

NFPA[®]

53

**Recommended Practice on
Materials, Equipment, and
Systems Used in Oxygen-Enriched
Atmospheres**

2016



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NFPA®53

Recommended Practice on

Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres

2016 Edition

This edition of NFPA 53, *Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres*, was prepared by the Committee on Oxygen-Enriched Atmospheres. It was issued by the Standards Council on November 14, 2015, with an effective date of December 4, 2015, and supersedes all previous editions.

This edition of NFPA 53 was approved as an American National Standard on December 4, 2015.

Origin and Development of NFPA 53

Development of NFPA 53 was initiated in 1965 largely as a result of interest in the area of oxygen-enriched atmospheres by the aerospace industry and medical personnel/researchers, who expressed a need for a single source of general data on the hazards of oxygen-enriched atmospheres.

The first edition was published in 1969 under NFPA procedures that did not require Association meeting action for NFPA documents. A second edition was formally adopted under NFPA procedures at the NFPA Annual Meeting in 1974. Subsequent editions were adopted in 1979, 1985, 1990, and 1994.

The 1994 edition reflected a complete review of the contents of the document and incorporated much new information gained by research at the National Aeronautics and Space Administration from 1984 to 1994.

The 1999 edition changed the document from a guide to a recommended practice. Also, some minor changes were made to the definitions of *oxygen-enriched atmosphere* and *ignition temperature*.

The 2004 edition of the recommended practice underwent editorial revisions to meet the NFPA *Manual of Style* and included only minor editorial changes.

The 2011 edition reconfirmed the provisions as they were written in the 2004 edition.

The 2016 edition adds heat of combustion and auto-ignition temperature data to the expanded table of nonmetallic materials for oxygen service. In addition, new fire experience reports have been added to Annex D.

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NOTE: Membership on a committee shall not in and of itself constitute an endorsement of the Association or any document developed by the committee on which the member serves.

Committee Scope: This Committee shall have primary responsibility for documents on the fire and explosion hazards that may exist in oxygen-enriched atmospheres. The Committee will correlate its work with the Committee on Health Care Facilities and other related NFPA committees as required.

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NOTICE: An asterisk (*) following the number or letter designating a paragraph indicates that explanatory material on the paragraph can be found in Annex A.

A reference in brackets [] following a section or paragraph indicates material that has been extracted from another NFPA document. As an aid to the user, the complete title and edition of the source documents for extracts in the recommendations sections of this document are given in Chapter 2 and those for extracts in the informational sections are given in Annex G. Extracted text may be edited for consistency and style and may include the revision of internal paragraph references and other references as appropriate. Requests for interpretations or revisions of extracted text should be sent to the technical committee responsible for the source document.

Information on referenced publications can be found in Chapter 2 and Annex G.

Chapter 1 Administration

1.1 Scope. This document establishes recommended minimum criteria for the safe use of oxygen (liquid/gaseous) and the design of systems for use in oxygen and oxygen-enriched atmospheres (OEAs).

1.2 Purpose. The purpose of this recommended practice is to provide information for the selection of materials, components, and design criteria that can be used safely in oxygen and OEAs.

1.3 Application. This recommended practice is applicable to the selection of materials and components, and to the design of new systems associated with OEAs. Such applications include, but are not limited to, gas and compressed air

supplies, spaceflight operations, industrial processes, welding applications, self-contained breathing apparatus (SCBA), self-contained underwater breathing apparatus (SCUBA), medical applications (including home assisted-breathing apparatus), underwater tunneling and caisson work, and commercial and military aviation.

1.4 Interpretations. The National Fire Protection Association does not approve, inspect, or certify any installation, procedure, equipment, or material. With respect to this recommended practice, and to fire and associated hazards in OEAs, its role is limited solely to an advisory capacity. The acceptability of a particular material, component, or system for use in an OEA is solely a matter between the user and the provider. However, to assist in the determination of such acceptability, the National Fire Protection Association has established interpretation procedures. These procedures are outlined in the NFPA Regulations Governing Committee Projects.

Chapter 2 Referenced Publications

2.1 General. The documents or portions thereof listed in this chapter are referenced within this recommended practice and should be considered part of the recommendations of this document.

2.2 NFPA Publications. National Fire Protection Association, 1 Batterymarch Park, Quincy, MA 02169-7471.

NFPA 51, *Standard for the Design and Installation of Oxygen-Fuel Gas Systems for Welding, Cutting, and Allied Processes*, 2013 edition.

NFPA 55, *Compressed Gases and Cryogenic Fluids Code*, 2013 edition.

NFPA 70®, *National Electrical Code*®, 2014 edition.

NFPA 90A, *Standard for the Installation of Air-Conditioning and Ventilating Systems*, 2015 edition.

NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*, 2015 edition.

NFPA 99, *Health Care Facilities Code*, 2015 edition.

NFPA 99B, *Standard for Hypobaric Facilities*, 2015 edition.

NFPA 496, *Standard for Purged and Pressurized Enclosures for Electrical Equipment*, 2013 edition.

2.3 Other Publications.

2.3.1 API Publications. American Petroleum Institute, 1220 L Street, NW, Washington, DC 20005-4070.

API 620, *Design and Construction of Large, Welded, Low-Pressure Storage Tanks*, 2013.

2.3.2 ASME Publications. American Society of Mechanical Engineers, Three Park Avenue, New York, NY 10016-5990.

ASME B31.3, *Process Piping*, 2012.

ASME B31.5, *Refrigeration Piping and Heat Transfer Components*, 2013.

ASME B31.8, *Gas Transmission and Distribution Piping Systems*, 2012.

ASME Boiler and Pressure Vessel Code, 2013.

2.3.3 CGA Publications. Compressed Gas Association, 14501 George Carter Way, Suite 103, Chantilly, VA 20151-2923.

CGA G-4, *Oxygen*, 2008.

CGA P-1, *Safe Handling of Compressed Gases in Containers*, 2008.

CGA S-1.1, *Pressure Relief Device Standards — Part 1 — Cylinders for Compressed Gases*, 2011.

CGA S-1.2, *Pressure Relief Device Standards — Part 2 — Cargo and Portable Tanks for Compressed Gases*, 2009.

CGA S-1.3, *Pressure Relief Device Standards — Part 3 — Stationary Storage Containers for Compressed Gases*, 2008.

2.3.4 U.S. Government Publications. U.S. Government Printing Office, Washington, DC 20402.

Title 49, Code of Federal Regulations, Part 173.301, “General Requirements for Shipment of Compressed Gases in Cylinders and Spherical Pressure Vessels,” 2013.

Title 49, Code of Federal Regulations, Part 173.302, “Charging of Cylinders with Non-Liquefied Compressed Gases,” 2013.

Title 49, Code of Federal Regulations, Part 173.337, “Nitric Oxide,” 2013.

Title 49, Code of Federal Regulations, Part 178.37, “Specification 3AA and 3AAX Seamless Steel Cylinders,” 2013.

Title 49, Code of Federal Regulations, Part 178.45, “Specification 3T Seamless Steel Cylinders,” 2013.

2.3.5 Other Publications.

Merriam-Webster’s Collegiate Dictionary, 11th edition, Merriam-Webster, Inc., Springfield, MA, 2003.

Phillips, B.R., “Resonance Tube Ignition of Metals,” Ph.D. Thesis, University of Toledo, Toledo, OH, 1975.

Pressure-Relieving Systems for Marine Cargo Bulk Liquid Containers, National Academy of Sciences, Washington, DC, 1973.

Schmidt, H. W.; and Forney, D. F. “ASRDI Oxygen Technology Survey, Volume IX: Oxygen Systems Engineering Review.” NASA SP 3090, NASA, Washington, DC, 1975.

2.4 References for Extracts in Recommendations Sections.

NFPA 68, *Standard on Explosion Protection by Deflagration Venting*, 2013 edition.

NFPA 921, *Guide for Fire and Explosion Investigations*, 2014 edition.

Chapter 3 Definitions

3.1 General. The definitions contained in this chapter apply to the terms used in this recommended practice. Where terms are not defined in this chapter or within another chapter, they should be defined using their ordinarily accepted meanings within the context in which they are used. *Merriam-Webster’s Collegiate Dictionary*, 11th edition, is the source for the ordinarily accepted meaning.

3.2 NFPA Official Definitions.

3.2.1* Approved. Acceptable to the authority having jurisdiction.

3.2.2* Authority Having Jurisdiction (AHJ). An organization, office, or individual responsible for enforcing the requirements of a code or standard, or for approving equipment, materials, an installation, or a procedure.

3.2.3* Code. A standard that is an extensive compilation of provisions covering broad subject matter or that is suitable for adoption into law independently of other codes and standards.

3.2.4 Labeled. Equipment or materials to which has been attached a label, symbol, or other identifying mark of an organization that is acceptable to the authority having jurisdiction and concerned with product evaluation, that maintains periodic inspection of production of labeled equipment or materials, and by whose labeling the manufacturer indicates compliance with appropriate standards or performance in a specified manner.

3.2.5* Listed. Equipment, materials, or services included in a list published by an organization that is acceptable to the authority having jurisdiction and concerned with evaluation of products or services, that maintains periodic inspection of production of listed equipment or materials or periodic evaluation of services, and whose listing states that either the equipment, material, or service meets appropriate designated standards or has been tested and found suitable for a specified purpose.

3.2.6 Recommended Practice. A document that is similar in content and structure to a code or standard but that contains only nonmandatory provisions using the word “should” to indicate recommendations in the body of the text.

3.2.7 Should. Indicates a recommendation or that which is advised but not required.

3.2.8 Standard. An NFPA Standard, the main text of which contains only mandatory provisions using the word “shall” to indicate requirements and that is in a form generally suitable for mandatory reference by another standard or code or for adoption into law. Nonmandatory provisions are not to be considered a part of the requirements of a standard and shall be located in an appendix, annex, footnote, informational note, or other means as permitted in the NFPA Manuals of Style. When used in a generic sense, such as in the phrase “standards development process” or “standards development activities,” the term “standards” includes all NFPA Standards, including Codes, Standards, Recommended Practices, and Guides.

3.3 General Definitions.

3.3.1 Activation Energy. The minimum energy that colliding fuel and oxygen molecules must possess to permit chemical interaction.

3.3.2 Autoignition or Autogenous Ignition Temperature. See 3.3.18, Ignition Temperature.

3.3.3 Combustible Material. A material capable of undergoing combustion.

3.3.4 Combustion. A chemical process of oxidation that occurs at a rate fast enough to produce heat and usually light in the form of either a glow or flame.

3.3.5 Concentration. The ratio of the amount of one constituent of a homogeneous mixture to the total amount of all constituents in the mixture.

3.3.6 Contaminant. A foreign or unwanted substance that can have deleterious effects on system operation, life, or reliability.

3.3.7 Deflagration. Propagation of a combustion zone at a velocity that is less than the speed of sound in the unreacted medium. [68, 2013]

3.3.8 Detonation. Propagation of a combustion zone at a velocity that is greater than the speed of sound in the unreacted medium. [68, 2013]

3.3.9 Diluent. A gas used to dilute or reduce the concentration of oxygen.

3.3.10 Fire. A rapid oxidation process, which is a chemical reaction resulting in the evolution of light and heat in varying intensities. [921, 2014]

3.3.11 Flame Propagation Rate. The velocity with which the combustion front travels through a body of gas, measured as the highest gas velocity at which stable combustion can be maintained, and the velocity at which combustion travels over the surface of a solid or liquid.

3.3.12 Flammable. A combustible that is capable of easily being ignited and rapidly consumed by fire. Flammables may be solids, liquids, or gases exhibiting these qualities.

3.3.13 Flammable Limits. The minimum and maximum concentration of fuel vapor or gas in a fuel vapor or gas/gaseous oxidant mixture (usually expressed as percent by volume) defining the concentration range (flammable or explosive range) over which propagation of flame will occur on contact with an ignition source. The minimum concentration is known as the lower flammable limit (LFL) or the lower explosive limit (LEL). The maximum concentration is known as the upper flammable limit (UFL) or the upper explosive limit (UEL).

3.3.14 Flash Point. The minimum temperature of a liquid or solid at which it gives off vapor sufficient to form an ignitable mixture with a gaseous oxidant (i.e., oxygen) near the surface of the liquid or solid under specified environmental conditions.

3.3.15 Fuel. Any material that will maintain combustion under specified environmental conditions.

3.3.16 Hyperbaric. Pressure greater than ambient.

3.3.17 Hypobaric. Pressure less than ambient.

3.3.18* Ignition Temperature. The minimum temperature required to initiate or cause self-sustaining combustion independently of the heating or heated element under specified environmental conditions. Ignition temperatures are commonly reported as the autogenous ignition temperature, autoignition temperature (AIT), or spontaneous ignition temperature (SIT).

3.3.19 Lower Flammable Limit or Lower Explosive Limit. See 3.3.13, Flammable Limits.

3.3.20* Minimum Ignition Energy. The minimum energy required to ignite a flammable mixture; usually the minimum energy of an electric spark or arc expressed in joules.

3.3.21 Mixture.

3.3.21.1 Lean Mixture. A fuel and oxidizer mixture having less than the stoichiometric concentration of fuel.

3.3.21.2 Rich Mixture. A fuel and oxidizer mixture having more than the stoichiometric concentration of fuel.

3.3.21.3 Stoichiometric Mixture. A balanced mixture of fuel and oxidizer such that no excess of either remains after combustion.

3.3.22* Oxidant. An oxygen-bearing chemical compound that supports combustion.

3.3.23 Oxidation. Reaction with oxygen either in the form of the element or in the form of one of its compounds.

3.3.24 Oxygen. A chemical element that, at normal atmospheric temperatures and pressures, exists as a colorless, odorless, and tasteless gas and comprises about 21 percent by volume of the earth's atmosphere.

3.3.25 Oxygen-Enriched Atmosphere (OEA). An atmosphere in which the concentration of oxygen exceeds 21 percent by volume or its partial pressure exceeds 21.3 kPa (160 torr).

3.3.26* Pressure. The force per unit of area. Values in this recommended practice are based on the unit of pressure derived from the International System of Units (SI), which is the pascal (Pa) or newton per square meter (N/m²).

3.3.26.1 Absolute Pressure. The total pressure being measured that equals gauge pressure plus atmospheric pressure.

3.3.26.2 Gauge Pressure. Pressure measured with reference to atmospheric pressure that equals absolute pressure minus atmospheric pressure.

3.3.27 Spontaneous Ignition Temperature. See 3.3.18, Ignition Temperature.

3.3.28 Upper Flammable Limit or Upper Explosive Limit. See 3.3.13, Flammable Limits.

3.3.29 Worst-Case. The maximum concentration, pressure, temperature, or flow-rate that can occur with a reasonable single-point failure or upset.

Chapter 4 Types of Systems Used in Oxygen-Enriched Atmospheres

4.1 General. Mechanical and electrical systems that can be found in oxygen-enriched atmospheres (OEAs) include the following:

- (1) Air conditioning: Heating, cooling, humidity control, purification, filtering, fresh air supply, and forced circulation
- (2) Hydraulic services (water and hydraulic fluids): Acceptable hydraulic fluids (chemically inert in oxygen), water supply and waste piping, valves, temperature controls, pressure regulators, fire extinguishment
- (3) Compressed air supply: Compressor, cylinder manifold for emergency use, pressure controls, and piping system from supply source to use location
- (4) Gas supply: Uses of gas in OEAs are as follows:
 - (a) Cylinders of compressed gases, such as oxygen, nitrous oxide, nitrogen, helium, and natural air, for human breathing
 - (b) Anesthetic vaporizers such as halothane, enflurane, and isoflurane
 - (c) Cylinder storage, cylinder fastenings in storage or in manifold assemblies, piping and fittings with check valves, flow valves, pressure regulators as required for safe transmission of gas from cylinder to termi-

- nal at use site, and hose and hose connections at use site for attaching dispensing equipment
- (d) Inhalation devices, such as face masks and endotracheal tubes, for connecting to dispensing equipment and for supplying air or gaseous mixtures to humans or animals for breathing
- (5) Suction apparatus: Vacuum pump with controls, piping system from pump to use site, pickup hose, and attachments and shutoff valves
- (6) Electrical-main and emergency systems: Conduit and conduit-fitting sealing compound, insulated conductors, convenience outlets, switches, overcurrent protective devices (fuses, circuit breakers, and relays), temperature-indicating and control devices (thermostats and thermistors), lighting (luminaires, lamps, conductors, and switches), electronic monitoring devices (oscilloscope, blood pressure and heart rate, and temperature and high-low alarms), medical instruments (defibrillator and recorders), clocks, elapsed time indicators, chamber temperature indicators, and pressure control devices
- (7) Communication systems: Telephone or intercommunication systems; microphone with speaker (receiver) for communication with others in other compartments of chamber, with monitor outside of chamberport, or with others at remote stations; and television and radio

Chapter 5 Materials Selection

5.1* General.

5.1.1* The rate of flame propagation and ignition susceptibility of materials of construction should be prime considerations in the promotion of safe design of systems associated with oxygen-enriched environments.

5.1.2 The oxygen compatibility characteristics of all materials involved in oxygen-enriched environments should be carefully and completely evaluated under end-use conditions.

5.1.2.1 Accelerated (time-temperature concentration) oxygen deterioration and degradation (by high-energy and ionizing radiation) tests for service durability also should be conducted for overall evaluation.

5.1.3 When selecting materials for oxygen service, situational or configurational flammability should be evaluated.

5.2 Nonmetals.

5.2.1* The use of nonmetals in oxygen systems should be limited, and their quantity and exposure to oxygen should be minimized.

5.2.2* When selecting materials, application-specific material tests and configurations should be considered.

5.2.3* When selecting a material for oxygen systems, its ability to undergo specific cleaning procedures to remove contaminants, particles, and combustible materials, without damage, should be considered.

5.2.4 When selecting nonmetals for high-pressure oxygen systems, the material's susceptibility to ignition and the possible ignition sources in the system at the use pressures should be given equal consideration with the structural requirements.

5.2.4.1 Criteria for selection of a material for oxygen service should also include the following:

- (1) Few reactions when tested by mechanical impact
- (2) A high autoignition temperature (AIT)
- (3) A low heat of combustion
- (4) A high oxygen index
- (5) A low flame temperature
- (6) A low burn rate
- (7) A low flame propagation rate

5.3 Metals.

5.3.1 Selection of the proper metals in an oxygen system should be coupled with good design practice to minimize the hazards of ignition and combustion of the metal.

5.3.2* The oxide coating of a metal should be considered when selecting it.

5.3.3* The use of aluminum alloys in lines, valves, and other components should be avoided whenever possible.

5.3.4* High-pressure oxygen systems fabricated from aluminum should be designed with extreme care to eliminate particles. Filters should be fabricated of materials less ignitable than aluminum.

5.3.5 Systems that use large areas of aluminum alloys in oxygen storage tanks should be designed to ensure that aluminum particles cannot cause ignition of other metallic materials downstream from the aluminum.

5.3.6 The use of cadmium, beryllium, magnesium, mercury, and titanium metals in oxygen systems should be restricted.

5.3.7* The ignitibility of other metals and alloys in high-pressure oxygen systems and their ability to propagate fire after ignition should be compared to the flammability properties of the common structural materials described in 5.3.6 before determining how suitable they are for use in high-pressure oxygen systems.

5.3.8 The use of nickel, copper, and their alloys is preferred in oxygen systems.

Chapter 6 Component Selection

6.1 Material Recommendations.

6.1.1 Designers of equipment for oxygen use should thoroughly understand the reactivity of selected materials in oxygen-enriched environments.

6.1.2 The designer should attempt to avoid using flammable materials; however, many materials that are flammable at operating conditions can be used safely in some applications by carefully avoiding ignition sources.

6.1.3 The designer should not compromise safety to reduce material costs.

6.2* General Design Recommendations. Designs should consider system dynamics, component interactions, and operational constraints in addition to component design requirements to prevent conditions leading to fires in OEAs.

6.3 Specific Component Design Guidelines. Oxygen system designers should incorporate the following criteria into the guidelines:

- (1)* Minimize the amount of organic, nonmetallic materials and their exposure to oxygen flow

- (2)* Limit gaseous oxygen pressurization rates
- (3)* Limit gaseous oxygen flow velocities
- (4)* Minimize mechanical impact
- (5)* Minimize frictional heating in oxygen
- (6)* Minimize ignition from particle impact
- (7)* Eliminate burrs and avoid sharp edges
- (8)* Minimize use-generated particles during manufacture, assembly, and operation
- (9)* Avoid rotating valve stems and sealing configurations that require rotation on assembly
- (10)* Minimize electrical arcing
- (11)* Avoid blind passages
- (12)* Avoid crevices for particle entrapment and resonant cavities (Phillips)
- (13) Design dynamic seals to minimize particle generation and to minimize coefficients of friction and surface finishes, and choose seal configurations to minimize particle generation that can cause particle impact ignitions
- (14)* Limit fluid-induced vibrations (over all operating ranges)
- (15)* Consider the effects of single-point seal failures
- (16)* Eliminate rotation of seals and rotation against seats
- (17)* Avoid thin walls
- (18)* Be cautious of single-barrier failures
- (19)* Allow sufficient seal squeeze to avoid O-ring extrusion
- (20)* Use metal-to-metal seals in some cases
- (21) Consider the effects of long-term operation, including the following:
 - (a)* Permanent deformation (cold flow) of seals
 - (b)* Seal extrusion (avoid extrusion-generated particles)
 - (c)* High-temperature excessive oxidation of copper
- (22) Design equipment so that power losses, control pressure leakage, or other loss of actuation sources return the equipment to a fail-safe position to protect personnel and property in an accident
- (23)* Consider the effects of thermal expansion

6.4 Components.

6.4.1 Valves.

6.4.1.1 All valves should be accessible for operation and maintenance and should be protected from accidental damage.

6.4.1.2 Valves in gaseous oxygen distribution systems should be kept to a minimum and should be of good quality.

6.4.1.2.1 All valve materials must be suitable for oxygen.

6.4.1.2.2 Stems, packing glands, and other parts vital to proper valve operation should be made of materials that will not readily corrode.

6.4.1.3 Isolation valves should operate either fully open or fully closed and not in a throttling or regulating mode.

6.4.1.4 Where required, a bypass should be provided around isolation valves. The bypass should be made of suitable materials. If remotely operated bypass valves are used, the valves should be fail-safe in case of power loss and should close on a system emergency shutdown signal.

6.4.2 Pressure-Relief Devices and Piping.

6.4.2.1 Relief valves or rupture disks should be installed on tanks, lines, and component systems to prevent overpressurization.

6.4.2.1.1 The capacity of a pressure-relief device should be equal to that of all the vessel and piping systems it is to protect.

6.4.2.1.2 These devices should be reliable and the settings secured against accidental alteration.

6.4.2.2 Relief valves and similar devices should not be considered secondary and passive components in the test hardware design.

6.4.2.2.1 It should be assumed that the valves will function at some point in time.

6.4.2.2.2 Personnel safety and hardware damage should be primary design considerations.

6.4.2.3 Relief valves should be functionally tested to verify that design requirements are satisfied, including testing in both the static and dynamic states.

6.4.2.4 Relief valve riser pipes on high-pressure oxygen systems should be analyzed for resonant tuning. Piping lengths should be changed if resonant tuning is determined.

6.4.2.5 All sections of the pipeline system should be adequately protected by pressure-relief devices and should have an adequate manual vent valve to allow for blowdown and purging.

6.4.2.5.1 All components in any oxygen system that should be permitted to be removed for inspection, maintenance, or replacement should be provided with a vent valve for blowdown and purging.

6.4.2.5.2 Safety valves, vent valves, and associated piping should be constructed of compatible materials.

6.4.2.5.3 Downstream relief devices and any vent lines should be built from the most ignition-resistant materials available and should be positioned in remote locations or isolated from personnel by barriers or shields.

6.4.2.6* Piping, tubing, and fittings should be suitable for the intended oxygen service.

6.4.2.7 Safety devices should be checked before use to prevent possible installation of incorrect pressure-rated devices.

6.4.2.8 The minimum relieving capacities of the safety devices should be as determined by the flow formulas in applicable codes and specifications (for example, Schmidt and Forney, and National Academy of Sciences).

6.4.2.8.1 Safety relief valves and frangible disks should be designed and installed in accordance with applicable codes and specifications (for example, CGA S-1.2).

6.4.2.9 Flexible Piping and Tubing.

6.4.2.9.1 Proper restraining cables and anchoring cables should be required for flexible hose.

6.4.2.9.2 Stainless steel tubing, which can be formed into loops to provide enough flexibility for easy hookup, should be an acceptable practice.

6.4.2.9.3* Flexible metal tube or pipe such as bellows sections should also be acceptable.

6.4.2.9.4* Polytetrafluoroethylene-lined flexible hose can be used if particular care is exercised to ensure that pneumatic impact ignitions cannot occur.

Chapter 7 System Design

7.1 Design Considerations. In the design of systems associated with OEAs, the following should be considered:

- (1) Characteristics of construction materials include ignition susceptibility, flame spread rate, and smoke development
- (2) Risks of fire initiation include ignition sources such as heat from compression of gases, friction, mechanical impact, and electrical arc or spark
- (3) Presence of potential energy sources, such as compressed gases
- (4) Removal or elimination of foreign materials or contaminants
- (5) Physical environment surrounding the system
- (6) Personnel safety

7.2 Worst-Case Conditions. The characteristics of all materials to be used in OEAs should be evaluated for use under worst-case conditions, such as maximum pressure, temperature, and flow.

7.3 Fire-Stopping Techniques. When designing an oxygen-enriched system, fire-stopping techniques should be used where appropriate to minimize ignition potential and fire spread. These techniques include the following:

- (1) Avoidance of mass concentration of combustible materials near potential heat or ignition sources
- (2) Spatial separation and configuration to minimize or eliminate flame propagation paths
- (3) Thermal damping by judicious placement of fire-resistant heat-sink masses
- (4) Flashover barriers
- (5) Sealed packaging, such as inerted compartments and fire-resistant encapsulation
- (6) Automatic fire detection and suppression such as infrared thermography, fire detectors, and fixed suppression systems

7.4* Personnel Qualifications. The design of an oxygen-enriched system should only be undertaken by qualified personnel.

7.5 Oxygen Transmission. Systems used in the transmission of oxygen should be cleaned prior to use and on a routine basis to remove contaminants.

7.6* Shutoff. A manual emergency oxygen shutoff that is accessible should be provided.

7.7 Electrical Equipment.

7.7.1* No electrical equipment should be installed or used in OEAs unless approved for use at the maximum proposed pressure and oxygen concentration.

7.7.1.1 Electrical equipment should be provided with noncombustible insulation to confine any burning of the insulation within the enclosure, unless the equipment is of construction that has been found, through testing, at the maximum pressure

and the oxygen concentration encountered in the chamber or system.

7.7.2* Fixed electrical equipment within an OEA should comply with the requirements of Article 500, Class I, Division 1, *NFPA 70*, and, in addition, equipment installed therein should be approved for use in the specific hazardous atmospheres at the maximum proposed pressure and oxygen concentration.

7.7.3 All electrical wiring installed in a system or chamber should comply with the requirements of the *NEC*, Article 500, Class I, Division 1.

7.7.3.1 The boxes and fittings should be approved for use in the specific hazardous atmospheres at the maximum pressure and oxygen concentration of the chamber or system.

7.7.4 Raintight fittings, boxes, and equipment should be used if such devices could be exposed to the water from a sprinkler or water spray system that is protecting the chamber in the event of a fire in the vicinity of the chamber while it is in operation.

7.7.5 All electrical circuits contained within the chamber or system should be supplied from an isolated electrical system, fed from isolation transformers located outside the chamber or system, and equipped with a line isolation monitor with appropriate signal lamps. This indicator should be capable of sensing single or balanced capacitive-resistive faults as well as leakage of current to ground.

7.7.6 Electrical wiring in high concentrations of gas oxygen should be encased in hermetically sealed conduits or conduits inerted with helium or nitrogen gas.

7.7.6.1 The instruments, switches, flow sensors, and electrical devices should be designed in modular structure, hermetically sealed, and inerted with nitrogen or helium gas.

7.8* Cleaning for Oxygen Service.

7.8.1* All hardware that is exposed to OEAs should be cleaned to remove contaminants.

7.8.2* The solvent or detergent should not leave a residual material on the cleaned surface.

7.8.3* A typical cleaning criterion for industrial gaseous oxygen systems specifies that the remaining organics should not exceed 500 mg/m² (1×10^{-4} lb/ft²) of oxygen-contacted surfaces.

7.8.4* Verification of cleanliness should be accomplished by one or more of the following methods:

- (1) Direct visual inspection with white light
- (2) Direct visual inspection with ultraviolet (UV) or black light
- (3) Inspection of a wipe sample using a clean, lint-free cotton or linen cloth or a piece of white filter paper examined under white or UV light
- (4) Solvent extraction to determine the level of extractable contaminants that includes nonvolatile residue analysis, volume of residue analysis, and spectroscopic technique
- (5) Aqueous cleaning and verification processes

7.8.5* Cleaned parts should be placed in sealed noncontaminating bags, or sealed with plugs in the case of long piping runs, and labeled "Cleaned for Oxygen Service."

7.8.5.1 Cleaned parts should not be handled with bare hands.

7.9* Combustibles. It is highly recommended that every possible effort be made to restrict the quantity of combustibles permitted within the system, vessel, chamber, surrounding physical environment (including interior surface finishes, such as paints, plastic coverings, and acoustical, thermal, and electrical insulation), coverings and housings of servicing apparatus, and instrumentation employed inside the system or chamber.

7.10 Applicable Standards.

7.10.1 Design and construction of housing vessels and chambers should be in accordance with the applicable provisions of the currently established practices described in the following documents:

- (1) *ASME Boiler and Pressure Vessel Code*, Section VII
- (2)* NFPA 99, Chapter 14
- (3) NFPA 99B
- (4) API 620, *Design and Construction of Large, Welded, Low-Pressure Storage Tanks*
- (5) CGA pamphlets as follows:
 - (a) CGA P-1, *Safe Handling of Compressed Gases in Containers*
 - (b) CGA S-1.1, *Pressure Relief Device Standards — Part 1 — Cylinders for Compressed Gases*
 - (c) CGA S-1.2, *Pressure Relief Device Standards — Part 2 — Cargo and Portable Tanks for Compressed Gases*
 - (d) CGA S-1.3, *Pressure Relief Device Standards — Part 3 — Stationary Storage Containers for Compressed Gases*

7.10.2 Oxygen storage, piping, and uses should be in accordance with the following standards:

- (1) NFPA 51
- (2) NFPA 55
- (3)* Hospital requirements in NFPA 99, as well as Chapter 5 and Chapter 11.
- (4) CGA G-4, *Oxygen*
- (5) ASME B31.3, *Process Piping*
- (6) ASME B31.5, *Refrigeration Piping and Heat Transfer Components*
- (7) ASME B31.8, *Gas Transmission and Distribution Piping Systems*
- (8) U.S. Code of Federal Regulations as follows:
 - (a) 49 CFR 173.301
 - (b) 49 CFR 173.302
 - (c) 49 CFR 173.337
 - (d) 49 CFR 178.37
 - (e) 49 CFR 178.45

7.10.3 Electrical equipment and instruments should be in accordance with the following standards:

- (1) NFPA 70, Articles 500, 501, and 517
- (2)* NFPA 99, Chapter 6 and Chapter 10
- (3) NFPA 496

7.10.4 Air-conditioning and ventilating systems should be in accordance with the following standards:

- (1) NFPA 90A
- (2) NFPA 91

Chapter 8 Fire Extinguishment

8.1 Oxygen Supply. The oxygen supply should be discontinued in the event of a fire.

8.2* Extinguishing Systems.

8.2.1 Due to the rapid flame spread in OEAs, fire-extinguishing systems should be capable of fast automatic actuation by fire detectors as well as by manual actuation.

8.2.2 Automatic actuation should occur in less than 1 second of detection of flame.

8.2.3 Manual actuation of the fire-extinguishing system should be provided.

8.3 Fixed Systems. Fixed systems should utilize an extinguishing agent acceptable for use on fires in OEA.

8.4 Water Hose. In addition to an automatic, fixed extinguishing system in occupied areas, a manually operated water hose not less than 19 mm ($\frac{3}{4}$ in.) inside diameter, and with an effective nozzle pressure of not less than 345 kPa (50 psi) above the ambient pressure, should be available.

8.5 Diluents. In unoccupied areas, diluents (e.g., carbon dioxide, nitrogen) can be used.

8.6* Limiting Fire Spread. Fire protection measures should be concentrated on limiting the spread of fire from involved components to other portions of the system.

8.7 Nontoxic Agents. Fire-extinguishing agents should be inherently nontoxic and should not produce significant amounts of toxic breakdown products when used.

8.8* Wetting. Where the combustible is present in more than one layer, all layers should be wetted by the water.

8.9 Instructions and Drills.

8.9.1 All personnel working in a space containing an OEA should be instructed in the special hazards involved, and the differences between fire in an OEA and fire in ordinary air should be emphasized.

8.9.2 Each person working in an OEA system should be assigned a specific fire emergency duty.

8.9.3 Other personnel working in associated monitoring areas should likewise be instructed and assigned specific duties appropriate to a fire emergency.

8.9.4 The instruction should be augmented by frequent drills so that proper action can be taken immediately upon the occurrence of a hazardous condition.

8.9.5 Such instruction and drill should be so comprehensive and specific that no time is lost in decision-making or considering alternative procedures. (*See Annex B.*)

Annex A Explanatory Material

Annex A is not a part of the recommendations of this NFPA document but is included for informational purposes only. This annex contains explanatory material, numbered to correspond with the applicable text paragraphs.

A.3.2.1 Approved. The National Fire Protection Association does not approve, inspect, or certify any installations, procedures, equipment, or materials; nor does it approve or evaluate testing laboratories. In determining the acceptability of installations, procedures, equipment, or materials, the authority having jurisdiction may base acceptance on compliance with NFPA or other appropriate standards. In the absence of such

standards, said authority may require evidence of proper installation, procedure, or use. The authority having jurisdiction may also refer to the listings or labeling practices of an organization that is concerned with product evaluations and is thus in a position to determine compliance with appropriate standards for the current production of listed items.

A.3.2.2 Authority Having Jurisdiction (AHJ). The phrase “authority having jurisdiction,” or its acronym AHJ, is used in NFPA documents in a broad manner, since jurisdictions and approval agencies vary, as do their responsibilities. Where public safety is primary, the authority having jurisdiction may be a federal, state, local, or other regional department or individual such as a fire chief; fire marshal; chief of a fire prevention bureau, labor department, or health department; building official; electrical inspector; or others having statutory authority. For insurance purposes, an insurance inspection department, rating bureau, or other insurance company representative may be the authority having jurisdiction. In many circumstances, the property owner or his or her designated agent assumes the role of the authority having jurisdiction; at government installations, the commanding officer or departmental official may be the authority having jurisdiction.

A.3.2.3 Code. The decision to designate a standard as a “code” is based on such factors as the size and scope of the document, its intended use and form of adoption, and whether it contains substantial enforcement and administrative provisions.

A.3.2.5 Listed. The means for identifying listed equipment may vary for each organization concerned with product evaluation; some organizations do not recognize equipment as listed unless it is also labeled. The authority having jurisdiction should utilize the system employed by the listing organization to identify a listed product.

A.3.3.18 Ignition Temperature. Spontaneous ignition temperature (SIT) should not be confused with temperatures associated with the spontaneous heating or combustion phenomenon that certain highly oxidizer-receptive materials undergo.

A.3.3.20 Minimum Ignition Energy. The minimum ignition energy is different for different flammable mixtures and varies with the concentration, temperature, and pressure, as well as the geometry and material, of the sparking or arcing electrodes.

A.3.3.22 Oxidant. Examples of oxidants include nitrous oxide, nitric oxide, and chlorates.

A.3.3.26 Pressure. A newton is that force that causes a mass of 1 kilogram to accelerate 1 meter per second.

One atmosphere (atm) = 33 feet of water (39.2°F) = 14.7 pounds per square inch (psi) = 760 millimeters of mercury (mm Hg) (0°C) = 760 torr = 101,325 newtons per square meter (N/m²) = 101,325 pascals (Pa).

A.5.1 See Annex F for additional guidance.

A.5.1.1 Other considerations include the deterioration stability as well as the careful assessment of any potential ignition sources capable of initiating combustion in such atmospheres.

A.5.2.1 Nonmetals are more susceptible to ignition than metals (most nonmetals are flammable in oxygen at 1 atm or greater). In many instances, failures of metallic components

are caused by a polymer ignition, which provides sufficient energy for the metal to ignite.

A.5.2.2 Materials in an oxygen environment below their auto-ignition temperature (AIT) do not ignite without an ignition source. The rate of energy input has to exceed the rate of heat dissipation before ignition can occur. Ignition temperature is dependent on the property of the material, the configuration, the environment (temperature, pressure, oxygen concentration, and fuel characteristics), and the dynamic conditions for flow systems.

Nonmetals, such as polymers, generally ignite at lower temperatures and pressures than metals; nonmetals can burn at oxygen pressures lower than 7 kPa (absolute pressure of 1 psi). The primary concern with nonmetals in oxygen systems is that, if ignited, they might cause damage to the oxygen system or injury to persons in the vicinity. Damage that might result includes propagation of the fire to metallic components, loss of function arising from system leaks, and toxic combustion and pyrolysis products entering the oxygen system.

In general, bulk metals are not easily ignited. When ignited, however, burning metals can cause more damage than burning nonmetals because of their higher flame temperatures and because they usually produce liquid combustion products that spread fires readily. Also, metals comprise the major system components, such as valve bodies and pressure vessels, so that when they ignite and burn, oxygen is released to the surrounding areas in an explosive manner.

A.5.2.3 For more information, see ASTM G93 and CGA G-4.1.

A.5.3.2 The resistance to ignition for metals can be enhanced by a protective oxide coating on the metal surface.

A.5.3.3 Aluminum alloys in high-pressure oxygen ignite easily, burn rapidly, and have very high heats of combustion. Aluminum is easily ignited by friction because the wear destroys its protective oxide layer; therefore, aluminum should not be used in systems where frictional heating is possible.

A.5.3.4 Nickel, silver, bronze, or Monel® alloys are recommended, although Monel wire meshes are known to be flammable in elevated-pressure oxygen environments, (Stoltzfus, Lowrie, and Gunaji). Aluminum alloys are more suitable for static components at low oxygen flow rates, such as oxygen storage tanks, than for components with internal movement and variable flow rates, such as valves and regulators.

A.5.3.7 Many other metals and alloys exist that have mechanical properties suited to applications in high-pressure oxygen systems. New alloys are continually being developed, and some are being designed that resist ignition and do not support self-sustained combustion in high-pressure oxygen systems.

A.6.2 The use of ignition- and burn-resistant materials for components in oxygen systems will not eliminate fires in OEAs. For more information, see ASTM G63, ASTM G88, and ASTM G94.

A.6.3(1) Organic, nonmetallic materials exposed to oxygen flow can be readily heated through rapid compression of the gas (Shelley, Christianson, and Stoltzfus, 1993) or readily ignited through kindling-chain reactions. Minimizing organic, nonmetallic materials' exposure by shielding with surrounding metals can significantly reduce ignition hazards.

A.6.3(2) Organic, nonmetallic materials, such as seals, coatings, and lubricants, are susceptible to ignition from heating caused by rapid pressurization. For example, Teflon®-lined flexible hose are sensitive to this ignition mode, and, therefore, their use with rapid pressurization applications is discouraged (Janoff et al., 1989). Pressurization rates of valve and regulator actuators should be minimized. In some applications, use of flow-metering devices is prudent for manually actuated valves, especially for quarter-turn ball valves.

A.6.3(3) Limiting flow velocities minimizes erosion problems and reduces the risk of particle-impact ignitions. Although each material and configuration combination needs to be reviewed individually, fluid velocities above 30.5 m/sec (100 ft/sec) should receive special attention, especially at flow restrictions (Williams, Benz, and McIlroy, 1988; Benz, Williams, and Armstrong, 1986; and CGA G-4).

A.6.3(4) Mechanical impact can cause ignition of contaminants and organic, nonmetallic materials. Relief valves, shutoff valves, regulators, and subminiature parts especially should be reviewed for this hazard.

A.6.3(5) Frictional heating, such as heating that occurs with bearings, pistons, and pump impellers, can cause ignitions (Dees and Peterson). Any contamination near the heated region can also be ignited. Frictional heating hazards can be reduced by carefully controlling surface finishes, coefficients of friction, alignment, and flow-induced cooling. Frictional heating has also been found to ignite materials in cryogenic applications.

A.6.3(6) The risk of particle impact ignitions can be reduced if potential impact surfaces are designed with shallow impact angles to reduce the kinetic energy absorbed by the impact surface upon impact (Christianson and Plante, 1989).

A.6.3(7) Burrs and sharp edges on equipment provide ignition sources for particle impact and the ingredients for kindling-chain combustion propagation (Christianson and Plante, 1989). Removal of this material is standard shop practice and is essential to avoid oxygen-enriched ignitions.

A.6.3(8) These particles could be a source of particle impact ignition. Designs should have provisions to minimize particle generation through the normal operation of valve stems, pistons, and other moving parts. Bearings, bushings, and configurations can be used to keep particles away from oxygen-wetted regions. Additionally, proper assembly, cleaning, and maintenance practices should minimize contamination.

A.6.3(9) Rotating valve stems and seals can gall and generate particles.

A.6.3(10) Electrical arcs in oxygen-enriched environments can lead to heating and subsequent ignition.

A.6.3(11) Long, narrow passages or blind passages are difficult to clean and to inspect for cleanliness. Additionally, these passages can provide a location for particles to accumulate during operation of the equipment. This contamination can make the equipment susceptible to particle impact, rapid compression, and resonant cavity ignitions.

A.6.3(12) Cavities, especially those formed at the intersection of mating parts in assemblies, create a location where contamination can accumulate and increase ignition risks, as in blind passages.

A.6.3(14) Vibrations can cause fretting, galling, impacting, and particle generation in components and systems. Check valve chatter and valve poppet oscillations are examples of this phenomenon. Particle accumulations will increase the risk of particle-impact ignitions.

A.6.3(15) Seals will degrade with time and use. Eventually, they can be expected to fail to seal the contained fluid. When this happens, the effects of an oxygen-enriched external environment, high-velocity leakage, and loss of mechanical integrity must be addressed.

A.6.3(16) Sealed parts that require rotation at assembly, such as O-rings on threaded shafts, can generate particles that can migrate into the flow stream. Particle generation also occurs in ball valves where operation of the valve rotates a ball on a nonmetallic seat.

A related phenomenon that can be described as feathering occurs when valve stems are rotated against some nonmetallic seats. Because of the mechanical properties of some nonmetallic materials, a thin, featherlike projection of material is extruded from the seat. The feathered material is more ignitable than the seat itself.

Nonmetallic materials subject to feathering should be used with caution for seals and seats in rotating configurations. Ball valves are not recommended for oxygen systems because of their tendency to generate particles and their fast opening times, which creates rapid pressurization of systems.

A.6.3(17) The walls between inner cavities or passageways and the outer surface of component housings can become so thin that stress concentrations result when pressure is introduced. Because geometries both inside and outside can be complex, it might not be obvious from drawings or even from direct inspection that such thin, highly stressed areas exist. If such walls become too thin, they might rupture under pressure loading. The energy released by the rupture can raise the temperature in the rupture zone. The failed section can expose bare, jagged metal that can oxidize rapidly and heat enough to ignite and burn.

A.6.3(18) A single-barrier failure is defined as a leak in which only the primary containment structure is breached. Such a leak introduces oxygen into a region not normally exposed to oxygen. The materials or configuration of parts in this region might not be compatible with high-pressure oxygen.

Any situation in which a single barrier can fail should be analyzed during the design phase. The single-barrier failure analysis might consist of an engineering evaluation of the configuration, including an analysis of the compatibility of materials exposed by the failure with the high-pressure oxygen. The purpose of the analysis should be to determine if a barrier failure is credible and if exposure of incompatible materials can create a hazard. If the hazard cannot be assessed adequately by analysis, a configurational test can be performed.

A.6.3(19) Standard manufacturers' dimensions and tolerances should be incorporated into designs unless an unusual overriding design constraint demands the change. Additionally, the dimensions of all parts in the valve assembly should be carefully inspected. Ideally, adequate gland size should be provided in the initial design.

A.6.3(20) Polymeric materials cannot be used as seals in valves that control the flow of hot oxygen because they lose sealing properties, ignite easily, and wear rapidly.

High pressures and high flow rates can produce side loads and oscillations on the poppet seal that can cause metal deterioration by fretting or galling. (Galling is the more severe condition, because it involves smearing and transferring material from one surface to another.) Fretting and galling can cause several problems in oxygen systems. The valve poppet might seize, resulting in loss of function. The frictional heat of the fretting or galling can lead to ignition of the valve. The particles generated by the fretting or galling can cause malfunction or ignition of another component downstream.

Where possible, the valve poppet should be designed for symmetrical flow so that no oscillatory side loads are created. The symmetrical flow centers the poppet in the bore and maintains design clearances between the poppet and bore surfaces.

For gaseous systems, it might be possible to reduce the volumetric flow rate, and thus the magnitude of oscillations and side loads, by installing an orifice. The orifice should be downstream of the poppet to minimize the pressure differential across the poppet. It is also possible to flexure-mount the poppet in the bore and to incorporate labyrinth seal grooves in the poppet surface.

To minimize the possibility of ignition, poppet and bore materials should be relatively resistant to ignition caused by frictional heating. Both can be hardened by nitriding or a similar process to minimize material loss by fretting or galling.

A.6.3(21)(a) Cold flow is a concern, especially for organic, nonmetallic materials with little resiliency. With applied loads, these materials permanently deform, usually resulting in sealing loss.

A.6.3(21)(b) Generally, seals with low hardnesses tend to provide better sealing. However, the softer seals will not withstand high temperatures and pressures. When such seals fail, they often extrude, generating particles. Pressure and thermal reversal cycles can also result in seal extrusion. Although silicone seals are not recommended, they can be found in existing oxygen systems. If found, careful examination during maintenance procedures is recommended. Excessive cross-linking of silicone elastomers in oxygen environments can occur, leading to embrittlement and degradation.

A.6.3(21)(c) Copper is often used for oxygen seals. It can provide a very reliable seal; however, at extremely high temperatures, the copper oxide that forms on exposed surfaces can dislodge from the substrate. The oxide is then likely to become a source of particles.

A.6.3(23) Buckling can create component failures.

A.6.4.2.6 Materials are described in Chapter 5 and Annex F. Systems built entirely of suitable materials can still develop the following problems if the pressurized gas flow is either started or stopped abruptly:

- (1) Abruptly starting or stopping pressurized gas flow can result in compression heating at elbows, dead ends, and valves. The resulting temperature rise can be sufficient to ignite all polymeric materials commonly used in gaseous oxygen systems.
- (2) Mechanical shock to the system can dislodge solid particles. If these particles are caught up in the flow and

impinge on a surface, hot spots will result that can cause ignition.

A.6.4.2.9.3 All-metal bellows are difficult to clean and cleaning fluids cannot be completely rinsed off, leading to corrosion.

A.6.4.2.9.4 The risks can be minimized if procedures are written so as to avoid operator error, and to incorporate a long, nonignitable metallic housing at the downstream end of the flexible hose in the design.

A.7.4 See Annex B for information on the training and education of personnel.

A.7.6 An automatic shutoff can also be provided.

A.7.7.1 Most metals burn freely in OEAs (see F.3.4), depending on the concentration and pressure of the oxygen. Electrical contacts likewise can burn away and initiate fires of the nearby insulation or materials unless proven by tests to be suitable for the particular pressure and oxygen concentration in the chamber or system. Apparatus and circuits that have been found to be safe in ordinary atmospheric conditions are not necessarily safe in oxygen concentrations or pressures higher than those of ordinary atmospheres. It is therefore necessary that equipment and circuits be tested for safe use at the maximum pressure and oxygen concentration as well as for the materials that might be in proximity to the electrical equipment or circuits.

A.7.7.2 Because there are no flexible cords available with noncombustible insulation, it is essential for safe operation that portable equipment be used in OEA only if required for life safety and under rigorously controlled conditions.

A.7.8 See ASTM G93.

A.7.8.1 Of particular importance is the removal of lint, dust, and organic matter such as oil and grease. The latter includes fingerprints. These contaminants are ignited relatively easily in oxygen and OEAs and could result in an explosion or a fire. A fire could, in turn, ignite the oxygen container or piping. (A list of ignition mechanisms is found in E.3.1.4 and F.3.2.6.)

A.7.8.2 A variety of cleaning methods is used in practice, including caustic or acid solutions, steam (with or without detergents), hot water (with or without detergents), solvents (with or without vapor-degreasing equipment), supercritical fluids, electropolishing, and sand or shot blasting. The method selected depends on the equipment available, foreign materials present, undesirable side reactions (e.g., acid attack of metals and solvent attack of nonmetals), level of cleanliness desired, ability to dispose of spent cleaning agents, worker exposure to the cleaning agents, and other factors.

A.7.8.3 The level of cleanliness required typically increases with the pressure of gaseous oxygen, and the required level of cleanliness is always high in liquid oxygen systems. Some organizations, including the U.S. military and the National Aeronautics and Space Administration (NASA), use criteria that are more stringent.

A.7.8.4 The reported level of residual organics can be misleading because it is an average level for the surface examined. The organic level actually might be concentrated in one area.

A.7.8.5 Shapes such as those of bellows tubing, Bourdon tubes in pressure gauges, small-diameter piping, dead-legs in piping, crevices in mated pipe threads, and so forth are difficult to clean. Explosions from residual cleaning agents have occurred

within products having these shapes. It is always advisable to fully disassemble components for cleaning, because this mitigates the hazard of remaining solvent. Adequate rinsing and drying time are important.

A.7.9 Total elimination of combustible materials is the ideal objective, though it might not be totally achieved in practice. Combustibles used on exterior support systems or units, such as ventilating, air-conditioning purification, or filter media, as well as auxiliary power and air-oxygen supplies, and any components associated therewith, including hydraulic fluids, gaskets, packing and joint compounds, and lubricants, should be regarded as potential fuels, until otherwise determined by suitable tests.

A.7.10.1(2) In NFPA 99, Chapter 14 covers hyperbaric facilities.

A.7.10.2(3) In NFPA 99, Chapter 5 covers gas and vacuum systems and Chapter 11 covers gas equipment. Hospital requirements were previously covered by NFPA 99, Chapter 13, in the 2005 edition, but have been dispersed throughout other chapters of the code in more recent editions.

A.7.10.3(2) In NFPA 99, Chapter 6 covers electrical systems and Chapter 10 covers electrical equipment.

A.8.2 Fire-extinguishing systems for use in OEAs face many requirements in addition to those required for conventional systems because of ignition susceptibility, increased flame spread rate and burning intensity, and the flammability of normally flame-resistant materials. Therefore, fire-extinguishing agents have to act rapidly to be effective. To protect occupants and real property, they should be inherently nontoxic and should not produce toxic or corrosive decomposition products. In general, these new requirements cannot be satisfied by the simple extension of traditional extinguishment techniques. Emergency personnel should receive special instruction and training, and special extinguishing agents and systems should be selected.

Water has shown to be an effective extinguishing agent in OEA when applied in sufficient quantities. Water at a spray density of 50 L/min/m² (1¼ gpm/ft²) applied for 2 minutes will extinguish cloth burning in 100 percent oxygen at atmospheric pressure. The application method of the water is all-important. Water extinguishing systems should be carefully designed such that all protected space is covered by the minimum spray density and that water is distributed to a depth sufficient to extinguish stratified fires in nonhomogeneous materials — for example, layers of cloth in clothing. New technology in the use of high-expansion, water-based foams has resulted in improved extinguishing properties. However, the applicability of this agent to each particular candidate system should be carefully evaluated with regard to the available space, required time, and application methods. More data has become available on the use of low-expansion foam and dry chemical extinguishing agents in normal atmospheres, but their applicability in OEAs is still unknown.

A.8.6 Because of the explosive nature of fires involving metals in pressurized oxygen systems, fire-extinguishing systems have little effect. For oxygen-enriched fires at atmospheric pressure involving metals (e.g., shop turnings), the fire will burn more intensely in an OEA. Fire-extinguishing systems need to react rapidly and effectively (Topscott et al.).

A.8.8 It has been noted that the underlayer of two layers of cloth can continue to burn even though the outer layer has been wetted and extinguished.

Annex B Training and Education

This annex is not a part of the recommendations of this NFPA document but is included for informational purposes only.

B.1 Training. Personnel should be properly trained in the use of oxygen and oxygen systems and be familiar with the following specific areas.

B.1.1 Personnel who handle and use oxygen or design equipment for oxygen systems must be familiar with its pertinent physical, chemical, and hazardous properties. Personnel should know what materials are compatible with oxygen and the cleanliness requirements of oxygen systems. They should also be qualified to recognize system limitations and how to respond properly to all foreseeable failure modes.

B.1.2 Personnel should be thoroughly familiar with the use and care of protective and safety equipment and with first aid techniques.

B.1.3 Operators should be trained in the selection of proper equipment for handling liquid oxygen and gaseous oxygen and in the procedures for handling spills and leaks and disposing of oxygen. Personnel involved in design and operations should adhere to accepted standards and guidelines and comply with established regulatory codes.

B.2 Education. To aid in the education of designers, the ASTM Committee G-04 has developed a standards technology training course, "Controlling Fire Hazards in Oxygen Handling Systems," which is accompanied by the course textbook *Fire Hazards in Oxygen Systems*. This course was developed by committee members from oxygen manufacturers, government agencies, equipment suppliers, and users. The course is based on the experience of committee individuals and their respective organizations. Course content was derived from all of the following documents:

- (1) CGA G-4.1, *Cleaning Equipment for Oxygen Service*
- (2) CGA G-4.4, *Industrial Practices for Gaseous Oxygen Transmission and Distribution Piping Systems*
- (3) CGA Video AV-8, "Characteristics and Safe Handling of Cryogenic Liquid Gaseous Oxygen"
- (4) CGA P-14, *Accident Prevention in Oxygen-Rich and Oxygen-Deficient Atmospheres*
- (5) CGA E-2, *Hose Line Check Valve Standards for Welding and Cutting*
- (6) EIGA 33/06/E, *Cleaning of Equipment for Oxygen Service*
- (7) EIGA 5/75/E, *Code of Practice for Supply Equipment and Pipeline Distributing Non-Flammable Gases and Vacuum Services for Medical Purposes*
- (8) EIGA 6/77, *Oxygen Fuel Gas Cutting Machine Safety*
- (9) EIGA 8/76/E, *Prevention of Accidents Arising from Enrichment or Deficiency of Oxygen in the Atmosphere*
- (10) EIGA 12/80/E, *Pipelines Distributing Gases and Vacuum Services to Medical Laboratories*
- (11) EIGA 10/09/E, *Reciprocating Compressors for Oxygen Service*
- (12) EIGA 27/82/E, *Turbo Compressors for Oxygen Service, Code of Practice*
- (13) NFPA 51
- (14) NFPA 53
- (15) NFPA 55

- (16) NFPA 99
- (17) ASTM G63, *Standard Guide for Evaluating Nonmetallic Materials for Oxygen Service*
- (18) ASTM G88, *Standard Guide for Designing Systems for Oxygen Service*
- (19) ASTM G93, *Standard Practice for Cleaning Methods and Cleanliness Levels for Material and Equipment Used in Oxygen-Enriched Environments*
- (20) ASTM G94, *Standard Guide for Evaluating Metals for Oxygen Service*
- (21) ASTM G128, *Guide for the Control of Hazards and Risks in Oxygen-Enriched Atmospheres*

Annex C Utilization of Oxygen-Enriched Atmospheres

This annex is not a part of the recommendations of this NFPA document but is included for informational purposes only.

C.1 General.

C.1.1 Oxygen is a clear, colorless, odorless, and tasteless gas comprising about 21 percent of the atmosphere of the earth. It supports combustion and is necessary for plant and animal life. The concentration of oxygen available in the atmosphere generally is sufficient for human needs during normal conditions of health and for most combustion applications. However, in the treatment of disease, in special types of fuel combustion, and in some chemical processes, an OEA is necessary. In addition, OEAs are employed for life support in closed environmental systems. This annex describes some of these applications as a basis for considering the extent of application of OEAs, the fire hazards associated with their use, and the methods used for eliminating or controlling those hazards.

C.1.2 The degree of fire hazard of an OEA varies with the concentration of oxygen present, the diluent gas, and the total pressure. An OEA is defined as any atmosphere in which the concentration of oxygen exceeds 21 percent by volume or the partial pressure of oxygen exceeds 21.3 kPa (160 torr). Other oxidants include nitrous oxide, nitric oxide, and chlorates. In most commonly encountered OEAs, an increased fire hazard is produced by the increased partial pressure of oxygen (e.g., in

an atmosphere of compressed air) or by the absence of the diluting effect of an inert gas (e.g., in pure oxygen at a pressure $\frac{1}{5}$ atm). An OEA does not, however, by definition produce an increased fire hazard. Certain OEAs can exhibit combustion-supporting properties similar to ambient air, whereas others are incapable of supporting the combustion of normally flammable materials (a decreased fire hazard). The latter case can frequently arise under hyperbaric conditions when the volumetric percentage of oxygen is significantly reduced in a nitrogen or helium mixture, even though the partial pressure of oxygen is equal to or greater than 21.3 kPa (160 torr). For example, a 4 percent oxygen mixture in nitrogen or helium at a total pressure of 12 atm will not support the combustion of paper even though the partial pressure of oxygen is 48.6 kPa (365 torr). A similar condition (i.e., a reduced fire hazard) can exist at very low hypobaric pressure, even though the volumetric percentage of oxygen is significantly high.

C.1.2.1 Table C.1.2.1 compares units of pressure to altitude above or depth below sea level. It also shows the partial pressure of oxygen in a rarefied or compressed-air atmosphere.

C.1.2.2 Figure C.1.2.2(a) and Figure C.1.2.2(b) depict three combustion zones for vertical filter paper strips in hyperbaric mixtures of oxygen-nitrogen and oxygen-helium, respectively. Those combinations of oxygen concentrations and total pressure lying above the 0.21 atm oxygen partial pressure isobar (lower dashed line) are, by definition, OEAs, but they could be located in any of three zones: complete combustion, incomplete combustion, or noncombustion.

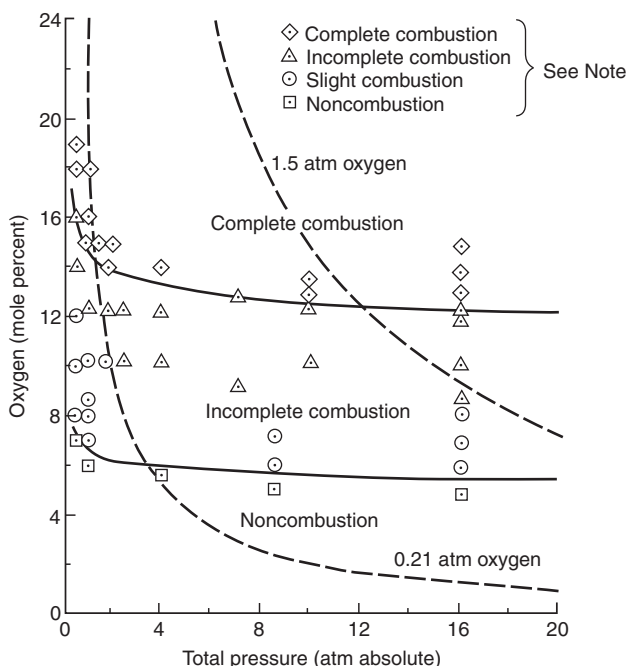
C.1.3 OEAs routinely exist or are utilized intentionally in medical practice, industry, underwater tunneling and caisson work, space and deep-sea exploration, hyperbaric chambers, and commercial and military aviation. Such atmospheres are inherent to oxygen processing, transporting, and storage facilities. OEAs can develop inadvertently at any time when oxygen or compressed air is transported, stored, or utilized.

Table C.1.2.1 Partial Pressure of Oxygen in a Rarefied or Compressed-Air Atmosphere

				Altitude Above or Depth Below Sea Level			
Total Absolute Pressure				Air or Sea Water		Partial Pressure of Oxygen if Atmosphere Is Air	Concentration of Oxygen if Partial Pressure of Oxygen Is 160 torr
Atm	torr	psi	kPa	m	ft	torr*	% by Volume
1/5	152	2.9	20	11,735	38,500	32	100.0†
1/3	253	4.9	33.8	8,832	27,500	53	62.7†
1/2	380	7.3	50.3	5,486	18,000	80	42.8†
2/3	506	9.8	67.6	3,353	11,000	106	31.3†
1	760	14.7	101.4	Sea level	—	160	20.9
2	1,520	29.4	202.7	-10	-33	320†	10.5
3	2,280	44.1	304.1	-20	-66	480†	6.9
4	3,040	58.8	405.4	-30	-99	640†	5.2
5	3,800	73.5	506.8	-40	-132	800†	4.2

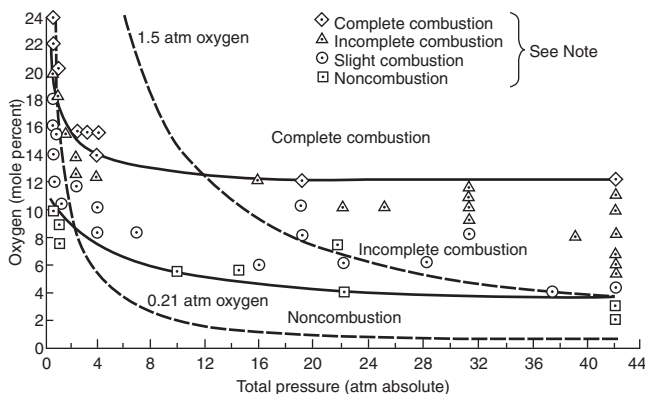
* This column shows the increased available oxygen in compressed-air atmospheres.

† Oxygen-enriched atmosphere.



Note: **Complete Combustion:** The filter paper strip burns completely. **Incomplete Combustion:** The filter paper strip burns for a length greater than 1 cm (2.54 in.) from a resistance wire igniter, but the flame extinguishes itself before the strip is completely consumed. **Slight Combustion:** The filter paper strip flames or smolders, but does not burn more than 1 cm (2.54 in.) from the resistance wire igniter. **Noncombustion:** No ignition.

FIGURE C.1.2.2(a) Illustration of Varying Degrees of Combustion in an Oxygen-Nitrogen Oxygen-Enriched Atmosphere. (Courtesy of *Journal of Fire and Flammability*.)



Note: **Complete Combustion:** The filter paper strip burns completely. **Incomplete Combustion:** The filter paper strip burns for a length greater than 1 cm (2.54 in.) from a resistance wire igniter, but the flame extinguishes itself before the strip is completely consumed. **Slight Combustion:** The filter paper strip flames or smolders, but does not burn more than 1 cm (2.54 in.) from the resistance wire igniter. **Noncombustion:** No ignition.

FIGURE C.1.2.2(b) Illustration of Varying Degrees of Combustion in an Oxygen-Helium Oxygen-Enriched Atmosphere. (Courtesy of *Journal of Fire and Flammability*.)

C.1.4 Oxygen is stored either in its liquid state or as a compressed gas. Compressed-gas storage pressures are variable and can be as high as 52 MPa (gauge pressure of 7500 psi). The density of oxygen in such conditions is high, and the fire hazard within pressure-containing components greatly increases.

C.1.4.1 Liquid oxygen is the most concentrated common source of oxygen. Contamination of liquid oxygen with most organic substances often renders the mixture subject to violent explosion.

C.1.4.2 Most common textile materials, including clothing, that become contaminated with oxygen are susceptible to rapid combustion. However, certain specialized materials, such as glass fabric, are not susceptible to combustion in OEAs. Other special materials burn less rapidly than common textiles in OEAs. (See Annex F.)

C.1.4.3 Whenever liquid oxygen is exposed to materials at ambient temperatures, rapid warming and evaporation of the liquid take place. OEAs are created around and within the materials upon which the liquid is spilled.

C.1.5 Nitrous oxide, a stable, nontoxic oxide of nitrogen, is widely employed for medical and industrial uses. As a gas, nitrous oxide is useful as a mild anesthetic agent. It also is used as a combustion-enhancing agent in racing vehicles. In industry, nitrous oxide is used as a propellant for a variety of aerosol products. It is used as a liquid refrigerant for the rapid freezing of certain food products.

It should be noted that an OEA can develop in situations in which nitrous oxide is employed.

C.1.6 The use of other oxidants, such as chlorine, chlorates, nitric oxide, and ozone, can result in enhanced combustion. Appropriate safety literature, such as material safety data sheets, should be reviewed before using these oxidants.

C.2 Processing, Transport, Storage, and Dispensing of Oxygen.

C.2.1 Preparation of oxygen conventionally involves the compression of air, followed by cooling and re-expansion, a cycle that is repeated until the temperature of the air falls below the oxygen's critical temperature, causing it to liquefy. Fractional distillation of the liquid air then separates its various gaseous components. The oxygen is collected and can be stored as a compressed gas or as a liquid. Oxygen is also separated from air by adsorption and membrane-based systems.

C.2.2 Oxygen is transported to the consuming facility as a compressed gas or as a liquid, or it is transmitted by pipeline. NFPA 55 covers these applications.

C.2.2.1 Transport of liquid oxygen to the site of the consuming facility is usually in cryogenic tank trucks. Spillage of liquid oxygen during transport or during transfer from the tank can create OEAs.

C.2.3 When gaseous oxygen is dispensed at the consuming facility, it is drawn from the storage container(s) through pressure-reducing regulators and interconnecting piping.

C.2.4 Leakage or venting of oxygen from any storage or dispensing equipment can create an OEA. (See C.8.1.)

C.2.5 Contamination of any pressure-containing component of an oxygen storage or dispensing system with any flammable or

combustible substance, such as oil, grease, solvents, dust, lint, or any organic substance, can produce a serious fire or explosion hazard.

C.2.6 Consult NFPA 55 for the installation of storage systems.

C.3 Medical Applications.

C.3.1 OEAs have been associated with inhalation anesthesia since the development in 1887 of a gas anesthesia apparatus incorporating means of administering oxygen and nitrous oxide. The use of such a machine allows for both the anesthetization of patients and the often necessary administration of high-oxygen concentrations. The use of a flammable volatile liquid or gaseous inhalation anesthetic agent in such an atmosphere creates severe fire and explosion hazards. Prior to the formation of the NFPA Committee on Health Care Facilities, a significant number of fatalities and injuries resulted from operating room fires and explosions. Such incidents have been drastically reduced through widespread adherence to the provisions of NFPA 99.

The reduction in use of flammable anesthetics in operating rooms has allowed for increased use of potential ignition sources (electrosurgical units, lasers, etc.). Advances in materials science have also introduced polymers (endotracheal tube) and fabrics (drapes and gowns), some of which are flammable in air, but all of which are flammable in the OEA of operating rooms. Therefore, the operating room environment continues to present fire hazards.

C.3.2 Since the early 20th century, the therapeutic value of oxygen in the treatment of respiratory and allied disorders has been recognized by the medical profession. In consequence, inhalation therapy, including ventilator-support of patients, currently is widely practiced. Most hospitals of larger size are equipped with central oxygen-piping systems for use in patient care facilities throughout the hospital. Recognizing the potential hazards of OEAs created by such use, NFPA published NFPA 56F and NFPA 56B, both of which are now part of NFPA 99.

C.3.2.1 Because ambulatory patients as well as hospital patients might require respiratory therapy, some patients purchase or rent therapy equipment, oxygen cylinders, oxygen concentrators, and liquid oxygen containers for use in their homes. Thus, the medical applications of OEAs are not limited to locations within hospitals.

C.3.2.2 Chapter 14 of NFPA 99, 2005 edition, covers nonhospital use.

C.3.3 Ambulances, rescue squads, fire and police vehicles, and swimming pools are often equipped with oxygen for resuscitation and life-support purposes. Use of oxygen in such an enclosed space can create a hazardous OEA.

C.3.4 The medical profession uses hyperbaric chambers to allow supersaturation of patients with oxygen. The patient, with or without attendants, is placed in a hyperbaric chamber that is sealed and pressurized, sometimes to 4 atm absolute or greater. Generally, pressurization is accomplished with compressed air, and the patient breathes pure oxygen from a mask. However, in some single-occupant (patient only) chambers, the atmosphere is pure oxygen. Although there might be some flammability-inhibiting effect of the increased nitrogen present in compressed air, this effect is more than offset by the increased

partial pressure of the oxygen present (up to 5 atm). (*See Chapter 14 of NFPA 99 for more information on hyperbaric facilities.*)

A particularly hazardous OEA exists in a chamber pressurized with oxygen or in a compressed-air chamber with inadequate ventilation when pure oxygen is spilled from the therapy apparatus; therefore adherence to Chapter 14 of NFPA 99 is highly recommended.

C.4 Industrial Applications.

C.4.1 Oxygen, as an industrial gas, is in widespread use in a variety of industries. Furthermore, its use continues to increase in new applications where additional environmental or service conditions can place severe demands on equipment, materials, and systems. Elevated temperatures, high corrosivity, and reduced contamination levels are factors, in addition to flammability, that need to be considered, because they could limit the options of materials selection for oxygen services in advanced applications.

C.4.2 In the petrochemical industry, large quantities of oxygen are utilized for partial oxidation of gaseous and liquid organics and coal to prepare other products. These products include alcohols, aldehydes, and syngases. Elevated-temperature stability, corrosion resistance, and oxygen compatibility can limit use to certain alloys that are resistant to ignition and combustion in oxygen.

C.4.3 In the steel industry, oxygen is used to refine steel in the basic oxygen furnace as well as to lance molten steel in several operations. Oxygen-fuel burners are used to reheat ingots and slabs and to preheat ladles. Oxygen-fuel burners are also used in glass furnaces. Generally, materials selection issues and operating practices have been well defined in the steel industry.

C.4.4 In the metal fabrication industry, oxy-fuel burners are used to weld, cut, braze, silver-solder, and harden various metals. This work is done in large and small factories, automobile repair shops, and home workshops. NFPA 51 and NFPA 51B cover such applications.

C.4.5 In the mining industry, oxygen is used to refine copper, gold, and other metals by means of pressure oxidation processes, where sulphurous "refractory ores" are mined. Elevated temperatures and severe corrosivity place severe limitations on materials selection options.

C.4.6 Oxygen, as an alternative to air, is widely used for secondary treatment of both municipal and industrial wastewaters. Ozone from oxygen is sometimes used as an intermediate or for tertiary water treatment. Increased corrosivity might be experienced in certain wastewaters that contain both oxygen and ozone. Ozone will aggressively attack certain nonmetals.

C.4.7 Further developments in hazardous waste disposal include incineration involving OEAs and wet oxidation where supercritical water is used to dissolve and oxidize hazardous species. Supercritical wet oxidation is a particularly challenging environment for structural materials because it involves high temperatures, high pressures, and corrosive species.

C.4.8 Ultra-high purity (UHP) oxygen is used to manufacture microchips in the semiconductor industry. The need to eliminate contaminants to reduce chip defects results in ultraclean systems that reduce the tendency towards promoted ignition-combustion scenarios. However, the presence of UHP oxygen can increase the flammability hazard with certain metals and nonmetallics. Aluminum alloys are a prime example of materials that show a dramatic increase in flammability when exposed to UHP oxygen (99.999+ percent). (See F.3.4.4.)

C.4.9 The paper and pulp industry uses extensive amounts of oxygen in the bleaching and delignification processes as an alternative to chlorine. The use of ozone in this industry might also increase. Materials selection issues are similar to those encountered in various other processes where oxygen and aqueous environments are involved.

C.4.10 As a result of new technologies, the oxygen concentration of systems originally designed for air can be increased by a small percentage to increase efficiency. Such systems, which might not have been cleaned initially for oxygen service or designed with oxygen-compatible or combustion-resistant materials, would be unique. The systems should be treated on an individual basis with respect to issues such as cleaning, filtration, degree to which the oxygen levels are increased, and so forth.

C.4.11 Oxygen fireflooding is an example of a tertiary, enhanced oil recovery process that has been pilot tested. Oxygen is injected at high pressures into heavy oil deposits that cannot be recovered by primary or secondary oil recovery techniques. Downhole combustion of heavy oil results in high temperatures, high corrosivity when water is present, and increased oil mobility, allowing recovery at collection wells. Oxygen fireflooding requires careful system design and special operating procedures for the safe production of heavy oils.

C.4.12 In many applications, the motivation to use oxygen is driven by at least one of many factors, including the following:

- (1) Higher combustion temperatures
- (2) Higher purity gaseous product (no nitrogen from air)
- (3) Higher output from a given size reactor (often in conjunction with debottlenecking a process)
- (4) Higher conversion efficiency
- (5) Reduced combustion emissions (NO_x emissions can be reduced without the nitrogen from air)
- (6) Previously unobtainable production from mineral or oil deposits

Service environments might limit or eliminate the use of many materials that can be selected on the basis of combustion resistance in OEAs. Experimental programs might be needed to optimize materials selection and system design problems in advanced oxygen applications for safe operation.

C.4.13 Large users of oxygen are generally supplied by a pipeline from a nearby oxygen plant that uses cryogenic distillation. Smaller user requirements can be met by liquid oxygen that is transported by truck to a storage tank at the site, from a membrane or adsorption oxygen generator at the site, or from high-pressure cylinders. Requirements for system design, materials selection, cleaning, safe operation, and so forth are well established for oxygen supply systems.

C.5 Caisson Work and Underwater Tunneling. When driving a tunnel under or setting a foundation on a river bed, it might be necessary to seal off the work area with an airtight compartment and elevate the air pressure therein to prevent the pressure of the overlying water from inundating the compartment with mud or water. For every 10 m (33 ft) of depth of water outside the compartment, the pressure therein needs to be raised 1 atm to compensate (see Table C.1.2.1). An OEA exists within the compartment while it is pressurized.

C.6 Space and Deep-Sea Exploration.

C.6.1 Liquid oxygen is employed as the oxidizer in liquid propellant rockets, and gaseous oxygen is used in the breathing atmospheres of spacecraft and spacecraft simulators. OEAs also exist in certain deep-sea diving equipment.

C.6.2 Liquid-fueled rockets employ liquid oxygen as the oxidizing agent. OEAs can, and generally do, develop from blow off and leakage whenever the rocket is tanked or while it is standing in readiness.

C.6.3 The practice of using aviator breathing oxygen (ABO) for spacecraft life-support systems has been the normal practice in the past and might be required in the future for long-duration missions. Previous space programs, such as Gemini, Mercury, and Apollo, used an ABO atmosphere in life-support systems. An OEA is currently used in the space shuttle program. During normal operations, the orbiter oxygen concentration can reach as high as 25.9 percent oxygen due to calibration margins in the control and caution/warning systems. Prior to each extravehicular activity (EVA), the orbiter atmosphere is changed to a 30 percent oxygen atmosphere at 70.3 kPa (absolute pressure of 10.2 psi). This 30 percent oxygen atmosphere is used for 6 to 10 hours prior to the actual EVA to precondition the crew for the space suit environment of 34.5 kPa (absolute pressure of 5 psi) 100 percent ABO atmosphere.

C.6.3.1 The space station is designed to operate at 70.3 kPa (absolute pressure of 10.2 psi) with a 30 percent oxygen atmosphere until it is permanently manned. The current schedule is for the space station to be occupied only when a shuttle is docked for the first 5 to 6 years of operations. Once the space station is permanently occupied, it is expected to operate at 1 atm with up to 25 percent oxygen concentration. The space station will have a hyperbaric chamber to treat the bends, if necessary. This chamber will be operated at 4 atm at 21 percent oxygen concentration and used only in an emergency.

C.6.3.2 The oxygen concentration on the spacecraft can be increased by leakage in the primary oxygen supply system or the emergency oxygen system. This situation has occurred in the orbiter cabin several times over the years. A leak in one of the systems caused the cabin oxygen concentration to reach 35 percent for a few hours. Once the leaks were found and corrected, the oxygen concentration was reduced to normal limits within a short time.

C.6.4 Experimental and conventional deep-sea diving equipment, including pressure chambers, will contain an OEA if the partial pressure of oxygen exceeds 21.3 kPa (160 torr).