325Pa) and 298K,

$$\text{Vol\%} \approx 0.0764C$$

Based on these correlations, the oxygen concentration is shown in Figure 4. Note that scenario 2 is more realistic.

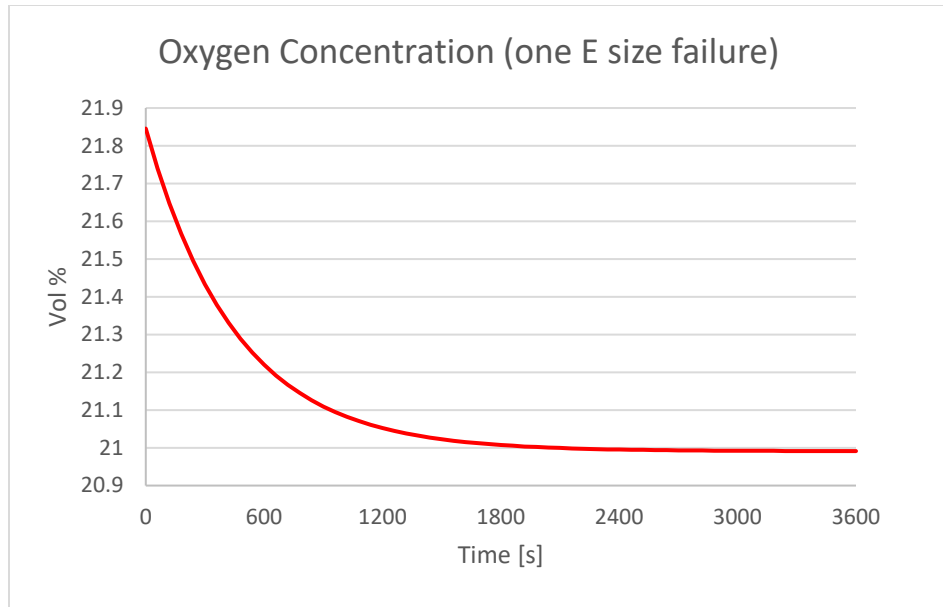


Figure 4: Estimated oxygen concentration after one size E oxygen cylinder failure in a 320 ft² large and 9 ft high compartment

The maximum value O₂ concentration right after the entire release of one fully charged E-sized cylinder is less than 21.9 Vol %, which is about 1 Vol% higher than the normal oxygen concentration. This indicates that a failure of one E size cylinder in a compartment of 320 ft² does not increase the oxygen concentration to the degree that reactivity of oxygen becomes a significant concern.

Following the same calculation method, the failure of three E-sized cylinders is required to increase the oxygen concentration above 23.5 % in the same compartment. It would take about 30 minutes for the oxygen concentration to get back to the normal oxygen concentration with 8 ACH. Considering that the probability of fire occurrence during these 30 minutes is very low, the risk associated with the increased oxygen concentration is not deemed significant.

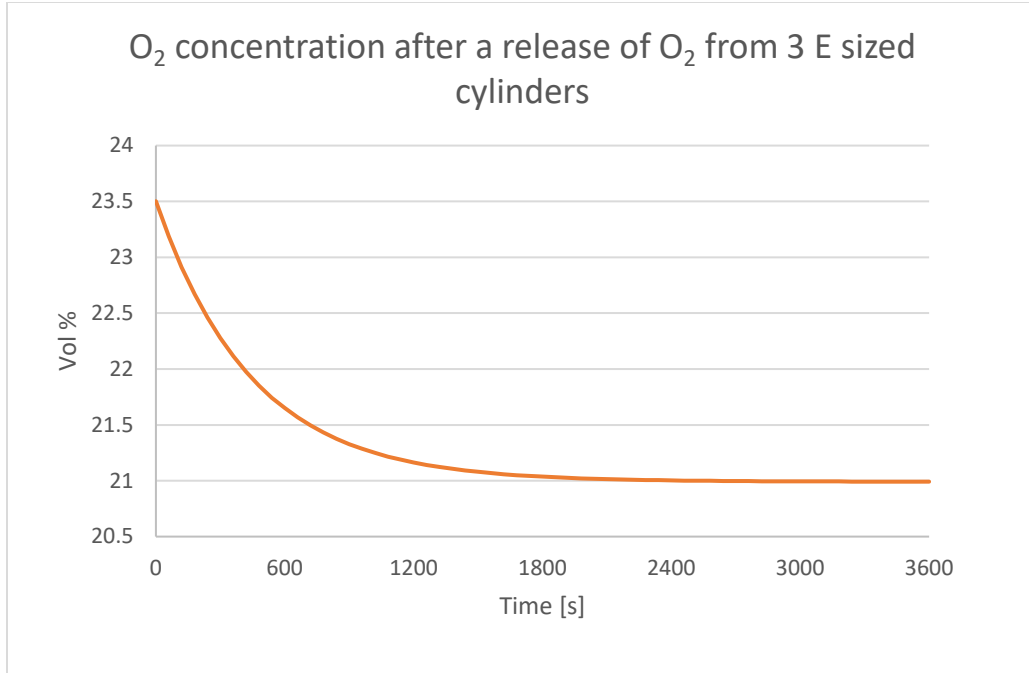


Figure 5: Estimated oxygen concentration after three E-sized oxygen cylinder failure in a 320 ft² large and 9 ft high compartment

The 300 ft³ medical gas volume is often considered equivalent to 12 E-sized cylinders. If all the oxygen from 12 E-sized cylinders was released in a 320 ft² large and 9 ft high compartment, the initial oxygen concentration becomes 31.3 %, which is much higher than the 23.5% threshold value. This means that the maximum number of oxygen cylinders that can fail and not exceed the threshold value of 23.5%, varies depending on the compartment size. In Figure 6 below, the number of E-sized oxygen cylinders that results in a 23.5% oxygen concentration for varying compartment volumes is calculated, assuming all the oxygen from the cylinders is released. The following correlation shows the relationship between them.

The number of E – sized O₂ cylinders for 23.5 O₂ vol%

$$= \left(\frac{1}{990} \right) \times \text{compartment volume (ft}^3\text{)}$$

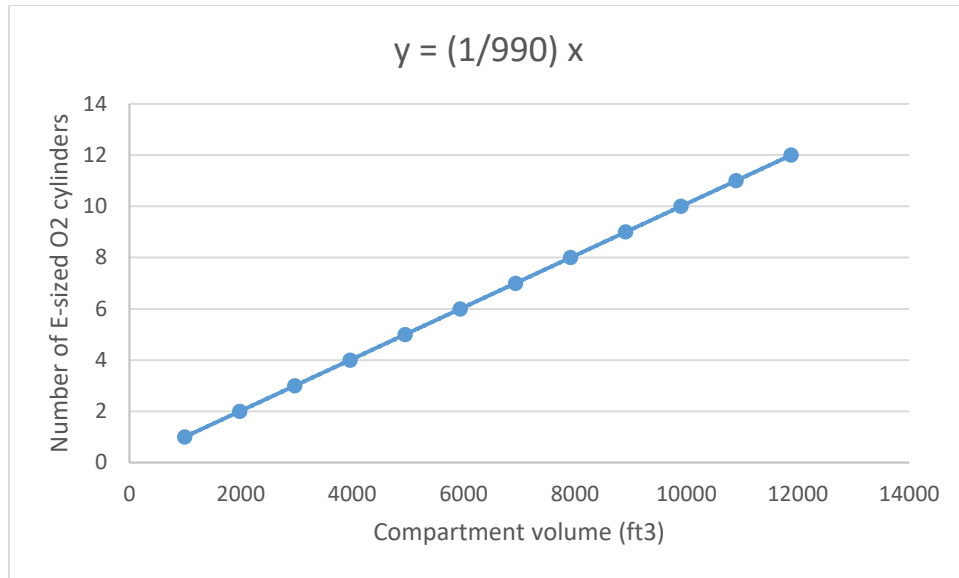


Figure 6: The number of fully charged E-sized oxygen cylinders resulting in 23.5 oxygen Vol% for varying compartment volumes

Based on the quantitative analysis for oxygen concentration in the case of oxygen release cylinders' failure, it is found that the fire risk by increased oxygen concentration may not be significant. At least a failure of three fully charged E-sized cylinders is necessary to cause oxygen concentration up to 23.5% in a typical patient room having a 320 ft² floor area with a 9 ft high ceiling; note that local oxygen concentration near the oxygen cylinders can be higher than this.

5 Discussion

The health care industry is changing rapidly as the world advances to accommodate the convenience of patients. The concept of micro-hospitals is one area that is showing positive trends. (*Micro Hospitals / Learn About A New Trend*, 2016). Micro hospitals are small-scale patient facility centers that have a wide range of medical services. Providing accommodation for a small number of patients admitted for a short stay is a significant factor in micro-hospitals. Since there are fewer patients in micro-hospitals, there will likewise be less equipment in these facilities than in regular hospitals. Micro-hospitals create an environment that is convenient for patients but also presents a lower vulnerability to the hazards present in hospitals. Fire risks within the micro-hospitals are relatively low due to the reasons above and result in a fewer number of individuals seeking aid upon a fire emergency. The use of medical devices at home is another increasing trend in the health care industry. However, despite these trends in the healthcare industry, the use of medical gases is increasing with time.

According to NFPA 101, the maximum size of a smoke compartment was permitted to be increased from 22,500 ft² to 40,000 ft² in areas where there are no patient rooms, or where the patient rooms are configured for only one patient. From the perspective of fire safety, this means that the number of people directly influenced by a fire is likely to be limited to those in the single patient room.

Further, there will be a lower quantity of medical equipment and combustible materials such that the ignition probability and fuel load are also limited by the single patient room.

6 Conclusion

In 2002, NFPA 99 designated 300 ft³ as the maximum volume of open medical gas storage in a smoke compartment, outside of a designated enclosure. In the current study, the hazards associated with medical gases was investigated through literature review and previous fire incidents. Based on the characterization of fuel, ignition source, additional oxygen source and the fire statistics in section 4.1, it is found that the oxygen concentration did not appear to be directly correlated to the actual fire risk. However, note that this conclusion is only based on the limited data assessed herein. In addition, for a typical single patient room (320 ft² large and 9 ft high), the failure of at least 3 E-sized oxygen cylinders are required to increase the oxygen concentration above 23.5%, the maximum threshold value per NFPA 99 (2018) as analyzed in section 4.2. Based on this, as long as the oxygen volume stored in a typical single patient room is below that equivalent to 3 E-sized oxygen cylinders, the fire risk due to an increased oxygen concentration is reduced to the level that NFPA 99 (2018) prescribes.

Based on this study, the authors suggest that actual and typical storage locations of medical gas cylinders be further investigated in healthcare facilities. This study can help NFPA identify recommended storage locations which, of course, should not be near the cooking equipment (kitchen area) or other appliances having a higher ignition probability.

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