2nd Edition

Safe Use of Oxygen and Oxygen Systems:

Handbook for Design, Operation, and Maintenance

Harold D. Beeson
Sarah R. Smith
Walter F. Stewart
Editors

standards Worldwide

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Foreword

This edition of THE SAFE USE OF OXYGEN AND OXYGEN SYSTEMS is sponsored by Committee G4 on Compatibility and Sensitivity of Materials in Oxygen-Enriched Atmospheres. The editorial and review work for this edition were coordinated by Sarah R. Smith, NASA Johnson Space Center White Sands Test Facility, Las Cruces, New Mexico.

This edition of the handbook is an extensive revision of the original ASTM Manual 36. This revision includes large structural changes in the document as well as updates to the information and data contained herein.

This manual contains minimum guidelines; users are encouraged to assess their individual programs and develop additional requirements, as needed.

"Shalls" and "wills" denote requirements that are mandated by other existing documents, which are referenced.

Acknowledgments

The original material was contained in the *NASA Safety Standard for Oxygen and Oxygen Systems,* NSS 1740.15, which established a uniform NASA process for oxygen system design, materials selection, operation, storage, and transportation. The NASA document represented a wealth of information, knowledge, and experience gained by NASA and its contractors. This information, knowledge, and experience should be extremely valuable to industry, particularly the small or infrequent user of oxygen who has little or no experience and staff to draw upon.

The NASA Oxygen Safety Handbook was originally prepared under NASA contract by Paul M. Ordin, Consulting Engineer. The support of the NASA Hydrogen-Oxygen Safety Standards Review Committee in providing technical monitoring of the original standard is recognized. The Committee included the following members:

William J. Brown–NASA Lewis Research Center
Frank J. Benz–NASA Johnson Space Center
Mike Pedley–NASA Johnson Space Center
Dennis Griffin–NASA Marshall Space Flight Center
Coleman J. Bryan–NASA Kennedy Space Center
Wayne Thomas–NASA Lewis Research Center
Wayne Frazier–NASA Headquarters

The editors also gratefully acknowledge the special contributions of Grace B. Ordin for aiding the preliminary review, organizing the material, and editing the original drafts, and William A. Price of Vitro Corporation for input into the original standard. The NASA Oxygen Safety Handbook was prepared and edited by personnel at the NASA Johnson Space Center White Sands Test Facility. Specific contributors include: David Hirsch, Jan Goldberg, Elliot Forsyth, Mike Shoffstall, Mohan Gunaji, Rollin Christianson, Richard Shelley, Subhasish Sircar, Larry Bamford, Jim Williams, Jack Stradling, and Joel Stoltzfus. The expertise of these professionals in the area of oxygen system hazards, design, and operation is gratefully acknowledged.

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The sponsoring committee for this manual is ASTM G4 on Compatibility and Sensitivity of Materials in Oxygen-Enriched Atmospheres. The committee chairman is Joseph Slusser. The oxygen manual review taskgroup consisted of Alain Colson, Barry Newton, Bob Zawierucha, Eddie Davis, Elliot Forsyth, Herve Barthelemy, Jake Jacobs, Joe Million, Joe Slusser, Kim Dunleavy, Lee Birch, Mike Shoffstall, Michael Slockers, Gwenael Chiffoleau, John Somavarapu, Steve Herald, Joel Stoltzfus, and Ting Chou. The work of these individuals is gratefully acknowledged.

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Nomenclature

AAR	American Association of Railroads
AGA	American Gas Association
AHJ	Authority Having Jurisdiction
AIChE	American Institute of Chemical Engineers
AIHA	American Industrial Hygiene Association
AIT	Autoignition Temperature
Al_2O_3	Aluminum Oxide
ANSI	American National Standards Institute
API	American Petroleum Institute
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
ASRDI	Aerospace Safety Research and Data Institute
ASTM	American Society for Testing and Materials
BCL	Battelle Columbus Laboratories
BM	Bureau of Mines
CDR	Concept Design Review
CFR	Code of Federal Regulations
CGA	Compressed Gas Association
CHEMTREC	Chemical Transportation Emergency Center
CNS	Central Nervous System
CP	Critical Point
CPIA	Chemical Propulsion Information Agency
Cr_2O_3	Chromium Oxide
CTFE	Chlorotrifluoroethylene
DCR	Design Certification Review
DI	Deionized
DOD	Department of Defense
DODESB	Department of Defense Explosives Safety Board
DOE	Department of Energy
DOT	Department of Transportation
ECTFE	Poly(chlorotrifluoroethylene-*co*-ethylene)
EIGA	European Industrial Gases Association
EPR	Emergency Procedures Review
ETFE	Poly(ethylene-*co*-tetrafluoroethylene)
FAA	Federal Aviation Administration
FDR	Final Design Review
FeO	Iron Oxide
FEP	Fluorinated Ethylene-propylene
FMEA	Failure Modes and Effects Analysis
FSA	Final Safety Analysis
GN_2	Gaseous Nitrogen
GOX	Gaseous Oxygen
HAZMAT	Hazardous Material
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFE	Hydrofluoroether
HMRB	Hazardous Materials Regulation Board
IEEE	Institute of Electrical and Electronic Engineering
IPA	Isopropyl Alcohol
ISO	International Organization for Standardization
LANL	Los Alamos National Laboratory
LH_2	Liquid Hydrogen
LNG	Liquified Natural Gas
LOI	Limiting Oxygen Index
LOX	Liquid Oxygen
MAPTIS	Materials and Processes Technical Information System
MAWP	Maximum Allowable Working Pressure
MCA	Manufacturers' Chemists Association
MCA	Materials Compatibility Assessment

M&P	Materials and Processes
MRHT	Marked Rated Holding Time
MSDS	Material Safety Data Sheet
MSFC	Marshall Space Flight Center
MSS	Manufacturers' Standardization Society
NASA	National Aeronautics and Space Administration
NBP	Normal Boiling Point
NBS	National Bureau of Standards (this organization is now the National Institute of Standards and Technology (NIST))
NEMA	National Electrical Manufacturers' Association
NER	Normal Evaporation Rate
NFPA	National Fire Protection Association
NHB	NASA Handbook
NiO	Nickel Oxide
NSS	NASA Safety Standard
NTIS	National Technical Information Service
NTP	Normal Temperature and Pressure (Absolute), 293.15 K (68°F) and 101.325 kPa (14.696 psi)
NTSB	National Transportation Safety Board
NVR	Nonvolatile Residue
OCA	Oxygen Compatibility Assessment
OHFRA	Oxygen Hazards and Fire Risk Assessment
OHM	Office of Hazardous Materials
OPR	Operating Procedures Review
ORI	Operational Readiness Inspection
ORR	Operational Readiness Review
OSHA	Occupational Safety and Health Administration
OTR	Operator Training Review
PDR	Preliminary Design Review
PHA	Preliminary Hazard Analysis
PICT	Promoted-Ignition Combustion Transition
PMMA	Polymethylmethacrylate
PSA	Preliminary Safety Analysis
PTFE	Polytetrafluoroethylene (Teflon®)
QA	Quality Assurance
RHT	Rated Holding Time
RP-1	Rocket Propellant-1 (Kerosene)
S&A	Safe and Arm
SAR	Safety Analysis Report
SAsR	Safety Assessment Review
SiO_2	Silicon Oxide
SOP	Standard Operating Procedure
SOW	Statement of Work
SR	Safety Review
SRM&QA	Safety, Reliability, Maintainability & Quality Assurance
SS	Stainless Steel
SSA	System Safety Analysis
SSA/SR	System Safety Analysis/Safety Review
SSPP	System Safety Program Plan
STP	Standard Temperature and Pressure (Absolute), 273.15 K (32°F) and 101.325 kPa (14.696 psi)
T_g	Glass Transition Temperature
TNT	Trinitrotoluene
TRR	Test Readiness Review
USCG	U.S. Coast Guard
WSTF	White Sands Test Facility
ZrO_2	Zirconium Oxide

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Basic Oxygen Safety Guidelines

Introduction

OXYGEN, WHICH CONSTITUTES APPROXIMATELY 21 % of the Earth's atmosphere, is a colorless, odorless, and tasteless gas at standard temperature and pressure. The normal boiling point temperature of oxygen is 90.25 K (−297.3°F). High-purity liquid oxygen (LOX) is light blue, odorless, and transparent. Two significant properties of oxygen are its ability to sustain life and its ability to support combustion. Although oxygen itself is chemically stable, is not shock-sensitive, will not decompose, and is not flammable, its use involves a degree of risk†[1] that should never be overlooked. Oxygen is a powerful oxidizer in both the gaseous and liquid states. Many materials that will not burn in air will do so in an oxygen-enriched† atmosphere and will have lower ignition energies and burn more rapidly. Oxygen is reactive at ambient conditions, and its reactivity increases with increasing pressure, temperature, and concentration.

Most nonmetals† are flammable† in 100 % oxygen at ambient pressure, and most metals are flammable in oxygen at increased pressure. Catastrophic fires have occurred in low-pressure and high-pressure† oxygen systems, in gaseous oxygen and liquid oxygen systems, and even in oxygen-enriched† systems operating with less than 100 % oxygen. When fires occur in oxygen systems, personnel may be injured or killed, equipment may be damaged or destroyed, and system or mission objectives may be aborted. Therefore, ignition hazards† in oxygen systems must be reduced or eliminated through proper materials selection, system design, and maintenance practices.

The successful design, development, and operation of oxygen systems require special knowledge and understanding of ignition mechanisms, material properties, design practices, test data, and manufacturing and operating techniques. All oxygen systems should be reviewed by a person, or preferably a group, trained in fire hazards in oxygen systems, design principles, and materials selection. Furthermore, the system designer, owner, and user should be knowledgeable in oxygen-related hazards and maintain control of configurational changes after a system is in service. Each organization must establish its own "approval authority" and system control mechanisms to suit its own needs and to satisfy OSHA requirements.

Basic Principles for the Safe Use of Oxygen

Specific hazards and ignition mechanisms are addressed in Chapters 2 and 5, but the following principles apply to nearly all oxygen systems:

1. Every oxygen system is considered unique and independent, requiring individual assessment to evaluate the materials compatibility and the presence of fire hazards.
2. Ignition sources should be minimized or eliminated through purposeful design of components and systems.
3. It is preferable to use ignition- and combustion-resistant materials.
4. Materials that are highly reactive in oxygen should be avoided.
5. Materials that are less reactive, but are still situationally flammable, can be used if protected from ignition sources.
6. Oxygen systems should be kept clean because contaminants, such as oils or particulates, can be easily ignited and provide a kindling chain to ignite surrounding materials.
7. Leak prevention and adequate ventilation should be ensured to prevent unintentional oxygen enrichment of the environment surrounding an oxygen system.
8. All oxygen system equipment and power sources should be verified for safe performance in both the normal and maximum operating regimes. In the event of any failure, systems should revert to conditions that will be the safest for personnel and cause the least damage to the surrounding environment.
9. Safety systems should include at least two barriers or safeguards so that at least two concurrent associated undesired events must occur before there is any possibility of personnel injury, loss of life, or major equipment or property damage.

Oxygen Handling Hazards

The principal hazards associated with handling oxygen are related to fire, health, pressure, and temperature as described below. Information on how to deal with these hazards can be found later in this chapter in the section "Emergencies."

Fire

Catastrophic fires have occurred as a result of the ignition hazards inherent with the use of oxygen systems, as well as a result of oxygen exposure. In general, materials in oxygen-enriched† atmospheres ignite more readily, burn at higher flame temperatures, and burn more rapidly than in air. Furthermore, many materials that will not burn in air will burn vigorously in oxygen-enriched environments. Fires in oxygen systems can occur when a system material or contaminant ignites and burns. Materials not originally intended for use in oxygen can be exposed to oxygen as a result of leaks or improper handling practices and can be exposed to LOX during fill and transfer operations, chill-down operations, or when LOX is spilled. Gaseous oxygen (GOX) is slightly denser than air, and LOX is slightly denser than water. Therefore, GOX and LOX will tend to accumulate in low points or depressions. In addition, because LOX is approximately 800 times more dense

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[1] The † indicates a term defined in the Glossary (Appendix G).

than GOX, spills or leaks of LOX can lead to rapid oxygen enrichment. Oxygen can saturate clothing and skin, rendering them extremely flammable and ignitable by seemingly small ignition energy† sources. Many porous materials, such as asphalt, leather, and cork, can become impact-sensitive when exposed to LOX [1]. A few materials, including strong reducing agents such as monomethylhydrazine, may spontaneously ignite upon contact with LOX [2].

Health

The low temperature of LOX can pose a health hazard. For example, frostbite may occur if skin comes into contact with LOX, uninsulated piping containing LOX, or cold GOX. Therefore, operators and users must be protected from the extremely low temperatures. In addition, the use of GOX and LOX is increasing for medical applications, such as treatment for respiratory illnesses, wounds, or soft-tissue injuries. Breathing high concentrations of oxygen for extended periods of time can cause health problems such as oxygen toxicity. Low-pressure oxygen poisoning, or pulmonary oxygen toxicity, can begin to occur if more than 60 % oxygen at one atmosphere is breathed for 24 h or longer. The rate of symptom onset increases if the individual is exposed to an increased pressure, such as during diving or hyperbaric chamber operations. The symptoms of pulmonary oxygen toxicity may begin with a burning sensation on inspiration and progress to pain on inspiration, dry coughing, and inner ear pain. If exposure continues, it may result in permanent lung damage or pneumonia. High-pressure oxygen poisoning, or central nervous system (CNS) oxygen toxicity, is most likely to occur when divers or hyperbaric chamber occupants are exposed to 1.6 atmospheres of oxygen (equivalent to 100 % oxygen at a depth of 6 meters, or 20 feet). Susceptibility to CNS oxygen toxicity varies from person to person and exposure to exposure. Unconsciousness and violent convulsions are the most serious consequence of CNS oxygen toxicity. Removal of the subject from exposure to high oxygen concentration will result in the convulsions subsiding [3]. For more information on specific physiological hazards and effects of breathing either pure or high concentrations of oxygen for extended periods of time, it is recommended that a physician or an appropriate reference on human physiology be consulted.

Pressure

GOX and LOX are commonly stored under pressure. Any pressure vessel rupture can produce dangerous flying debris. Furthermore, the materials of construction of pressure vessels used to store GOX and LOX may be rendered flammable as a result of the increase in oxygen concentration. This flammability can increase the severity of the effects of pressure vessel rupture. Oxygen cannot be kept as a liquid if its temperature increases above the critical temperature, that is, 155 K (−181°F). Even in well-insulated cryogenic storage containers, LOX is continually boiling to a gas. Thus, pressure relief for these closed containers is extremely important to minimize the risk of overpressure. Any LOX trapped within a closed system and allowed to warm can build up extreme pressure, causing the system to rupture and possibly produce dangerous flying debris.

Temperature

As described previously, contact with LOX or cold GOX, or uninsulated items containing LOX or cold GOX, can result in frostbite because of the low temperature involved. In addition, the mechanical and thermal properties of materials used in LOX or cold GOX service must be suitable for the low temperature involved to avoid a material, and consequently, a component failure.

Oxygen Purity

Oxygen for breathing applications should be purchased to conform to the Performance Standard, Oxygen: Aviators Breathing, Liquid and Gas (MIL-PRF-27210G [4]). Oxygen for propellant† applications should be purchased to conform to Performance Specification, Propellant, Oxygen (MIL-PRF-25508G [5]). Medical oxygen must meet the United States Pharmacopeia requirements for medical oxygen. For other applications, oxygen should be purchased to conform to the equivalent industrial standards, such as the Commodity Specification for Oxygen (CGA G-4.3) and the Commodity Specification for Oxygen Produced by Chemical Reaction (CGA G-4.5), which specify the oxygen purity and level of contaminants that are allowed appropriate to the intended application.

Oxygen is easily contaminated because many gases and liquids are soluble or completely miscible in it. Mixing an odorless and colorless gas in oxygen can create an invisible hazard. For example, health hazards can be produced in breathing gas systems when toxic gases are present, or when inert gases, such as argon and nitrogen, displace oxygen and cause asphyxiation as a result of reduced oxygen concentration. In addition, explosions† can occur as a result of inadvertent mixing of flammable gases with oxygen. The very low temperature of LOX may result in condensing and/or solidifying impurities, resulting in the concentration of contaminants.

Importance of Cleaning Oxygen System and Components

Scrupulous cleaning is the most fundamental fire safety measure that can be applied to oxygen systems. The presence of contaminants in otherwise-robust oxygen systems can lead to catastrophic fires. To reduce the hazard of ignition, components used in oxygen systems should always be reasonably clean before initial assembly to ensure the removal of contaminants such as particulates and hydrocarbon oils and greases that could potentially cause mechanical malfunctions, system failures, fires, or explosions. Visual cleanliness is not a sufficient criterion when dealing with oxygen systems because of the hazards associated with contaminants that cannot be detected with the naked eye. See Chapter 6 for more information on cleaning and maintaining cleanliness.

Personnel Training

Personnel, including designers of equipment for oxygen service, operators and maintainers of oxygen systems, and users of oxygen, should be properly trained in several specific areas, including:

1. Oxygen's physical, chemical, and hazardous properties,
2. Oxygen materials compatibility, ignition mechanisms, and fire propagation,
3. Cleanliness requirements for oxygen systems,
4. Recognition of system design parameters and how to respond properly to *all foreseeable* failure modes,
5. First-aid techniques,
6. Use and care of protective and safety equipment,
7. Selection of proper equipment for handling LOX and GOX, and

8. Procedures for disposing of oxygen and handling spills and leaks.

Personal Protective Equipment

The purpose of personal protective equipment is to reduce exposure to hazards. Because there are hazards associated with using oxygen, the need for personal protective equipment should be evaluated for both oxygen-enriched and oxygen-deficient environments.

Oxygen-Enriched Environments

OSHA defines an oxygen-enriched atmosphere as an environment that has an oxygen concentration of 22 vol % or greater [6].

Clothing

Oxygen will saturate normal clothing, rendering it extremely flammable. Clothing described as flame-resistant or flame-retardant under normal atmospheric conditions will burn fiercely in environments containing as little as 30 % oxygen, and no material should be considered burn-proof or burn-resistant in oxygen-enriched environments unless it is known to have been subjected to proper testing. Clothing worn in areas of possible oxygen enrichment should be free from oil and grease, well fitting, and easy to remove. This clothing should be carefully selected for minimum combustibility.

Glass fiber and asbestos are the only untreated textile materials that are truly nonflammable in 100 % oxygen, but they are unsatisfactory for making clothes without the addition of combustible fibers. Some synthetic materials may be fire-resistant, but can lead to more serious burns because they may adhere to skin when molten. From a practical point of view, wool is probably as good as any other ordinary clothing material. It is readily available and can be quickly extinguished in normal air.

When working around LOX, precautions should be taken to ensure that workers are protected from thermal injuries. Therefore, the pants must have no external pocket openings or cuffs. If LOX is being handled in an open system, an apron of impermeable material should be worn to protect the wearer from thermal injuries.

Any clothing that has been soaked with oxygen or splashed with LOX should not be removed until completely free of oxygen enrichment. Therefore, personnel exposed to oxygen-enriched atmospheres should leave the area and avoid all sources of ignition until the oxygen in their clothing dissipates. The time required for oxygen enrichment in clothing to dissipate is highly variable depending on the type of clothing and the surrounding atmospheric conditions; however, a general practice is to avoid ignition sources and not remove any clothing for 30 min after exposure to oxygen.

Note: Possible sources of ignition include sparks from tools, cigarettes, and static electricity.

Gloves

Gloves for use around LOX systems must have good insulating quality. They must be designed for quick removal in case LOX gets inside.

Footwear

Because LOX may get inside of footwear, shoes must have high tops and pant legs must be worn outside and over the shoe tops. The shoes should be made of leather.

Head and Face Protection

To prevent injury as a result of LOX exposure, personnel handling LOX should wear a face shield or a hood with a face shield.

Ancillary Equipment

Appropriate ancillary equipment should be available during operations involving GOX or LOX. This equipment may include:

- Portable oxygen detectors in situations where oxygen leakage may increase fire and explosion hazards,
- Safety showers and eyewash fountains to deal with fire and corrosive chemicals (but not cryogenic burns), and
- Water hoses to thaw valves and fittings on cryogenic storage containers, or to thaw the ice if someone's gloved hand freezes to a valve handle.

Oxygen-Deficient Environments

OSHA defines an oxygen-deficient atmosphere as an environment that has an oxygen concentration of less than 19.5 vol % [6].

Respiratory Protection

Personnel should use appropriate breathing equipment when working in an area in which respiratory protection is required, as during cleaning, venting, or purging operations. The breathing air used should be periodically tested to ensure it meets CGA Grade D air specifications. Absorbent types of respirators are totally ineffective and, consequently, should not be used in an oxygen-deficient environment. Recommended types of breathing equipment include:

- self-contained breathing apparatus, and
- supplied-air respirator, in which the respirator is connected by a hose of adequate length and diameter to a compressed air supply, or to a region where the atmosphere is of satisfactory composition to support life. The respirator should incorporate a suitable one-way valve system to ensure asphyxiation does not occur as a result of breathing the same air repeatedly.

Warning Systems and Controls

Warning systems should be incorporated in oxygen systems to monitor storage, handling, and use parameters, such as pressure, temperature, and oxygen-enrichment. Control of oxygen systems should include warning systems with sensors to detect malfunctions and incipient failures that may endanger personnel and cause environmental damage. Oxygen systems should be designed with sufficient redundancy to prevent any single-point failure from compromising the system's integrity in any way. The warning systems should be shielded and designed so the operation of a single detection device serves to alarm but not necessarily to initiate basic fire and emergency protection. Equipment should be installed for control of automatic equipment to reduce the hazards indicated by the warning systems.

Safety Reviews

Planning for personnel safety at or near oxygen systems must begin in the earliest stages of the design process to reduce the risk of injury or loss of life. Safety reviews should be regularly conducted to ensure the safe use of oxygen. These reviews should include oxygen compatibility assessments at the component and system levels (Chapter 4), as well as at the facility level (Chapter 8), to identify conditions that may cause injury, death, or major property damage. In addition, operating procedures, emergency procedures, instrumentation, and process controls should be reviewed. Safety documentation should describe the safety organization and comment specifically on inspections, training, safety communications and meetings, operations safety and instruction manuals, incident investigations, and safety instruction records. More information on safety reviews can be found in Appendix F.

Organizational Policies and Procedures

Any organization involved in the use of oxygen should define, develop, establish, document, implement, and maintain policies and procedures to govern and control all phases of a product or system that involves the use of oxygen. These policies and procedures should govern the use of oxygen from the beginning concepts through removal from service and decommissioning. It is important that the policies and procedures of each organization include appropriate reviews (such as design reviews and safety reviews) and approvals (such as for the materials and processes used) for a product or system that involves oxygen. A summary of the safety-related organizational policies and procedures that are recommended for organizations involved in the use of oxygen is given in Appendix F.

Emergencies

The authority having jurisdiction at a facility is responsible for the preparation of emergency plans and implementing emergency procedures. Evacuation routes, requirements, and responsibilities of site personnel should be included in these plans. Dry runs of safety procedures should be conducted using both equipment and personnel. Periodic safety inspections and surveys should be performed to ensure that emergency procedures are being performed safely.

Supervisors should periodically monitor oxygen-handling operations to ensure that all safety precautions are taken during transfer, loading, testing, and disposal. Local fire or other emergency personnel should be informed of any unusual or unplanned operations. Also, the accessibility and usability of fire protection and spill response equipment should be verified prior to the commencement of oxygen-handling operations. Written emergency procedures should be included in all operating procedures involving oxygen.

Types of Emergencies

Leaks and Spills

The primary danger from oxygen leaks and spills is a fire or explosion caused by the ignition of combustible materials in the presence of a high concentration of oxygen. The possibility of ignition and fire can be significantly increased by enriching the oxygen concentration of air by even a few percent, or by a slight increase in oxygen partial pressure. Experience has shown that when LOX is spilled in an open space, the hazardous oxygen concentrations usually exist only within the visible cloud associated with the spill. Oxygen-enriched environments greatly increase the rate of combustion of flammable materials.

Oxygen at normal temperature and pressure (NTP†) is approximately 10 % denser than air, and oxygen vapor at the normal boiling point (NBP†) is approximately 3.7 times the density of air. Consequently, oxygen from a LOX spill or from a GOX leak (even at room temperature) will settle into the lowest surrounding space, such as low areas of the terrain and trenches. Electrical conduits that are not gas-tight and are located in a trench or low area may provide a path for oxygen gas to travel to locations where it could be a hazard.

Oxygen leaks can result in oxygen-enriched environments, especially in confined spaces. Because LOX is approximately 800 times more dense than GOX at NTP, spills or leaks of LOX can lead to rapid oxygen enrichment of the immediate vicinity as the liquid vaporizes. When a spill or leak is detected, the following actions may be appropriate:

- The oxygen source should be immediately isolated or disconnected.
- If fuel and oxygen are mixed but not burning, quickly isolate the area from ignition sources, evacuate personnel, and allow the oxygen to evaporate. Mixtures of fuel and oxygen are extremely hazardous.
- Any equipment inherently heat- or spark-producing should be turned off or disconnected.
- Smoking should be prohibited.
- Hydrocarbon oils and greases should be avoided.
- Affected areas should be completely roped off or otherwise controlled to limit personnel movement.
- The equipment or piping should be thoroughly vented and warmed before repair of the leak is attempted.
- Disassembly and repair of leaking lines should begin only after the area has been properly ventilated.

> *Note*: *Special caution is required to avoid mechanical impacts when there are LOX spills.*

Porous hydrocarbons such as asphalt, wood, and leather can become shock-sensitive in LOX and react explosively when impacted even with relatively small amounts of energy [1]. LOX spills on pavements such as asphalt have resulted in impact-sensitive conditions that caused explosions from traffic or dropped items [7]. Testing has shown that the presence of contamination on hydrocarbon materials will increase the hazard [8]. In addition, the presence of contaminants such as oil, grease, or other organic materials, can create a mechanical impact hazard on materials that are not normally susceptible to mechanical impact ignition, such as concrete. Furthermore, some cleaning solvents are known to become shock-sensitive in LOX. If LOX comes into contact with any porous hydrocarbon materials or contaminated nonporous materials, care should be taken to avoid mechanical impacts of any kind until the LOX has dissipated. The affected areas should be completely roped off or otherwise controlled to limit vehicle and personnel movement. Electrical sources should be turned off or disconnected. No attempt should be made to hose off the affected area, and the area should not be cleared for access until the oxygen-rich cold materials are adequately warmed and the absorbed oxygen has evaporated. The amount of time required for the absorbed oxygen to evaporate is dependent on many variables including the weather, the size of the LOX spill, and the porosity of the materials exposed to LOX. A general practice is to control access to the area for 30 minutes after any condensed water vapor cloud is observed.

Overpressurization

Oxygen cannot be kept liquid if its temperature rises above the critical temperature of 155 K (−181°F). Even in well-insulated cryogenic storage containers, LOX is continually boiling to GOX. Consequently, if LOX is trapped in a closed system and allowed to warm, extreme pressures can result in overpressurization of the system. For example, LOX trapped between valves can rupture the valves or the connecting pipe. Pressure relief of some kind must be provided where trapping might occur. Moreover, relief and vent systems must be sized to accommodate the flow so that excessive backpressures will not occur. Cryogenic liquid storage vessels are protected from overpressurization by a series of pressure relief devices. These relief devices are designed to protect the inner vessel and the vacuum-insulated portion of the tank from failures caused by inner and outer shell damage, overfilling, and heat load from insulation damage or from a fire.

In specific instances, such as when these vessels are involved in a fire that impinges upon the ullage area of the tank, container failure could result. In these instances, water should be directed onto the flame-impinged portion of the tank to allow the tank to cool. Enough water should be directed onto this area to keep the tank wet. Water should not be directed toward the relief devices, as the venting gas may cause the water to freeze and thereby seal off the relief device.

Frost appearing on the outer wall of an insulated cryogenic vessel may be indicative of a thermal insulation loss. A thermal insulation loss could be the result of a number of causes such as a movement of the insulation in the annular area of the tank, a loss of vacuum in the annular area, or a failure of the inner vessel. The appearance of frost on the outer wall could be an important signal that should not be ignored, especially if the outer wall material is subject to cold embrittlement. Assistance from knowledgeable and responsible pressure-systems personnel should be obtained.

Personnel should listen and watch for indication of pressure-relief device actuation. Special care should be taken if the sound of the relief device changes and becomes higher pitched while operating. Continued pressure increase while the relief device is actuated indicates a major system malfunction. If constant relief device actuation is occurring with continually increased flow rates or pressures (as indicated through audible pitch or otherwise), immediately evacuate the area and if it can be performed safely, physically rope off and control access to the area. Venting the vessel is recommended, if possible. Do not apply water, as this would only act as a heat source to the much colder oxygen and aggravate the boiloff.

Transportation Emergencies

Vehicular incidents involving oxygen transports can result in leaks, spills, and container rupture. Spills and leaks may result in fires and explosions. The first priority in an emergency situation is to protect personnel from hazards resulting from a spill or release of oxygen. The next priority is protection of property and the environment, which should occur only after personal safety hazards have been mitigated. Consult the *DOT Emergency Response Guidebook* [9] and other references shown below for information regarding the emergency action to take in the event of an incident involving LOX or GOX.

Additional information can be obtained 24 h a day by calling the Chemical Transportation Emergency Center (CHEMTREC) at **800-424-9300** (worldwide 202-483-7616). Other emergency procedure information can be obtained from the Association of American Railroads (AAR), Bureau of Explosives, *Emergency Handling of Hazardous Materials in Surface Transportation* [10], and the National Response Center at the U.S. Coast Guard Headquarters at **800-424-8802** or **202-267-2675.**

First-Aid Procedures

Cryogenic Injuries

Direct physical contact with LOX, cold vapor, or cold equipment can cause serious tissue damage. Momentary contact with a small amount of the liquid may not pose as great a danger of burn because a protective film may form. Danger of freezing occurs when large amounts are spilled and exposure is extensive. Cardiac malfunctions are likely when the internal body temperature drops to 300 K (80°F), and death may result when the internal body temperature drops to 298 K (76°F). Education regarding the risk of cold injury as well as preventive and emergency care should be incorporated into operations and emergency response training programs.

> *Note: This information represents the most current understanding regarding cold injuries. It may change, and anyone dealing with cryogenic oxygen systems should keep informed on the latest recommended procedures.*

The following are guidelines for response to a cryogenic injury.

- The injured person should not be exposed to ignition sources such as smoking, open flame, or static-electric sparks.
- The injured person should be carefully removed from the cold source and kept warm and at rest.
- The injured area should be protected (covered) with a loose, dry, sterile dressing that does not restrict blood circulation.
- Medical assistance should be obtained as soon as possible. Treatment of truly frozen tissue requires medical supervision because improperly rendered first aid invariably aggravates the injury. In general, the recommended in-field response to a cold injury[†] is that non-medically trained personnel do only what is absolutely necessary.
- The injured person should be transported, as directed by medical personnel, to a medical facility as soon as possible.
- The affected part may be warmed to its normal temperature.
    - The injured part may be immersed in, or gently flushed with, warm water at a temperature of 311 K to 313 K (100°F to 104°F).
    - The affected part should not be exposed to a temperature greater than 315 K (108°F). Exposure to a higher temperature may superimpose a burn, and gravely damage already injured tissue.
    - Safety showers, eyewash fountains, or other sources of water shall not be used because the water temperature will almost certainly be therapeutically incorrect and aggravate the injury. Safety showers should be tagged, "NOT TO BE USED FOR TREATMENT OF CRYOGENIC BURNS."
- Frozen gloves, shoes, or clothing that could restrict circulation to the injured area may be removed, but only in a slow, careful manner such that the skin is not pulled off with the item being removed. An injured person, with any

unremoved clothing, may be put into a warm water bath at the temperature specified previously.

- The affected part should not be subjected to a rapid stream of water; nor should the affected part be massaged or rubbed with snow or ice, or have any type of ointment applied to it. These actions should not be taken either before or after warming of the injured part.
- Actions (such as smoking tobacco or drinking alcohol) that result in decreasing the blood supply to the injured part should not be permitted.

Exposure to, or Injury Within, an Oxygen-Enriched Environment

Personnel exposed to an oxygen-enriched environment should leave the area and avoid all sources of ignition until the oxygen in their clothing dissipates. The time required for oxygen enrichment in clothing to dissipate is highly variable depending on the type of clothing and the surrounding atmospheric conditions; however, a general practice is to avoid ignition sources and not remove any clothing for 30 min after exposure to oxygen. Possible sources of ignition include sparks from tools, cigarettes, and static electricity.

Rescuers of a victim in an oxygen-enriched environment should not enter the affected area unless they can be deluged with water or they are equipped with fire rescue suits. The clothing of first-responders is most likely highly susceptible to ignition from flames or sparks; consequently, victims in an oxygen-enriched environment often cannot be removed immediately from the affected area. The victim should be deluged with water from a hose, series of fire buckets, or shower and should be moved into fresh air as soon as possible. Medical assistance should be summoned immediately [11].

Exposure to, or Injury Within, an Oxygen-Deficient Environment

An oxygen-deficient environment is a serious physiological hazard. For example, exposure to an atmosphere containing 12 % or less oxygen will bring about unconsciousness without warning so quickly that the people will not be able to help themselves. Medical assistance should be sought immediately for anyone involved in, or exposed to, an oxygen-deficient environment. Rescue should not be attempted under any circumstances without proper breathing equipment and proper training in rescue procedures while using breathing equipment. Rescue personnel need to be provided with an adequate supply of air or oxygen from self-contained breathing apparatus or fresh air lines [12].

Anyone exposed to an oxygen-deficient environment should be moved to an area of open (normal) air without delay and kept warm. If the victim is not breathing, oxygen should be administered from an automatic resuscitator, if available, or artificial respiration should be applied by an approved method. Resuscitation procedures should be continued until the victim revives or until a doctor gives other instructions.

Fire-Fighting Techniques

Some general guidelines for fighting fires involving oxygen-enriched atmospheres are as follows:

- The first step should be to shut off the oxygen supply. In some cases, when the oxygen supply cannot be shut off, the fire may burn so vigorously that containment and control are more prudent than trying to put out the fire.
- If possible, shut off and remove fuel sources.
- Water is the recommended extinguishment agent.
- If a fire is supported by LOX flowing into large quantities of fuel, shut off the oxygen flow. After the excess oxygen is depleted, put out the fire with the extinguishing agent recommended for the particular fuel.
- If a fire is supported by fuel flowing into large quantities of LOX, shut off the fuel flow and allow the fire to burn out. If other combustible materials in the area are burning, water streams or fogs may be used to control the fires.
- If large pools of oxygen and water-soluble fuels, such as hydrazine or alcohol, are burning, use water to dilute the fuel and reduce the fire's intensity.

Materials for fire fighting involving an oxygen-enriched environment should be restricted to water (preferred), sand, or chemical fire extinguishers using dry chemicals based on sodium or potassium bicarbonate, carbon dioxide, phosphates, or an appropriate grade of halogenated hydrocarbon (except chlorinated hydrocarbons). Methyl bromide fire extinguishers should not be used [11]. Water has been shown to be an effective extinguishing agent for fires involving oxygen-enriched atmospheres. More information on fire protection may be found in Chapter 8.

References

[1] Smith, S. R. and Stoltzfus, J. M., "Determining the Time Required for Materials Exposed to Liquid Oxygen to Return to Normal Air Ignitability by Mechanical Impact," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres, Tenth Volume, ASTM STP 1454*, T. A. Steinberg, H. D. Beeson, and B. E. Newton, Eds., ASTM International, West Conshohocken, PA, 2003[JM1].

[2] Bannister, W., *Evaluation of LOX/MMH Mixing Special Test Data Report*. NASA White Sands Test Facility, Las Cruces, NM, WSTF Nos. 93-27434 and 93-27435, March 1994.

[3] United States Navy Diving Manual Rev. 4, SS521-AG-PRO-010 / 0910-LP-708-8000.

[4] MIL-PRF-27210G, *Oxygen: Aviators Breathing, Liquid and Gas*, Performance Specification, United States Department of Defense, Washington, DC, April 1997.

[5] MIL-PRF-25508G, *Propellant, Oxygen,* Performance Specification, United States Department of Defense, Washington, DC, November 2006.

[6] *Code of Federal Regulations*, Title 29 CFR Part 1915.11 (OSHA), Superintendent of Documents, U.S. Government Printing Office, Washington, DC.

[7] Weber, U., *Explosions Caused by Liquid Oxygen*, United Kingdom Atomic Energy Authority translation, translated by R. A. Slingo, Harwell, Berkshire, England, 1966.

[8] Moyers, C. V., Bryan, C. J. and Lockhart, B. J., "Test of LOX Compatibility for Asphalt and Concrete Runway Materials," NASA Technical Memorandum X-64086, Kennedy Space Center, FL, 1973.

[9] DOT P5800.5, *Emergency Response Guidebook*, United States Department of Transportation, Washington, DC, 1993.

[10] Bureau of Explosives, *Emergency Handling of Hazardous Materials in Surface Transportation, Hazardous Materials Systems*, Association of American Railroads, Washington, DC, 1989.

[11] CGA P-39, *Oxygen-Rich Atmospheres*, Compressed Gas Association, Inc., 4221 Walney Rd., 5th Floor, Chantilly, VA.

[12] CGA SB-2, *Oxygen-Deficient Atmospheres*, Compressed Gas Association, Inc., 4221 Walney Rd., 5th Floor, Chantilly, VA.

2

Oxygen System Ignition Mechanisms

Introduction

THE PURPOSE OF THIS CHAPTER IS TO PROVIDE a basic understanding of the ignition mechanisms associated with the use of oxygen. This basic understanding is an integral part of selecting materials (Chapter 3) and designing systems (Chapter 5) for oxygen use. A systematic approach for evaluating ignition mechanisms in oxygen systems is described in Chapter 4.

Ignition Mechanisms

Ignition mechanisms in oxygen systems are simply sources of heat that can lead to ignition of the materials of construction or contaminants. The following is a list of some potential ignition mechanisms for oxygen systems. This list is not intended to be representative of all possible ignition mechanisms but should be considered as a starting point for identifying sources of heat in oxygen systems.

- Particle impact
- Heat of compression
- Flow friction
- Mechanical impact
- Friction
- Fresh metal exposure
- Static discharge
- Electrical arc
- Chemical reaction
- Thermal runaway
- Resonance
- External heat

Descriptions of the ignition mechanisms follow. For any ignition mechanism to be active, certain "characteristic elements" must be present. These characteristic elements are unique for each ignition mechanism, and they represent the best understanding of the elements typically required for ignition to occur. Therefore, efforts to minimize ignition mechanisms should focus on minimizing or removing the characteristic elements.

Particle Impact

The particle impact ignition mechanism is heat-generated when particles strike a material with sufficient velocity to ignite the particles and/or the material. Particle impact is a very effective ignition mechanism for metals; nonmetals†[1] are considered to be less susceptible to ignition by particle impact than metals, but limited data exist. The characteristic elements necessary for ignition by particle impact are as follows:

- particles that can be entrained in the flowing oxygen,
- high gas velocities, typically greater than ~30 m/s (100 ft/s) [1], and
- an impact point ranging from 45° to perpendicular to the path of the particle.[2]

These elements are described further in Table 2-1.

Data: Particle impact data for metal and nonmetal targets are shown in Chapter 3. In general, copper- and nickel-based alloys are resistant to ignition by particle impact. Hard polymers have been ignited in particle impact tests, but limited data exist.

Example: Assembly-generated particles traveling at high velocities can cause particle impact ignition by striking the flammable body just downstream of the control element of a valve (Fig. 2-1).

Heat of Compression

The heat of compression ignition mechanism, also known as rapid pressurization and adiabatic compression,† is heat generated when a gas is rapidly compressed from a low pressure to a high pressure. Heat of compression is the most efficient igniter of nonmetals, but is generally not capable of igniting bulk metals. The characteristic elements for heat of compression are as follows:

- rapid pressurization of oxygen (generally less than 1 s for small-diameter, higher-pressure systems, and generally on the order of a few seconds for larger-diameter systems),
- an exposed nonmetal close to the rapidly pressurized dead end, and
- a pressure ratio that causes the maximum temperature from compression to exceed the situational autoignition temperature† of the nonmetal.

These elements are further described in Table 2-2.

Data: Autoignition temperature† and rapid pressurization data for nonmetals are shown in Chapter 3.

Example: A fast-opening valve can cause heat of compression ignition when it releases high-pressure oxygen into a dead-end tube or pipe, which compresses the oxygen initially in the tube and causes heat of compression at the dead-end (Fig. 2-2).

Flow Friction

The flow friction ignition mechanism is presently understood to be heat-generated when oxygen flows across or impinges upon a nonmetal (usually a polymer) and produces erosion,

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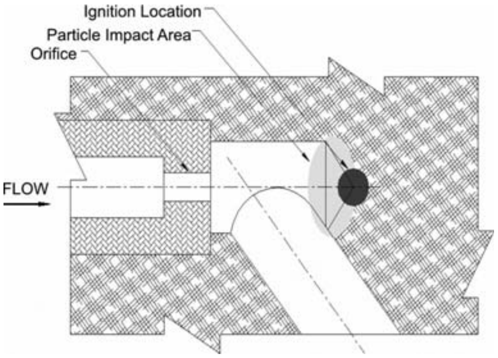
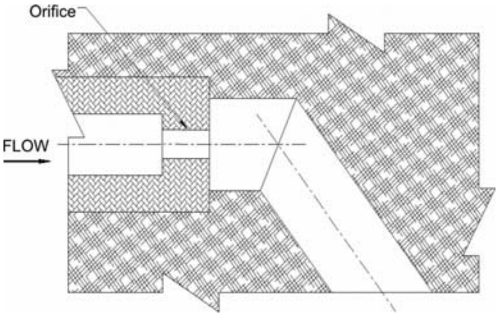
[1] The † indicates a term defined in the Glossary (Appendix G).

[2] Personal communication from David Pippen to Director of Materials and Processes Laboratory at George C. Marshall Space Flight Center. Benz, F., *Summary of Testing on Metals and Alloys in Oxygen at the NASA White Sands Test Facility (WSTF) During the Last 6 Months*. In RF/DLPippen:kp:09/14/88:5722, WSTF Metals Work Memo, September 15, 1988.

TABLE 2-1—Characteristic elements for particle impact.

Characteristic Element	Description/Rationale
Particles that can be entrained in the flowing oxygen	Even in systems that have been cleaned for oxygen service, particulate can be generated during assembly and operation. Therefore, it is assumed that particles could be present in any oxygen system. Test data show that, in most cases, the particulate must be flammable[†] to produce ignition of the target material. However, some highly reactive materials, such as aluminum and titanium, can be ignited when impacted by inert particles such as sand. Test data suggest that metallic powders are more likely to cause particle impact ignition than large, single particles.
High gas velocities, typically greater than ~30 m/s (100 ft/s) [1]	Even in systems with low nominal gas velocities, high gas velocities may be present wherever pressure drops occur. For instance, flow restrictions such as orifices, valves, and regulators may create high gas velocities. Furthermore, opening regulators or valves while pressurized will result in transient high gas velocities.
Impact point ranging from 45° to perpendicular to the path of the particle	Particle impact tests were conducted at the NASA White Sands Test Facility to simulate the configuration of the Space Shuttle Type II Main Propulsion System oxygen flow control valve. The test fixtures were fabricated from Inconel 718 in two configurations: • with drill points downstream of the flow control orifice similar to the actual valve as shown in Fig. T2-1a, and • with drill points removed, resulting in an impact angle of 45° as shown in Fig. T2-1b. The tests were performed in 31.7 MPa (4 600 psi) oxygen at a temperature of 600 K with 10 mg of a particle mixture consisting of 26 % Inconel 718, 29 % 21-6-9 stainless steel, and 45 % aluminum 2 219 by weight. The test fixture with a drill point ignited and burned on the second test. The test fixture without a drill point showed no evidence of ignition when subjected to 40 tests. (The Space Shuttle flow control valve was subsequently redesigned.)
	 **Fig. T2-1a**—Test fixture with drill point.  **Fig. T2-1b**—Test fixture with 45° impact angle.

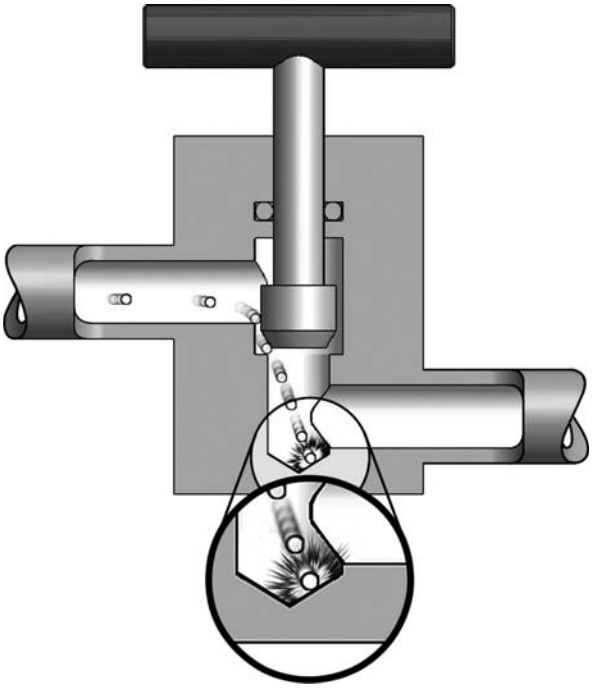


Fig. 2-1—Particle impact ignition.

friction, and/or vibration. Flow friction is a poorly understood ignition mechanism that has never been intentionally reproduced in a laboratory setting. However, current theory indicates that the characteristic elements for flow friction ignition are as follows:

- oxygen at elevated pressures, generally greater than 3.4 MPa (500 psi),
- a nonmetal exposed to the flow, and
- flow or leaking that produces erosion, friction, or vibration of the nonmetal.

These elements are further described in Table 2-4.

Data: Test data do not exist for flow friction because a test method has not yet been developed. Nonetheless, flow friction has been the cause of several unintentional fires.

Example: A leak past a damaged nonmetal seat could cause flow friction ignition.

Mechanical Impact

The mechanical impact ignition mechanism is heat generated as a result of single or repeated impacts on a material. Most metals cannot be ignited by mechanical impact; however, nonmetals are susceptible to ignition by mechanical impact.

TABLE 2-2—Characteristic elements for heat of compression.

Characteristic Element	Description/Rationale
Rapid pressurization of oxygen (generally less than 1 s for small-diameter, higher-pressure systems, and generally on the order of a few seconds for larger-diameter systems)	Components such as quarter-turn ball valves, plug valves, solenoid valves, and cylinder valves generally open rapidly enough to provide rapid pressurization of downstream components.
Exposed nonmetal close to the rapidly pressurized dead end	Depending on their configuration, valve seats and flexible hose linings are examples of nonmetals that could be exposed to heat from rapid pressurization.
Pressure ratio that causes the maximum temperature from compression to exceed the situational autoignition temperature[†] of the nonmetal	The maximum theoretical temperature from isentropic (adiabatic,[†] i.e., no heat loss) compression of an ideal gas can be calculated using the following equation: $$\frac{T_f}{T_i} = \left(\frac{P_f}{P_i}\right)^{\frac{(n-1)}{n}}$$ where T_f = final temperature (absolute), T_i = initial temperature (absolute), P_f = final pressure (absolute), P_i = initial pressure (absolute), and n = ratio of specific heats (1.40 for oxygen). Table 2-3 shows some maximum theoretical temperatures that could be obtained by isentropically (adiabatically) compressing oxygen from 0.1 MPa (14.7 psia) to the pressures shown. Pressure ratios and the resulting maximum theoretical temperatures are shown in Table 2-3. Rapid pressurization testing at the NASA White Sands Test Facility has demonstrated that, for small-diameter systems with initial upstream pressures of less than 1.90 MPa (275 psia) and initial downstream pressures of ambient or above, the actual temperature rise (with real heat loss) is too small for ignition to occur. These tests were performed on polyethylene foam contaminated with WD-40™ and the test samples were pressurized to 95 % of the test pressure in a minimum of 10 and a maximum of 50 ms. There was no ignition in 60 sets of five impacts with 100 % oxygen at 1.90 MPa (275 psia).

TABLE 2-3—Theoretical maximum temperatures obtained when isentropically (adiabatically) compressing oxygen from an initial pressure (P_i) of 0.1 MPa (14.7 psia) at an initial temperature (T_i) of 293 K (68°F).

Final Pressure (P_f)		Pressure Ratio (P_f / P_i)	Final Temperature (T_f)	
kPa	psia		°C	°F
345	50	3.4	143	289
690	100	6.8	234	453
1 000	145	9.9	291	556
1 379	200	13.6	344	653
2 068	300	20.4	421	789
2 758	400	27.2	480	896
3 447	500	34.0	530	986
5 170	750	51.0	628	1 163
6 895	1 000	68.0	706	1 303
10 000	1 450	98.6	815	1 499
13 790	2 000	136	920	1 688
27 579	4 000	272	1 181	2 158
34 474	5 000	340	1 277	2 330
100 000	14 500	986	1 828	3 322

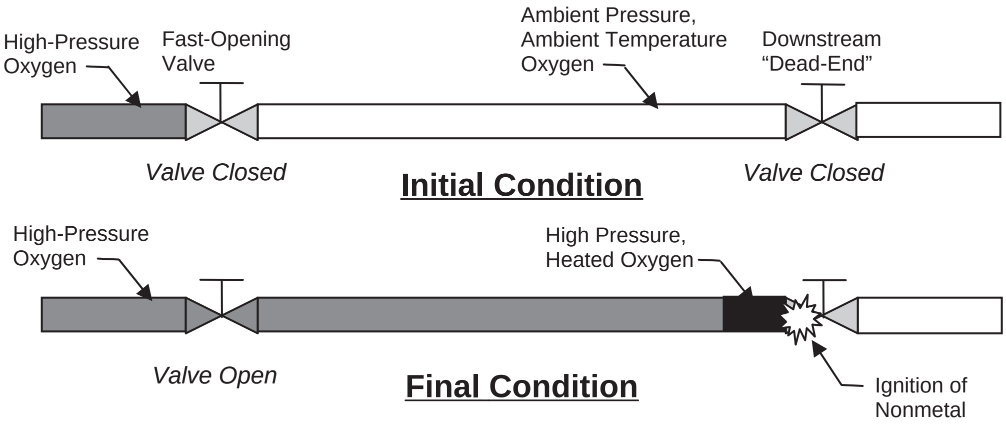


Fig. 2-2—Heat of compression ignition.

TABLE 2-4—Characteristic elements for flow friction.

Characteristic Element	Description/Rationale
Oxygen at elevated pressures, generally greater than 3.4 MPa (500 psi)	In small, high-pressure systems, flow friction ignition has not been observed at pressures below 6.9 MPa (1 000 psi). However, in large industrial systems, flow friction ignition has been observed at pressures as low as ~3.4 MPa (~500 psi).
Nonmetal exposed to the flow	Current theory indicates that a longer flow path across the nonmetal corresponds to a greater risk for flow friction ignition. Surfaces of nonmetals that are highly fibrous from being chafed, abraded, eroded, or plastically deformed may be more susceptible to flow friction ignition. In addition, materials with high oxygen permeability such as silicone may be more susceptible to ignition by flow friction.
Flow or leaking that produces erosion, friction, or vibration of the nonmetal	Real-life fires that have been attributed to flow friction occurred when systems were pressurized but not intentionally flowing. Without any intentional flow, ignition mechanisms such as particle impact and heat of compression could not be the cause of the fires.

The characteristic elements for mechanical impact ignition are as follows:

- a single large impact or repeated impacts, and
- a nonmetal or reactive metal at the point of impact.

These elements are further described in Table 2-5.

Data: Data have shown that aluminum, magnesium, titanium, and lithium-based alloys, as well as some lead-containing solders, can be ignited by mechanical impact. Mechanical impact data for nonmetals are shown in Chapter 3.

Example: A wrench dropping onto a porous hydrocarbon (e.g., asphalt) soaked with liquid oxygen could cause mechanical impact ignition (Fig. 2-3).

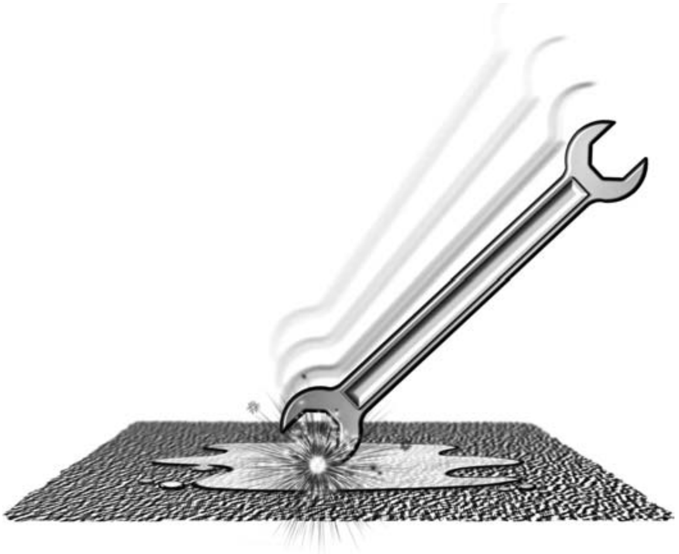


Fig. 2-3—Mechanical impact ignition.

Friction

As two or more parts are rubbed together, heat can be generated as a result of friction and galling at the rubbing interface. Data from friction tests currently available indicate that metals, not polymers, are most susceptible to ignition by friction and galling. Current research indicates that polymers and composites may also be susceptible to ignition under certain conditions. The characteristic elements for friction ignition are as follows:

- two or more rubbing surfaces, generally metal-to-metal,
- rapid relative motion, and
- high normal loading between surfaces.

These elements are further described in Table 2-6.

Data: Friction ignition data for various pairings of metals are located in Chapter 3. There are limited data for friction ignition of nonmetals.

Example: Damaged or worn soft goods resulting in metal-to-metal rubbing between the piston and the cylinder of a reciprocating compressor could lead to friction ignition (Fig. 2-4).

Fresh Metal Exposure

Ignition as a result of fresh metal exposure can occur as a result of heat of oxidation when an unoxidized metal is exposed to an oxidizing atmosphere. This ignition mechanism usually acts in conjunction with other ignition mechanisms that damage metal surfaces, such as frictional heating and particle impact. The characteristic elements of fresh metal exposure are as follows:

- the presence of a metal that oxidizes quickly and has a high heat of formation for its oxides, such as an aluminum or titanium alloy,
- destruction or rapid removal of the oxide layer, and
- a configuration that minimizes heat loss.

Data: Test data do not exist for fresh metal exposure because a test method has not yet been developed.

Example: Titanium may be ignited as a result of fresh metal exposure if it is scratched in the presence of oxygen. This ignition mechanism may also be present with a fracture or tensile failure of an oxygen-wetted pressure vessel.

Static Discharge

Ignition as a result of static discharge can occur when a static charge discharges with enough energy to ignite the material receiving the discharge or exposed to the discharge energy. Static discharge is more likely to occur in dry gas environments; in environments with a humidity of greater than 65 %, static charges are dissipated because of the presence of a thin surface

TABLE 2-5—Characteristic elements for mechanical impact.

Characteristic Element	Description/Rationale
Single large impact or repeated impacts	Some components, such as relief valves, check valves, and regulators, may become unstable and "chatter" during use. Chattering can result in multiple impacts in rapid succession on nonmetal poppets or seats within these components, creating heat from the impacts that can ignite the nonmetal.
Nonmetal or reactive metal at the point of impact	Most metals are not susceptible to ignition by mechanical impact.

TABLE 2-6—Characteristic elements for friction.

Characteristic Element	Description/Rationale
Two or more rubbing surfaces, generally metal-to-metal	Test data indicate that metals, not polymers, are most susceptible to ignition by friction in the friction heating tests presently available. Current research indicates that polymers and composites may also be susceptible to ignition in certain conditions.
Rapid relative motion	For ignition to occur, the normal loading and rubbing frequency must be severe enough for temperatures at the rubbing interface to reach the autoignition temperature† of the rubbing materials. Components that have rapid relative motion during operation, such as pumps and compressors, are especially susceptible to friction ignition. Some components, such as relief valves, check valves, and regulators, may become unstable and "chatter" during use. Chattering can result in rapid oscillation of the moving parts within these components, creating a friction ignition hazard.
High normal loading between surfaces	For ignition to occur, the normal loading and rubbing frequency must be severe enough for temperatures at the rubbing interface to reach the autoignition temperature of the rubbing materials.

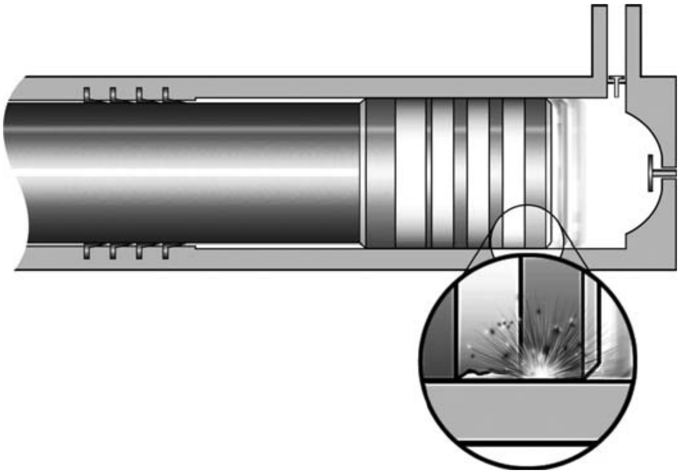


Fig. 2-4—Friction ignition.

layer of moisture on the materials. Generally, two charged surfaces are not likely to arc unless one material is conductive. The characteristic elements for static discharge are:

- electrostatic charge buildup on the surface of an insulator (e.g., nonmetal) or throughout the body of an electrically isolated (ungrounded) conductor (e.g., metal),
- a discharge configuration, generally between materials with differing electrical potentials, and
- discharge energy sufficient for ignition (two isolated conductors will produce a greater arc energy than an arc between a conductor and an insulator and far greater than an arc between two insulators).

Data: Static discharge ignition data are located in Chapter 3.

Examples: Static charges can accumulate as a result of dry oxygen contaminated with particles or dust flowing through ungrounded or electrically isolated polymer hoses. Flammable† personal hygiene products in hyperbaric chambers can be ignited by static discharge.

Electrical Arc

Ignition as a result of electrical arc can occur when there is an electrical arc from a power source with enough energy to ignite the material receiving the arc. The characteristic elements necessary for ignition by electrical arc are:

- an electrical power source, and
- an arc with sufficient energy to melt or vaporize materials.

Data: Electrical arc ignition data are presented in Chapter 3.

Examples: A defective pressure switch could cause ignition when it arcs to a flammable material. An insulated electrical heater element undergoing a short circuit could produce ignition by arcing through its sheath to a combustible material.

Chemical Reaction

Ignition as a result of chemical reaction can occur when there is a reaction between a combination of chemicals that could release sufficient heat to ignite the surrounding materials. The characteristic elements for chemical reaction ignition depend on the reactants involved. For example, some mixtures may be self-igniting while others need an external heat source. In oxygen-hydrogen mixtures, the ignition energy is so low that ignition of the mixture is assumed.

Data: Test data are not available for chemical reaction because a test method has not yet been developed.

Examples: Oxygen reacting with the palladium getter in a vacuum-jacketed vessel could produce ignition.

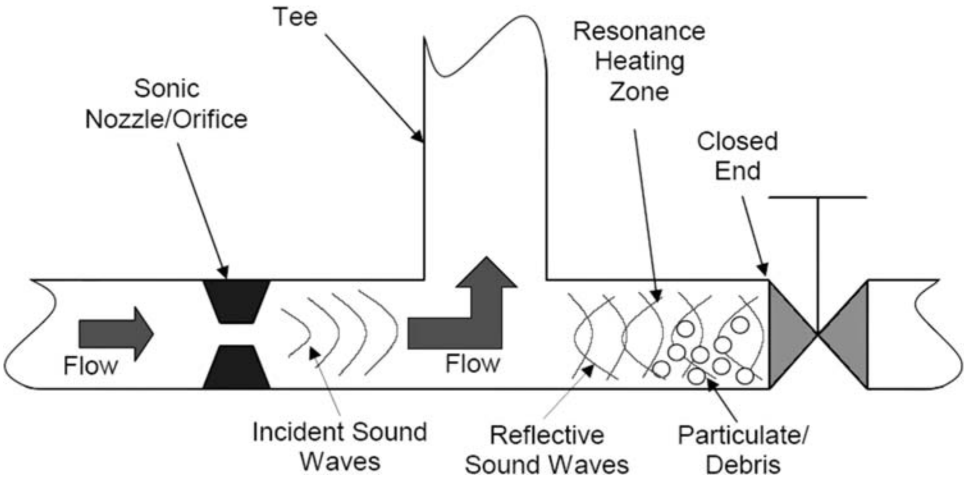


Fig. 2-5—Favorable configuration for resonance heating.

Hydrogen leaking into the oxygen section of an oxygen-hydrogen fuel cell system can be ignited by a chemical reaction ignition.

Thermal Runaway

Some materials, notably certain accumulations of fine particles, porous materials, or liquids, may undergo reactions that generate heat. If the rate of heating compared with the rate of dissipation is unfavorable, the material will increase in temperature. Thermal runaway can occur when self-heating rapidly accelerates to high temperatures. In some cases, a thermal runaway temperature may be attained and sometime later the material may spontaneously ignite. Ignition and fire may occur after short periods of time (seconds or minutes) or over long periods of time (hours, days, or months). In the most extreme cases, the thermal runaway temperature may be near or below normal room temperature. The characteristic elements for thermal runaway ignition include the following:

- a material with a high surface-area-to-volume ratio (such as dusts, particles, foams, etc.) that reacts exothermically (such as through oxidation or decomposition) at temperatures significantly below its ignition temperature, and
- an environment that does not adequately dissipate heat (such as an insulated or large volume vessel or an accumulation of fine particles).

Data: Test data are not available for thermal runaway because a test method has not yet been developed.

Examples: Ignition could occur as a result of an accumulation of small particulate generated by rubbing and abrasion during proof-testing in an inert environment, which is then exposed to oxygen. Contaminated adsorbent or absorbent materials, such as molecular sieves (zeolites), alumina, and activated carbon, may become highly reactive in oxygen-enriched atmospheres.

Resonance

The resonance ignition mechanism is heat generated by acoustic oscillations within resonant cavities. The likelihood of ignition is greater if particles or contaminants are present. The characteristic elements for resonance ignition include the following:

- a favorable system geometry, which includes a throttling device (such as a nozzle, orifice, regulator, or valve) directing a sonic gas jet into a cavity or closed-end tube (Fig. 2-5),
- acoustic resonance, which is often audible, and
- easily ignited materials such as exposed nonmetals, particulates, or contaminants at the location of heating.

The distance between the throttling device and the cavity or closed-end tube affects the frequency of acoustic oscillations as a result of the interference of incident and reflecting sound waves, similar to a pipe organ with a closed end. This distance also affects the temperature produced in the cavity. Higher harmonic frequencies have been shown to produce higher system temperatures [2].

Data: Resonance test data are available in *Resonance Tube Ignition of Metals* [2].

Example: Resonance ignition could occur in a capped tee fitting downstream of a valve or orifice, similar to Fig. 2-5.

External Heat

External heat ignition mechanisms originate outside oxygen systems. Potential ignition sources to consider should include any external heat sources such as lightning, explosive charges, personnel smoking, open flames, shock waves from tank rupture, fragments from bursting vessels, welding, and exhaust from internal combustion engines.

References

[1] Williams, R. E., Benz, F. J. and McIlroy, K., "Ignition of Steel by Impact of Low-Velocity Iron/Inert Particles in Gaseous Oxygen," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Third Volume, ASTM STP 986*, D. W. Schroll, Ed., American Society for Testing and Materials, Philadelphia, PA, 1988, pp. 72–84.

[2] Phillips, B. R., *Resonance Tube Ignition of Metals*, Ph.D. Thesis, University of Toledo, Toledo, OH, 1975.

3

Materials Information Related to Flammability, Ignition, and Combustion

Introduction

THE FIRE HAZARDS INHERENT IN OXYGEN SYSTEMS make materials selection a crucial step in designing and maintaining a safe system. To ensure the safety of any oxygen system, the system designer must have an understanding of the numerous factors relating to the selection of suitable materials for oxygen service, including material properties related to the design and operating conditions, compatibility with the operating environment, ignition and combustion behavior, property changes that occur at cryogenic temperatures, and ease of fabrication, assembly, and cleaning. The focus of this chapter is materials selection related to flammability, ignition, and combustion. Information on other areas of materials selection, such as mechanical and thermal properties of engineering materials, is located in Appendix B.

A test that can produce either absolute ignition limits or consistent relative ratings for all materials is not available [1-4]. Therefore, materials evaluation and selection criteria for fire hazards are based on data generated from materials testing for ignition and combustion characteristics, as well as studies of liquid oxygen (LOX)- and gaseous oxygen (GOX)-related successes and failures. This chapter begins with a description of the test methods and data used to evaluate ignition and combustion characteristics of materials, followed by discussions of nonmetallic materials and metallic materials. This chapter is concluded with a short discussion of materials control. A systematic approach that can be used for selecting materials for oxygen service is found in Chapter 4. Additional test data not described in this document may be located in the *ASTM Standard Guide for Evaluating Nonmetallic Materials for Oxygen Service* (G 63), the *ASTM Standard Guide for Evaluating Metals for Oxygen Service* (G 94), *ASTM Standard Technical Publications on Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres, Fire Hazards in Oxygen-Enriched Atmospheres* (NFPA 53), and Refs [13] through [15]. In addition, data obtained from standard NASA materials tests are stored in the NASA Marshall Space Flight Center (MSFC) Materials and Processes Technical Information System (MAPTIS) and are published periodically [14].

Ignition and Combustion Test Methods and Data

Multiple test methods for evaluating the ignition and combustion characteristics of materials for oxygen systems have been developed. The data from these tests provide a means to rank materials and can be used in selecting materials. When applying the data, it is important to have a good understanding of the test method used to generate the data so that the data may be applied appropriately.

The test methods can be categorized as combustion tests, damage potential tests, and ignition tests. The combustion tests that are described in this chapter are promoted ignition and oxygen index. The damage potential test that is discussed is heat of combustion. The ignition tests that are discussed are ignition temperature of metals, friction, particle impact, mechanical impact, autogenous ignition (autoignition) temperature of nonmetals,†[1] pneumatic impact, and resonance cavity. Caution is recommended when applying the test data because, with the exception of the heat of combustion test, all the test data are configuration-dependent.

Promoted Ignition of Metals in GOX (ASTM G 124)

Test Method

The promoted ignition test, also known as the upward flammability test, is used to determine the ability of a metallic rod to propagate flame upward when ignited at the bottom by an ignition source. The test apparatus is depicted in Fig. 3-1, and the procedure used is the *Standard Test Method for Determining the Combustion Behavior of Metallic Materials in Oxygen-Enriched Atmospheres* (ASTM G 124). According to the standard, a promoter is attached to the bottom of a material sample that is suspended vertically in the test chamber. The promoter is intended to be an overwhelming ignition source that releases enough energy to melt the bottom of the material sample. Once the promoter is ignited, the material sample is observed for evidence of self-sustained burning in an upward direction. With a standardized promoter, the test results give a relative ranking of a material's flammability in stagnant gaseous oxygen at pressures up to 68.9 MPa (10 000 psi). The standard sample for the test is a 0.32-cm (0.125-in.)-diameter rod, but a limited number of tests have been performed with different configurations.

According to the ASTM G 124 test standard and ASTM G 126 standard definitions, the threshold pressure is defined as the minimum pressure required for self-sustained combustion of the entire standard sample. Other definitions of threshold pressure exist in the literature, and it is therefore very important that the applicable definition of threshold pressure is understood when applying or referencing promoted ignition data. For any metallic material, the flammability (or threshold pressure) increases with increasing pressure and decreases with increasing thickness.

As pressure increases, materials do not make a rapid transition from nonflammable to flammable. Ref [15] describes the promoted-ignition combustion transition (PICT), which is

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[1] The † indicates a term defined in the Glossary (Appendix G).

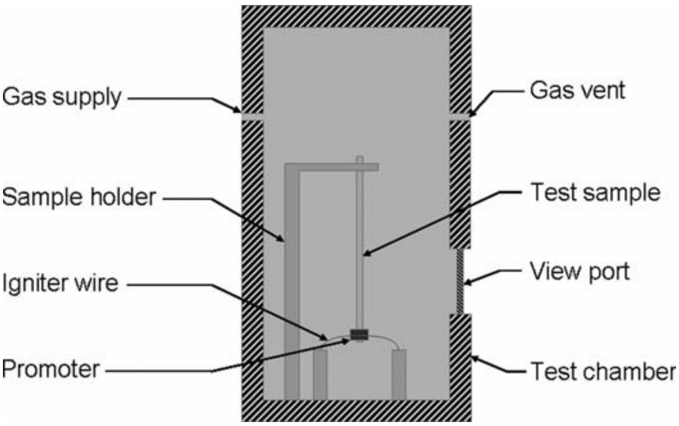

Fig. 3-1—Upward flammability test apparatus.

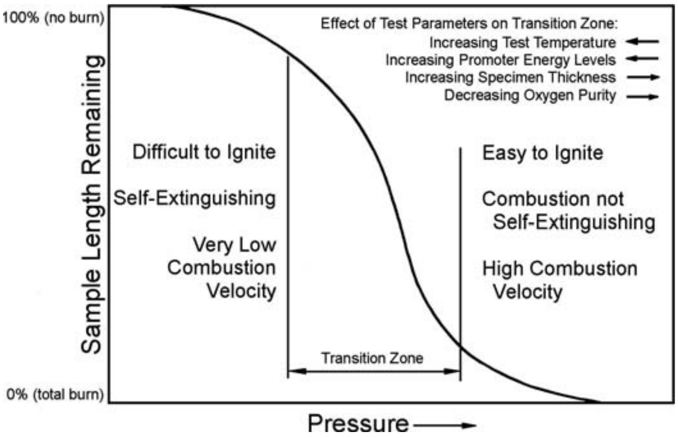

Fig. 3-2—Schematic of the PICT [15].

the transition zone where ignition propagation is unpredictable and erratic. The PICT is shown in Fig. 3-2.

Note that upward flame propagation is used for this test because it provides more repeatable data and better distinguishes the performance of different materials than downward propagation. However, most metallic materials burn downward more readily than upward as a result of their liquid combustion products. In addition, materials that are self-extinguishing in upward propagation may burn completely in the downward configuration.

Data

Table 3-1 shows promoted combustion data for common alloys and commercially pure metals configured as 0.32-cm (0.125-in.)-diameter rods. The data in this table are presented in terms of “lowest burn pressure” and “highest no-burn pressure,” and a burn is defined as consumption of ≥2.54 cm (≥1 in.) of the material. Materials with greater no-burn pressures are generally considered to be less flammable[†] than materials with low no-burn pressures. The data in Table 3-1 show that adding even small amounts of highly flammable metals to materials that have high threshold pressures can dramatically affect flammability. For example, a 0.32-cm (0.125-in.)-diameter rod of copper will not burn in 68.9 MPa (10 000 psi) oxygen; however, the same size rod of aluminum bronze (which contains 93 % copper and 7 % aluminum) will burn in 1.4 MPa (250 psi) oxygen. This difference illustrates the dramatic effect of alloying a material with a low burn pressure, such as aluminum, with a material that exhibits a high burn pressure, like copper.

Promoted ignition testing is typically performed in 100 % oxygen to determine the flammability limits of metals. However, it may also be performed at lower oxygen concentrations and varying pressures to determine the flammability limits. Fig. 3-3 shows results from such testing on several common engineering alloys [16].

Although promoted ignition testing typically is performed in a stagnant oxygen environment according to the standard, a limited amount of testing also has been performed to analyze the effect of flowing oxygen on flammability [17]. The data indicate that flow dynamics may increase the flammability of metals in certain environments. It is theorized that, with flow, oxygen is able to better reach the combustion interface, thereby increasing the efficiency of burning. However, high flow may actually inhibit burning as it may remove the heated region of the rod.

Promoted ignition testing also has been performed to verify the effects of configuration on the flammability limits of metals. Table 3-2 displays the results of testing metallic wire meshes that were wrapped into 0.32-cm (0.125-in.) cylinders [18]. Table 3-3 shows the results of testing 0.32-cm (0.125-in.)-diameter rods made from metal configured similar to sintered filter elements [19]. The data in Tables 3-2 and 3-3 illustrate that configuration has a dramatic effect on flammability. For example, when configured as a solid 0.32-cm (0.125-in.)-diameter rod, Monel 400 will not support combustion at 68.9 MPa (10 000 psi). However, when configured as a sintered cylinder, Monel 400 will support combustion at 0.69 MPa (100 psi), and as a cylinder of wire mesh, Monel 400 will support combustion at 0.085 MPa (12.4 psi). Promoted ignition testing has also been performed on several materials in rod vs. tube configurations, revealing that tube configurations will support combustion at lower pressures than solid rods [20].

Ignition Temperature of Metals

Tests have been performed to determine the ignition temperature of metals; however, no standard method exists. The ignition temperature of a metal is dependent on the test procedure, material configuration, and presence or lack of oxide layers. A general rule of thumb is that the ignition temperature of a metal is at or greater than the melting point of the metal, and the flame temperature is at or greater than the boiling point or decomposition temperature of the metal oxide. In one study on the ignition temperature of metals, it was noted that although the metals burned at a much greater rate in oxygen, there was no appreciable difference in the ignition temperature as a result of oxygen concentration [21]. Ignition temperature data for selected metals are shown in Table 3-4.

Friction

Test Method

The friction test is a nonstandardized method that measures the susceptibility of materials to ignite by friction in GOX and LOX. The test is performed by rotating the end of one hollow cylinder against a staionary hollow cylinder, as shown in Fig. 3-4. This test is typically used for metals, but a small amount of testing has been performed with nonmetallic

TABLE 3-1—Promoted ignition data for 0.32-cm (0.125-in.)-diameter metallic rods ignited at the bottom in stagnant oxygen. A burn is defined as consumption of at least 2.54 cm (1 in.) of the rod.

	Lowest Burn Pressure				Highest No-Burn Pressure					
Material	MPa	psia	No. Tests	Burn Length (in.)	MPa	psia	No. Tests	Burn Length (in.)	Rod Length (in.)	Source[a]
Copper (commercially pure)	None				>68.9[b]	>10 000[b]	2	0-0.6	5	WSTF[c]
Nickel (commercially pure)	None				>68.9[b]	>10 000[b]	Unknown		Unknown	ASTM STP1267 p. 104
Platinum (commercially pure)	None				>68.9[b]	>10 000[b]	3	0.3	3	WSTF 94-28159
Gold (commercially pure)	None				>68.9[b]	>10 000[b]	3	0	Unknown	WSTF 90-24243
Bronze C93600	None				>68.9[b]	>10 000[b]	3	0.3-0.4	6	WSTF 92-26705
Silver (commercially pure)	None				>68.9[b]	>10 000[b]	3	0	6	WSTF 90-24243
Monel K-500	None				>68.9[b]	>10 000[b]	5	0.25-0.38	12.5	WSTF 89-22906
Inconel MA754	None				>68.9[b]	>10 000[b]	10	0.3-0.4	6.5	WSTF 88-22205 and MAPTIS 55748
Monel 400	None				>68.9[b]	>10 000[b]	13	0-0.4	6	MAPTIS 55695
Brass 360 CDA	None				>68.9[b]	>10 000[b]	1	0.25	Unknown	WSTF 86-20068
Copper-beryllium	None				>68.9[b]	>10 000[b]	3	0-0.125	Unknown	WSTF 86-20499
Nickel 200	None				>68.9[b]	>10 000[b]	20	0.1-0.3	12	MAPTIS 54195
Copper 102	None				>55.2[b]	>8 000[b]	2	0	5	ASTM STP910 p. 145
Red brass	None				>48.3[b]	>7 000[b]	5	0.2	5	ASTM STP 986 p. 36
Tin-bronze	None				>48.3[b]	>7 000[b]	5	0.1	5	ASTM STP 986 p. 36
Yellow brass	None				>48.3[b]	>7 000[b]	5	0.2	5	ASTM STP 986 p. 36
Zirconium copper	None				>33[b]	>4 800[b]	40	0.3	6	WSTF 06-40239
Silicon (commercially pure)	26.2	3 800	1	1.25	20.7	3 000	1	0.75	5	WSTF 90-24252
Haynes 188	≤20.7[d]	≤3 000[d]	5	0.94-3.38	None				12.5	WSTF 89-22903
Haynes 242	≤20.7[d]	≤3 000[d]	5	2.5-5.25	None				12.5	WSTF 89-22904
Hastelloy C276	≤20.7[d]	≤3 000[d]	20	0.3-12	None				12	MAPTIS 55874
Hastelloy C22	≤17.2[d]	≤2 500[d]	10	0.4-5.8	None				12	MAPTIS 55795
Inconel 600	17.2	2 500	4	0.4-5.0	13.8	2 000	11	0.1-0.4	12	WSTF 95-29293 and MAPTIS 10135/55441/55431
Stellite 6	17.2	2 500	7	1.2-5.0	6.9	1 000	4	0.3	5	ASTM STP986 p. 36
MP 35N	≤10.3[d]	≤1 500[d]	5	0.3-3.0	None				12.5	WSTF 89-22899
Elgiloy	≤10.3[d]	≤1 500[d]	10	0.1-4.0	None				12.5	WSTF 89-22907
Inconel 625	≤6.9[d]	≤1 000[d]	20	0.4-2.1	None				12	MAPTIS 10404/10288/10727
Hastelloy alloy G3	6.9	1 000	4	0-5	3.4	500	2	0.25-0.5	5	WSTF 89-22992
Incoloy 800	6.9	1 000	2	1.1-5.0	3.4	500	5	0.4	5	ASTM STP986 p. 36
Waspaloy	6.9	1 000	4	0.8-5.8	3.4	500	3	0.8	5.8	MAPTIS 30125
Waspaloy (9110)	≤6.9[d]	≤1 000[d]	6	0.2-3.6	None				5.6	WSTF 99-33689
Haynes 214^{-}	≤6.9[d]	≤1 000[d]	14	0.1-2.2	None				8.8	WSTF 98-33169

TABLE 3-1—Promoted ignition data for 0.32-cm (0.125-in.)-diameter metallic rods ignited at the bottom in stagnant oxygen. A burn is defined as consumption of at least 2.54 cm (1 in.) of the rod. *(Cont'd)*

	Lowest Burn Pressure				Highest No-Burn Pressure					
Material	**MPa**	**psia**	**No. Tests**	**Burn Length (in.)**	**MPa**	**psia**	**No. Tests**	**Burn Length (in.)**	**Rod Length (in.)**	**Source[a]**
Colmonoy	6.9	1 000	1	2.4	3.4	500	5	0.25	5	WSTF[c]
Invar 36	≤6.9[d]	≤1 000[d]	6	3		None			3	WSTF 86-19834 /86-19840
Inco X-750	≤6.9[d]	≤1 000[d]	5	0.1-2.2		None			5	WSTF 95-29097
Chromium (commercially pure)	4.1	600	2	0-5	3.4	500	3	0	5	WSTF 92-26153
440C Stainless steel	≤3.4[d]	≤500[d]	20	0-1.1		None			5.8	MAPTIS 30008/10106/ 50822/53129
420 Stainless steel	≤3.4[d]	≤500[d]	10	0-1.3		None			6	MAPTIS 54114/30136
422 Stainless steel	≤3.4[d]	≤500[d]	10	0-1.3		None			5.8	MAPTIS 53537/54040
430 Stainless steel	≤3.4[d]	≤500[d]	10	0-1.3		None			12	MAPTIS 30066
440A Stainless steel	≤3.4[d]	≤500[d]	5	0-1.1		None			5.8	MAPTIS 30002
Inconel 718	≤3.4[d]	≤500[d]	10	0.5-4.3		None			12	MAPTIS 54263/ 55488/10106
17-4 PH Stainless steel	≤3.4[d]	≤500[d]	6	0.8-1.8		None			5.8	MAPTIS 53654
Lead (commercially pure)	3.4	500	2	0-1	2.8	400	1	0.5	6	WSTF 90-23860/88-22158/89-23425
Antimony (commercially pure)	3.4	500	3	0.5-2	2.8	400	1	0.25	5	WSTF 92-26468
Beryllium (commercially pure)	≤3.4[d]	≤500[d]	6	0-1.25		None			4	WSTF[c]
Ductile cast iron	≤3.4[d]	≤500[d]	1	5		None			5	ASTM STP 986 p. 36
Nitronic 60	≤3.4[d]	≤500[d]	1	5		None			5	ASTM STP 986 p. 36
9 % Nickel steel	≤3.4[d]	≤500[d]	1	5		None			5	ASTM STP 986 p. 36
Tin (commercially pure)	3.4	500	2	0-6	1.4	200	6	0	6	WSTF 89-23123/89-22728
Udimet 700	≤2.8[d]	≤400[d]	5	0-1.75		None			12.5	WSTF 89-22900
Zinc (commercially pure)	2.1	300	1	1.6	1.4	200	1	0.5	5.5	WSTF 90-24249
Udimet 720	≤1.7[d]	≤250[d]	9	0.8-2.4		None			8.5	MAPTIS 55801
Aluminum-bronze	1.7	250	2	0-6	1.4	200	1	0	6	WSTF 92-26731
300 Series stainless steel	1.4	200	20	0.1-1.3	0.8	111	20	0.1-0.9	6.3	WSTF 97-31575/06-40375
Inconel 800 HT	1.4	200	5	0.2-1.8	0.2	35	5	0.2-0.5	3.5	WSTF 98-33388
AMS 6278	1.4	200	2	0-5.5	0.7	100	5	0	5.5	WSTF 90-24243
Welda-lite 2195	≤0.8[d]	≤125[d]	10	0.2-5.1		None			12	MAPTIS 54314
Aluminum 1100	0.7	100	6	0-5	0.3	50	3	0-0.9	12	WSTF 88-21971
Molybdenum (commercially pure)	0.7	100	1	5.5	0.3	50	3	0	5.5	WSTF 90-24245
AISI 9310	0.7	100	2	0-5.5	0.3	50	3	0	5.5	WSTF 90-24233

TABLE 3-1—Promoted ignition data for 0.32-cm (0.125-in.)-diameter metallic rods ignited at the bottom in stagnant oxygen. A burn is defined as consumption of at least 2.54 cm (1 in.) of the rod. *(Cont'd)*

Material	Lowest Burn Pressure				Highest No-Burn Pressure				Rod Length (in.)	Source[a]
	MPa	psia	No. Tests	Burn Length (in.)	MPa	psia	No. Tests	Burn Length (in.)		
Carbon steel	≤0.7[d]	≤100[d]	3	>1.16	None				3.8	ASTM STP 1040 p. 44
Welda-lite 049	0.6	80	6	0.59-1.46	0.2	30	1	0.86	5	WSTF 89-23362
Iron (commercially pure)	≤0.5[d]	≤75[d]	1	5	None				5	WSTF 89-23136/ 89-23135
Tungsten (commercially pure)	0.17	25	1	2.2	0.09	12.4	1	0	3	WSTF 90-24247
Aluminum 2219	0.17	25	4	0-1.9	0.1	15	1	0.2	6	WSTF 89-23149
Vanadium (commercially pure)	≤0.17[d]	≤25[d]	1	2.6	None				5.5	WSTF 90-24248
Indium (commercially pure)	0.14	20	2	0-5	0.08	12.3	4	0-0.5	Unknown	WSTF 92-26215
Aluminum (commercially pure)	0.09	12.4	1	2.93	None				3	WSTF 90-23856/90-23857
Tantalum (commercially pure)	>0.09[b]	>12.4[b]	3	0	None				Unknown	WSTF 92-26424
Magnesium (commercially pure)	≤0.09[d]	≤12.4[d]	2	0-2.6	None				6	WSTF[c]
Ytterbium (commercially pure)	0.08	12	1	5	None				Unknown	WSTF 92-26154
Hafnium (commercially pure)	≤0.06[d]	≤8[d]	1	5	None				5	WSTF[c]
Zirconium (commercially pure)	≤0.06[d]	≤8[d]	1	Unknown	None				6	WSTF 88-22650
Titanium (commercially pure)	≤0.007[d]	≤1[d]	5	3.0-6.0	None				6	WSTF 88-21969
Ti-6A1-4V	≤0.007[d]	≤1[d]	4	Unknown	None				6	WSTF 88-21970
Strontium (commercially pure)	≤Ambient air[f]				None				Unkown	ASTM STP1267 p. 104
Lithium (commercially pure)	≤Ambient air[f]				None				Unknown	ASTM STP1267 p. 104

[a] Sources of data include WSTF (White Sands Test Facility), MAPTIS, and ASTM Standard Technical Publications (STP). WSTF data are typically referenced by a WSTF number, and MAPTIS data are referenced by a specific material code.

[b] > indicates that this was the highest pressure tested and the material did not burn greater than 1 in. The burn pressure, if it exists, is greater than the stated value.

[c] No WSTF number.

[d] ≤ indicates that no tests were conducted at lower pressures and therefore the material may burn at pressures less than or equal to the stated value.

[e] The exact composition of this Haynes 214 alloy is unknown. Haynes 214 alloys have dramatically different results in this test depending on the specific alloy composition. For instance, while this unknown alloy burned greater than 1 in. at 1 000 psi, Haynes 214 composed of 4.42 % Al, <0.0025 % B, 0.0370 % C, 0.0081 % Cb, 0.0075 % Co, 15.16 % Cr, 2.10 % Fe, 0.1830 % Mn, 0.0010 % S, 0.0490 % Si, and <0.0050 % Mg, Mo, P, Ti, W, Y, and Zr with the balance being Ni did not burn greater than 1 in. in 10 tests in oxygen at 10 000 psi (WSTF 97-31129).

[f] Samples burned completely in ambient air at an atmospheric pressure of 85 kPa (12.3 psia).

LIVE GRAPH
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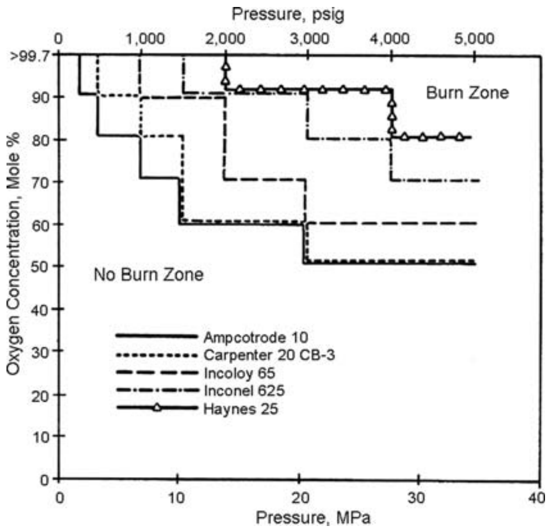

Fig. 3-3—Effect of oxygen concentration on flammability for several engineering alloys configured as 0.32-cm (0.125-in.)-diameter rods burning in the upward direction [16].

materials. The test variables include oxygen pressure, normal loads, rubbing velocity, and test material. The friction test is typically performed at a test pressure of 6.9 MPa (1 000 psi). The maximum normal load that can be applied is 4 450 N (1 000 lbf) and the maximum rotation is 500 Hz (30 000 rpm). For each test, the maximum *Pv* product is measured, where *P* is the load divided by the initial cross-sectional area of the sample and *v* is the relative surface velocity. The *Pv* product is a measure of the energy absorbed per unit area of rubbing surface per unit time. The characteristics of the metallic surfaces, such as the coefficient of friction, have a large influence on ignition as a result of friction.

Ignition of metallic materials by friction can occur in LOX systems as well as in GOX. Metallic materials are more difficult to ignite as a result of friction in LOX than in GOX because of the low initial temperatures. However, once ignition takes place, propagation is inevitably more extensive in LOX because of the large quantity of oxygen present in the condensed phase. The relative ranking of metallic

TABLE 3-2—Promoted ignition data for 60 × 60 wire meshes rolled into 12.7 cm (5 in.) long, 0.64-mm (0.25-in.)-diameter cylinders ignited at the bottom in stagnant oxygen [18]. A burn is defined as consumption of at least 2.0 cm (0.8 in.) of the rod.

	Lowest Burn Pressure				Highest No-Burn Pressure				
Material	MPa	psia	No. Tests	Burn Length (in.)	MPa	psia	No. Tests	Burn Length (in.)	Rod Length (in.)
Nickel 200			None		>68.9[a,b]	>10 000[a,b]	Unknown		Unknown
Copper 100	0.3[c]	47[c]	5	0-5	0.085	12.4	1	0	5
Monel 400	≤0.085[c]	≤12.4[c]	1	>0.8			None		5
316 SS	≤0.085[c]	≤12.4[c]	1	>0.8			None		5
304 SS	≤0.085[c]	≤12.4[c]	1	>0.8			None		5
Carbon steel	≤0.085[c]	≤12.4[c]	1	>0.8			None		5

[a] WSTF unpublished data.

[b] > indicates that this was the highest pressure tested and the material did not burn greater than 2.0 cm (0.8 in.). The burn pressure, if it exists, is greater than the stated value.

[c] ≤ indicates that no tests were conducted at lower pressures and therefore the material may burn at pressures less than or equal to the stated value.

TABLE 3-3—Promoted ignition data for metals configured similarly to sintered filter elements ignited at the bottom in stagnant oxygen [19].

	Lowest Burn Pressure				Highest No-Burn Pressure						
Material	MPa	psia	No. Tests	Burn Length (in.)	MPa	psia	No. Tests	Burn Length (in.)	Rod Length (in.)	Rod Diameter (in.)	Rod Cross-Section
Monel 400	0.69	100	3	0–3	0.082	12.4	3	<0.5	3	0.16 × 0.14	Elliptical
316L SS	≤ 0.082	≤ 12.4	1	2.3		None			2.3	0.18	Circular
Tin-bronze 10P			None		>68.9[a]	>10 000[a]	3	<0.5	3	0.25	Circular
Tin-bronze 90P			None		>68.9[a]	>10 000[a]	3	<0.5	3	0.25	Circular
Tin-bronze 250P			None		>68.9[a]	>10 000[a]	3	<0.5	3	0.25	Circular
Tin-bronze 153A	37.9	5 500	3	0–3	27.6	4 000	3	<0.5	3	0.25	Circular
Tin-bronze 103A	68.9	10 000	4	0–3	55.2	8 000	3	<0.5	3	0.25	Circular
Tin-bronze 61A			None		>68.9[a]	>10 000[a]	3	<0.5	3	0.25	Circular
Tin-bronze 68HP			None		>68.9[a]	>10 000[a]	3	<0.5	3	0.25	Circular
Tin-bronze 23HP			None		>68.9[a]	>10 000[a]	3	<0.5	3	0.25	Circular

[a] > indicates that this was the highest pressure tested and the material did not burn greater than 1.27 cm (0.5 in.). The burn pressure, if it exists, is greater than the stated value.

[b] ≤ indicates that no tests were conducted at lower pressures and therefore the material may burn at pressures less than or equal to the stated value.

TABLE 3-4—Ignition temperature of selected metals (bulk solids).[a]

Metal	Ignition Temperature		Gas	Pressure (MPa/psia)	Reference
	K	°F			
Aluminum, 6061[b]	2 210	3 518	Oxygen	0.1/14.7	[22]
Barium	448	347	Oxygen	0.1/14.7	[21]
Berylco 10	1 228 to 1 233	1 750 to 1 760	Air, oxygen	0.1 to 0.7/14.7 to 103	[21]
Calcium	823	1 022	Oxygen	0.1/14.7	[21]
Cerium	593	608	Oxygen	0.1/14.7	[21]
Iron	1 203	1 706	Oxygen	0.1/14.7	[21]
Magnesium	906	1 171	Oxygen	0.1 to 1.0/14.7 to 147	[21]
Magnesium alloys					
20 % Aluminum	775	936	Oxygen	0.1/14.7	[21]
70 % Zinc	813	1 004	Oxygen	0.1/14.7	[21]
25 % Nickel	774	934	Oxygen	0.1/14.7	[21]
20 % Antimony	866	1 099	Oxygen	0.1/14.7	[21]
63 % Aluminum	734	862	Oxygen	0.1/14.7	[21]
Molybdenum	1 033	1 400	Oxygen	0.1/14.7	[21]
Monel	1 473	2 192	Oxygen	>4.8/>700	[23]
Nickel alloys	1 423 to 1 643	2 102 to 2 498	Oxygen	>1.4/>200	[23]
Steel, carbon	1 313	1 904	Oxygen	>4.8/>700	[23]
Steel, mild	1 500 to 1 550	2 240 to 2 330	Air[c]	0.1 to 0.7/14.7 to 103	[21]
Steel, stainless 310	1 253	1 796	Oxygen	>4.8/>700	[23]
Steel, stainless 321	1 588	2 399	Oxygen	>4.8/>700	[23]
Steel, stainless, 430	1 622 to 1 639	2 460 to 2 490	Oxygen[d]	0.1 to 0.7/14.7 to 103	[21]
Steel, tool	1 503 to 1 593	2 246 to 2 408	Oxygen	0.3 to 2.8 MPa/50 to 400	[22]
Strontium	993	1 328	Oxygen	0.1/14.7	[21]
Tantalum	1 511 to 1 555	2 260 to 2 340	Air[c]	0.1 to 0.7/14.7 to 103	[21]
Thorium	773	932	Oxygen	0.1/14.7	[21]
Titanium alloys					
RC-70	1 855 to 1 900	2 880 to 2 960	Air, oxygen	0.1 to 0.7/14.7 to 103	[21]
RS-70	1 861 to 1 889	2 890 to 2 940	Air, oxygen	0.1 to 0.7/14.7 to 103	[21]
RS-110-A	1 844 to 1 872	2 860 to 2 910	Oxygen[d]	0.1 to 0.7/14.7 to 103	[21]
RS-110-BX	1 839 to 1 878	2 850 to 2 920	Oxygen[d]	0.1 to 0.7/14.7 to 103	[21]
Tungsten	1 516 to 1 561	2 270 to 2 350	Air[c]	0.1 to 0.7/14.7 to 103	[21]
Uranium	593	608	Oxygen	0.1/14.7	[21]

[a] It was noted that, although the metals burned at a much greater rate in oxygen, there was no appreciable difference in the ignition temperature as a result of oxygen. concentration [21].

[b] LASER-ignited aluminum.

[c] Not tested in oxygen, but probably ignites in oxygen at about the same temperature.

[d] Did not ignite in air.

materials in LOX is essentially the same as that in ambient temperature GOX.

Data

Test data indicate that metals, not polymers, are most susceptible to ignition by friction in the friction heating tests presently available. Current research indicates that polymers and composites also may be susceptible to ignition in certain conditions. Data on the ignitability of metallic materials by friction in gaseous oxygen are shown in Tables 3-5 and 3-6. Metals and alloys with low-*Pv* products at ignition are more easily ignited than those with high-*Pv* products at ignition. Table 3-5 shows data for tests in which the stationary and rotary samples were made of the same material, whereas Table 3-6 shows data for tests in which the stationary and rotary samples were made of dissimilar materials. The data in Table 3-6 demonstrate that, when the materials of the stationary and rotary samples have different frictional ignition characteristics, the more reactive material tends to have the greatest effect on the *Pv* product required for ignition.

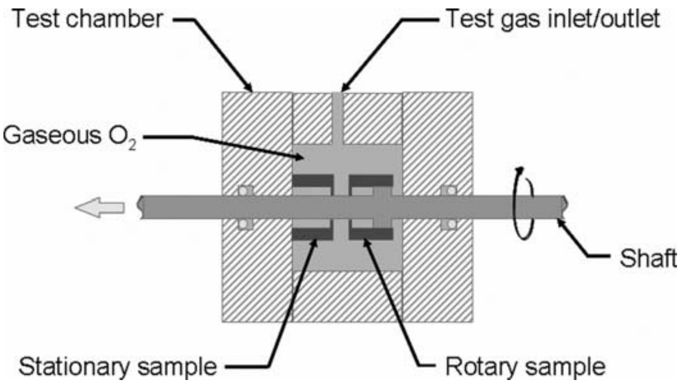

Fig. 3-4—Friction test apparatus.

TABLE 3-5—Friction ignition test data for similar pairs.[a,b]

Test Materials		*Pv* Product at Ignition	
Stator	Rotor	($W/m^2 \times 10^{-8}$)	(lbf/in.^{2} × ft/min × 10^{-6})
Inconel MA754	Inconel MA754	3.96 to 4.12[c]	11.30 to 11.75[c]
Haynes 214	Haynes 214	3.05 to 3.15	8.73 to 8.98
Inconel MA758	Inconel MA758	2.64 to 3.42	7.53 to 9.76
Nickel 200	Nickel 200	2.29 to 3.39[d]	6.54 to 9.66[d]
Tin-bronze	Tin-bronze	2.15 to 2.29[e]	6.15 to 6.55[e]
Hastelloy C-22	Hastelloy C-22	2.00 to 2.99[f]	5.72 to 8.52[f]
Inconel 600	Inconel 600	2.00 to 2.91[d]	5.70 to 8.30[d]
Inconel MA6000	Inconel MA6000	1.99 to 2.66	5.68 to 7.59
Glidcop Al-25	Glidcop Al-25	1.95 to 3.59	5.56 to 10.2
Hastelloy 230	Hastelloy 230	1.79 to 2.19	5.10 to 6.24
NASA-Z	NASA-Z	1.77 to 2.63	5.05 to 7.52
Copper-zirconium	Copper-zirconium	1.68 to 3.19	4.81 to 9.11
Inconel 625	Inconel 625	1.62 to 1.73[f]	4.65 to 4.94[f]
Hastelloy B-2	Hastelloy B-2	1.61 to 2.16[f]	4.60 to 6.12[f]
Waspaloy	Waspaloy	1.55 to 2.56	4.45 to 7.31
Monel 400	Monel 400	1.44 to 1.56[d]	4.12 to 4.46[d]
Monel 400	Monel 400	1.42 to 1.55[g]	4.05 to 4.43[g]
Haynes 230	Haynes 230	1.40 to 1.82	4.00 to 5.20
Monel K-500	Monel K-500	1.37 to 1.64[d]	3.91 to 4.68[d]
13-4 PH	13-4 PH	1.31 to 2.06[e]	3.74 to 5.88[e]
Hastelloy C-276	Hastelloy C-276	1.21 to 2.82[f]	3.45 to 8.06[f]
Incoloy 903	Incoloy 903	1.20 to 1.44	3.41 to 4.11
Inconel 718	Inconel 718	1.10 to 1.19	3.13 to 3.37
17-4 PH (H 900)	17-4 PH (H 900)	1.00 to 1.21	2.87 to 3.45
Yellow brass	Yellow brass	0.97 to 1.22	2.77 to 3.49
Hastelloy X	Hastelloy X	0.93 to 1.05[d]	2.66 to 3.02[d]
Hastelloy G-30	Hastelloy G-30	0.90 to 1.28[f]	2.58 to 3.68[f]
14-5 PH	14-5 PH	0.88 to 1.04	2.51 to 2.96
304 Stainless steel	304 Stainless steel	0.85 to 1.20	2.43 to 3.41
17-4 PH	17-4 PH	0.85 to 1.07	2.42 to 3.05
Inconel 706	Inconel 706	0.81 to 1.21	2.33 to 3.45
303 Stainless steel	303 Stainless steel	0.78 to 0.91	2.25 to 2.60
Stellite 6	Stellite 6	0.79 to 0.82	2.25 to 2.35
316 Stainless steel	316 Stainless steel	0.75 to 0.86[g]	2.14 to 2.46[g]
Brass CDA 360	Brass CDA 360	0.70 to 1.19[e]	1.98 to 3.41[e]
17-4 PH (condition A)[h]	17-4 PH (condition A)	0.61 to 1.05	1.75 to 2.99
Invar 36	Invar 36	0.60 to 0.94[e]	1.71 to 2.68[e]
Incoloy MA 956	Incoloy MA 956	0.53 to 0.75	1.51 to 2.14
316 Stainless steel	316 Stainless steel	0.53 to 0.86[e]	1.50 to 2.46[e]
440C Stainless steel	440C Stainless steel	0.42 to 0.80	1.19 to 2.28
Nitronic 60	Nitronic 60	0.29 to 0.78	0.82 to 2.22
Incoloy 909	Incoloy 909	0.29 to 1.15	0.85 to 3.30
Aluminum 6061-T6	Aluminum 6061-T6	0.061[e]	0.18[e]
Ti-6A1-4V	Ti-6A1-4V	0.0035[e]	0.01[e]

[a] 2.5-cm (1-in.) diameter by 0.25-cm (0.1-in.) wall thickness by 2-cm (0.8-in.) high specimens rotated axially, horizontally in stagnant 6.9 MPa (1000 psia), aviator's breathing grade oxygen. Tests were conducted by keeping *v* constant at 22.4 m/s (73.5 ft/s) and increasing *P* at a rate of 35 N/s until ignition.

[b] Data are from frictional heating tests performed at NASA Johnson Space Center White Sands Test Facility unless otherwise noted.

[c] This material did not ignite at these *Pv* products.

[d] Ref. [24].

[e] Ref. [25].

[f] Ref. [26].

[g] Ref. [27].

[h] Solution annealed.

TABLE 3-6—Friction ignition test data for dissimilar pairs.[a,b]

Test Materials		***Pv* Product at Ignition**	
Stator	**Rotor**	**(W/m^2 × 10^{-8})**	**(lbf/in.^{2} × ft/min × 10^{-6})**
Monel K-500	Hastelloy C-22	1.57 to 3.72	4.51 to 10.61
Monel K-500	Hastelloy C-276	1.41 to 2.70[c]	4.00 to 7.70[c]
Monel K-500	Hastelloy G-30	1.34 to 1.62	3.81 to 4.63
Ductile cast iron	Monel 400	1.28 to 1.45[c]	3.65 to 4.13[c]
Gray cast iron	410 Stainless steel	1.19 to 1.48[c]	3.39 to 4.24[c]
Gray cast iron	17-4 PH (H 1150 M)	1.17 to 1.66[c]	3.35 to 4.75[c]
Copper-beryllium	Monel 400	1.10 to 1.20	3.14 to 3.42
Ductile cast iron	410 Stainless steel	1.10 to 1.23[c]	3.12 to 3.43[c]
AISI 4140	Monel K-500	1.09 to 1.35[c]	3.10 to 3.85[c]
Ductile cast iron	17-4 PH (H 1150 M)	1.09 to 1.17[c]	3.00 to 3.35[c]
Monel 400	Nitronic 60	1.03 to 1.69	2.93 to 4.78
Inconel 718	17-4 PH Stainless steel	1.02 to 1.06[d]	2.91 to 3.03[d]
Bronze	Monel K-500	0.99 to 1.84[c]	2.82 to 5.26[c]
Tin-bronze	304 Stainless steel	0.97 to 1.25[c]	2.78 to 3.56[c]
Monel K-500	Inconel 625	0.93 to 2.00	2.67 to 5.70
17-4 PH Stainless steel	Hastelloy C-22	0.93 to 1.00	2.65 to 2.86
Monel K-500	304 Stainless steel	0.92 to 1.13[d]	2.63 to 3.24[d]
Inconel 718	304 Stainless steel	0.90 to 1.18[d]	2.58 to 3.37[d]
17-4 PH Stainless steel	Hastelloy C-276	0.89 to 1.10	2.55 to 3.14
Bronze	17-4 PH (H 1150 M)	0.89 to 1.02[c]	2.55 to 2.90[c]
316 Stainless steel	303 Stainless steel	0.89 to 0.90[d]	2.53 to 2.57[d]
Inconel 718	316 Stainless steel	0.86 to 0.96[d]	2.44 to 2.73[d]
Monel 400	304 Stainless steel	0.85 to 0.94[d]	2.43 to 2.69[d]
17-4 PH Stainless steel	Hastelloy G-30	0.84 to 1.02	2.41 to 2.90
Monel K-500	303 Stainless steel	0.84 to 1.00[d]	2.41 to 2.88[d]
Ductile cast iron	Stellite 6	0.84 to 1.16[c]	2.39 to 3.32[c]
Copper-zirconium	316 Stainless steel	0.83 to 0.90	2.39 to 2.58
Ductile cast iron	Tin-bronze	0.81 to 1.69[c]	2.32 to 4.82[c]
Monel K-500	17-4 PH Stainless steel	0.80 to 1.00[d]	2.27 to 2.39[d]
Bronze	410 Stainless steel	0.79 to 1.20[c]	2.25 to 3.60[c]
304 Stainless steel	303 Stainless steel	0.77 to 0.79[d]	2.21 to 2.26[d]
Tin-bronze	Aluminum-bronze	0.77 to 0.84	2.20 to 2.38
316 Stainless steel	17-4 PH Stainless steel	0.77 to 0.85[d]	2.18 to 2.41[d]
Monel 400	303 Stainless steel	0.76 to 0.93	2.17 to 2.67
Inconel 718	303 Stainless steel	0.75 to 0.87[d]	2.14 to 2.48[d]
Monel K-500	316 Stainless steel	0.75 to 0.91[d]	2.10 to 2.61[d]
304 Stainless steel	17-4 PH Stainless steel	0.69 to 1.09[d]	1.97 to 3.12[d]
316 Stainless steel	304 Stainless steel	0.68 to 0.91[d]	1.93 to 2.60[d]
Stellite 6	Nitronic 60	0.66 to 0.77	1.90 to 2.18
Monel 400	17-4 PH Stainless steel	0.66 to 1.53[d]	1.89 to 4.38[d]
303 Stainless steel	17-4 PH Stainless steel	0.65 to 0.88	1.86 to 2.51
17-4 PH Stainless steel	Inconel 625	0.64 to 1.09	1.83 to 3.11
304 Stainless steel	Copper-beryllium	0.63 to 1.24	1.81 to 3.54
Monel 400	316 Stainless steel	0.62 to 0.91[d]	1.75 to 2.59[d]
Ductile cast iron	Nitronic 60	0.44 to 0.75	1.25 to 2.15
Aluminum-bronze	C355 Aluminum	0.30 to 0.32	0.85 to 0.91
Nitronic 60	17-4 PH (H 1150 M)	0.28 to 0.61	0.80 to 1.75
Babbitt on bronze	17-4 PH (H 1150 M)	0.09 to 0.21	0.25 to 0.60
Babbitt on bronze	Monel K-500	0.09 to 0.19	0.25 to 0.55
Babbitt on bronze	410 Stainless steel	0.08 to 0.09	0.24 to 0.27

[a] 2.5-cm (1-in.) diameter by 0.25-cm (0.1-in.) wall thickness by 2-cm (0.8-in.) high specimens rotated axially, horizontally in stagnant 6.9 MPa (1 000 psia) aviator's breathing grade oxygen. Tests were conducted by keeping v constant at 22.4 m/s (73.5 ft/s) and increasing P at a rate of 35 N/s until ignition.

[b] Data are from frictional heating tests performed at NASA Johnson Space Center White Sands Test Facility unless otherwise noted.

[c] Ref. [28].

[d] Ref. [27].

Particle Impact

Test Method

The particle impact test is a nonstandardized method that measures the susceptibility of a material to ignition by particle impact. The test apparatuses for supersonic and subsonic particle impact are depicted in Figs. 3-5 and 3-6, respectively. Both the supersonic and subsonic tests are performed by impinging a stream of gaseous oxygen with one or more entrained particles onto the test sample. Test variables include oxygen pressure, temperature, and velocity, as well as particle number, size, quantity, and material. The test gas temperature can be up to 699 K (800°F). The particulate is typically metal, and tests have shown that nonmetal particulate is not an effective igniter.

In the supersonic test system, both particle velocity and pressure at the target increase slowly with target temperature. For this configuration, the particle velocity at the target varies from approximately 370 to 430 m/s (1 200 to 1 400 ft/s) [29]. The pressure at the inlet of the particle impact tester is 26.9 MPa (3 900 psig); however, the absolute pressure at the target varies from approximately 8.7 to 9.0 MPa (1 260 to 1 310 psi) [30]. Supersonic tests are typically performed with single particles in the range of 1 600 to 2 000 μm. The particles are typically aluminum.

In the subsonic test system, the maximum test pressure is 27.5 MPa (4 000 psi). The gas velocity can be varied by using different orifice sizes. Subsonic tests can be performed with single particles or a mixture of particles ranging from 10 to 2 000 μm.

For both supersonic and subsonic tests, it is assumed that particle impact is most severe at the maximum possible pressure. This assumption has not been verified experimentally. Temperature effects are believed to depend on the size and ease of oxidation of the particulate. Usually, ignitability increases with increasing temperature; however, particulate oxidation at high temperatures can reduce the ignitability.

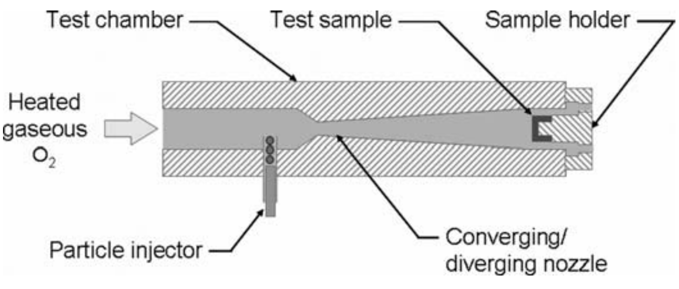

Fig. 3-5—Supersonic particle impact test apparatus.

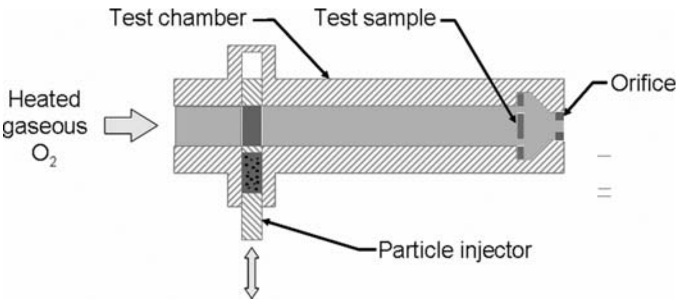

Fig. 3-6—Subsonic particle impact test apparatus.

Data

Particle impact data provide a rough relative ranking of the resistance of materials to ignition by particle impact. Materials able to withstand higher gas velocities and temperatures without ignition of the target are more oxygen compatible; however, not enough test data exist to provide absolute pass/fail criteria in use conditions. In general for both subsonic and supersonic particle impact tests, the data obtained to date suggest that metallic powders are more likely to cause particle impact ignition than large, single particles. The relative ranking of target materials is assumed to be similar for ignition by large, single particles and by powders, but no definitive study has been conducted.

Data on the ignitability of metallic target materials by impact of single 2 000-μm (0.0787-in.) aluminum particles in the supersonic particle impact test system are provided in Table 3-7. The targets were configured in the typical supersonic particle impact target configuration, which has a cup-like shape. The thickness of the surface exposed to the impacting particles is 0.15 cm (0.06 in.) [29].

Data on the ignitability of nonmetallic target materials by impact of single 2000-μm (0.0787-in.) aluminum particles in the supersonic particle impact test system are provided in Table 3-8. Two different target configurations were used. The first was the typical cup-like shape. The Teflon and Kel-F 81 could not structurally withstand the desired test pressure when configured in the cup-like shape. Therefore, a modified target configuration was used for those tests. The modified target configuration was a 0.15-cm (0.06-in.)-thick disc, which was press-fit into a metallic holder with a protective sleeve [31].

Data on the ignitability of metallic target materials by impact of 5 g of particulate in the subsonic particle impact test system are provided in Table 3-9. The particulate consisted of 2 g of iron powder and 3 g of inert particles. The targets were configured in the typical subsonic particle impact target configuration, which has a disc shape with holes for gas to flow through. The average gas temperature ranged from 338 to 355 K (149 to 179°F), and the gas velocity and pressure were varied [32]. The data indicate that fine iron particles will ignite iron or steel targets at flow velocities at or greater than approximately 45 m/s (150 ft/s) [30].

Data on the ignitability of 303 stainless steel in subsonic particle impact tests with various amounts of particulate are presented in Table 3-10. The average gas pressure ranged from 28.9 to 32.1 MPa (4 192 to 4 656 psi). The particulate was a mix of Inconel 718, 21-6-9 stainless steel, and aluminum 2219 particles with a maximum particle size of 250 μm [33].

A very limited number of subsonic particle impact testing on nonmetals have been performed using various amounts of AR-7[2] particulate [34]. In tests performed between approximately 27 and 31 MPa (4 000 and 4 500 psi) with a gas velocity of 31 m/s (101 ft/s), Kel-F 81 was ignited with 140 mg of particulate and Teflon TFE was ignited with 840 mg of particulate. This testing shows that it is possible to ignite nonmetals with subsonic particles; however, there are not enough test data to draw any further conclusions.

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[2] AR-7 is a high-solid aluminum elastomer manufactured by B. F. Goodrich.

TABLE 3-7—Ignitability of metals in supersonic particle impact tests with 2 000-μm (0.0787-in.) aluminum particles. Absolute pressure at the target varied from approximately 8.7 to 9.0 MPa (1 260 to 1 310 psi) [30]. Temperatures given in the table refer to the temperature of the test target before particle impact.

	Highest Temperature without Ignition[b] of Target[c]		Lowest Temperature with Ignition[b] of Target[d]	
Material[a]	°C	°F	°C	°F
Monel K500 (heat treated)	371[e]	700[e]	None	
Monel K500 (annealed)	371[e]	700[e]	None	
Haynes 214	371[e]	700[e]	None	
Monel 400	343[e]	650[e]	None	
Incoloy MA 754	343[e]	650[e]	None	
Yellow brass	316[e]	600[e]	None	
Inconel 600	316[e]	600[e]	None	
Tin-bronze	288[e]	550[e]	None	
Aluminum-bronze	260	500	316	600
Inconel 625	260	500	316	600
440C SS (annealed)	177	350	204	400
Inconel 718 (annealed)	149	300	204	400
Ductile cast iron	149	300	204	400
Incoloy 800	121	250	204	400
Incoloy 903	93	200	121	250
Haynes 230	38[e]	100[e]	None	
Nitronic 60	–18	0	121	250
316 SS	10	50	38	100
304 SS	–18	0	38	100
Incoloy MA 956	–46	–50	10	50
13-4 SS	None		10	50
14-5 PH SS	None		10	50
6061 Aluminum	None		–46	–50

[a] The targets were configured in a cup-like shape. The thickness of the surface exposed to the impacting particles was 0.15 cm (0.06 in.).

[b] Ignition is defined as an event that produces a visually observed fire with obvious consumption of the target.

[c] Indicates that at least nine tests were performed between this temperature and the lowest temperature with ignition of target.

[d] Indicates that there was at least one ignition of the target at this temperature.

[e] Indicates that the material did not ignite at the highest temperature at which it was tested.

TABLE 3-8—Ignitability of nonmetals in supersonic particle impact tests with 2 000-μm (0.0787-in.) aluminum particles [31]. Absolute pressure at the target varied from approximately 8.7 to 9.0 MPa (1 260 to 1 310 psi) [30]. Temperatures given in the table refer to the temperature of the test target before particle impact.

	Highest Temperature without Ignition[b] of Target[c]		Lowest Temperature with Ignition[b] of Target[d]	
Material[a]	°C ± 15°C	°F ± 27°F	°C ± 15°C	°F ± 27°F
Teflon TFE[d]	150[e]	300[e]	None	
Kel-F 81[d]	40	100	150	300
Vespel SP-1[f]	65	150	120	250
PEEK[f]	–30	–20	–5	25

[a] Ignition is defined as an event that produces a visually observed fire with obvious consumption of the target.

[b] Indicates that at least nine tests were performed between this temperature and the lowest temperature with ignition of target.

[c] Indicates that there was at least one ignition of the target at this temperature.

[d] The target configuration was a 0.15-cm (0.06-in.)-thick disc, which was press-fit into a metallic holder with a protective sleeve.

[e] A limited number of successful tests were performed on Teflon because of its loss of structural integrity upon impact in the desired test pressure. Therefore, only four successful impacts were performed at or greater than 150°C (300°F). Teflon did not ignite at the highest temperature at which it was tested.

[f] The targets were configured in a cup-like shape. The thickness of the surface exposed to the impacting particles was 0.15 cm (0.06 in.).

TABLE 3-9—Ignitability of metals in subsonic particle impact tests with 5 g of particulate (2 g of iron powder and 3 g of inert particles) [32]. The average gas temperature was 65 to 82°C (149 to 179°F).

Material[a]	Average Gas Velocity		Average Gas Pressure		No. Ignitions[b]/ No. Tests
	m/s	ft/s	MPa	psi	
Carbon steel	16	52	24	3 481	0/40
	31	102	20	2 901	0/2
	51	167	20	2 901	2/2
316 Stainless steel	14	46	27–32	3 916–4 641	0/9
	31	102	25–31	3 626–4 496	0/10
	51	167	22–23	3 191–3 336	1/2
304 Stainless steel	45	148	3–9	435–1 305	0/8
	45	148	14	2 031	0/3
	45	148	20–28	2 901–4 061	0/3

[a] The targets were configured in the typical subsonic particle impact target configuration, which has a disc shape with holes for gas to flow through.

[b] Ignition is defined as an event that produces a visually observed fire with obvious consumption of the target.

TABLE 3-10—Ignitability of 303 stainless steel in subsonic particle impact tests with various amounts of particulate [33]. The average gas pressure was 28.9 to 32.1 MPa (4 192 to 4 656 psi).

Quantity of Particles[a] (mg)	Average Gas Velocity		Average Gas Temperature		No. Ignitions[b]/ No. Tests
	m/s	ft/s	°C	°F	
500	45	148	325	617	0/39
500	86	282	326	619	0/20
500	113	371	42	108	0/10
500	157	515	333	631	3/10
1 000	87	285	333	631	0/2
1 000	154	505	304	579	1/1
2 000	45	148	331	628	0/9
2 000	63	207	49	120	0/10
2 000	73	240	153	307	0/10
2 000	86	282	328	622	1/2
2 000	98	322	208	406	1/7
2 000	132	433	155	311	2/9
2 000	140	459	204	399	2/3

[a] Particulate is a mix of Inconel 718, 21-6-9 stainless steel, and aluminum 2219 particles, with a maximum particle size of 250 μm.

[b] Ignition is defined as an event that produces a visually observed fire with obvious consumption of the target.

Heat of Combustion (ASTM D 4809)

Test Method

The heat of combustion test measures the heat evolved per unit mass when a material is burned in oxygen at pressures of 2.5 to 3.5 MPa (362 to 515 psia). The test apparatus is depicted in Fig. 3-7, and the procedure used is the *Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)* (ASTM D 4809). For many fire-resistant materials useful in oxygen systems, measured amounts of combustion promoter must be added to ensure complete combustion.

Heat of combustion data can be used to provide a relative ranking of materials, and to evaluate the potential for a material to ignite surrounding materials. The heat of combustion of a

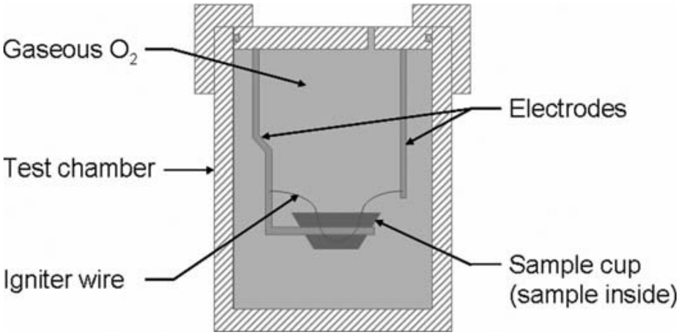

Fig. 3-7—Heat of combustion test apparatus.

material is invariant with temperature and pressure. However, at higher pressures materials will burn faster and thus release their heat of combustion more rapidly.

Data

Heat of combustion data for selected metals and alloys are shown in Table 3-11, and nonmetals heat of combustion data are shown in Table 3-12. The materials listed in Table 3-12 are described in Table 3-13. The higher the heat of combustion of a material, the more likely it could kindle to surrounding materials if ignited. Therefore, materials with lower heats of combustion are preferred for oxygen service.

Oxygen Index (ASTM D 2863)

Test Method

The oxygen index test is used to determine the minimum concentration of oxygen for a nonmetal to just support flaming combustion in a flowing mixture of oxygen and nitrogen. The test is performed at atmospheric pressure. The test apparatus is depicted in Fig. 3-8, and the procedure used is the *Standard Test Method for Measuring the Minimum Oxygen Concentration to Support Candle-Like Combustion of Plastics (Oxygen Index)* (ASTM D 2863). Oxygen index data can be used to provide a relative ranking of materials. The oxygen index of a material decreases with increasing pressure.

Data

Materials with greater oxygen indices are preferred for oxygen service. Although the oxygen index test is not commonly used for metals, some data for some aluminum alloys and bronzes are reported in Ref [52]. Nonmetals oxygen index data are shown in Table 3-12, and these data indicate that the majority of polymeric materials are flammable at an absolute pressure of 0.1 MPa (14.7 psi) in 100 % oxygen. Data on the oxygen index at elevated pressures for selected materials are shown in Fig. 3-9.

Autogenous Ignition (Autoignition) Temperature[†] of Nonmetals (ASTM G 72)

Test Method

The autoignition temperature test measures the minimum sample temperature in which a material will spontaneously ignite when heated in an oxygen or oxygen-enriched atmosphere. The test apparatus is depicted in Fig. 3-10, and the procedure used is the *Standard Test Method for Autogenous Ignition Temperature of Liquids and Solids in a High-Pressure Oxygen-Enriched Environment* (ASTM G 72). The most common test pressure is 10.3 MPa (1 500 psi); however, the test can be performed at pressures up to 21 MPa (3 000 psi). The oxygen concentration can be varied from 0.5 % to 100 %, and the temperature can be varied from 333 to 698 K (140°F to 800°F). This test method is generally used for nonmetals; metals autoignite at much higher temperatures than nonmetals, thus, this test apparatus is not sufficient for raising metals to their autoignition temperatures.

Autoignition temperature data can be used to provide a relative ranking of nonmetals. The temperature at which a material will spontaneously ignite varies with the system geometry,

TABLE 3-11—Heat of combustion of some metals and alloys.

	Heat of Combustion, ΔH_C		
Material[a]	**kJ/g**	**Btu/lb**	**Source**
Beryllium (BeO)	66.38	28 557	[35]
Aluminum (Al_2O_3)	31.07	13 365	[35]
Magnesium (MgO_2)	24.69	10 620	[35]
Titanium (TiO_2)	19.71	8 478	[35]
Chromium (Cr_2O_3)	10.88	4 680	[36]
Ferritic and martensitic steels	7.95 to 8.37	3 420 to 3 600	Calculated
Austenitic stainless steels	7.74 to 7.95	3 330 to 3 420	Calculated
Precipitation-hardening stainless steels	7.74 to 8.16	3 330 to 3 510	Calculated
Carbon steels	7.38 to 7.53	3 177 to 3 240	Calculated
Iron (Fe_2O_3)	7.385	3 177	[35]
Inconel 600	5.439	2 340	Calculated
Aluminum-bronzes	4.60 to 5.86	1 980 to 2 520	Calculated
Zinc (ZnO)	5.314	2 286	[36]
Tin (SnO_2)	4.895	2 106	[36]
Nickel (NiO)	4.10	1 764	[36]
Monel 400	3.64	1 566	Calculated
Yellow brass, 60 Cu/40 Zn	3.45	1 485	Calculated
Cartridge brass, 70 Cu/30 Zn	3.31	1 422	Calculated
Red brass, 85 Cu/15 Zn	2.89	1 242	Calculated
Bronze, 10 Sn/2 Zn	2.74	1 179	Calculated
Copper (CuO)	2.45	1 053	[35]
Lead (PbO)	1.05	450	[36]
Silver (Ag_2O)	0.146	63	[36]

[a] Species given in parentheses indicate the oxide assumed to be formed in the calculation of the heat of combustion.

TABLE 3-12—Ignition and combustion-related properties of selected polymers.

	Oxygen Index (downward)[b]		Autoignition Temperature[c]				Heat of Combustion, ΔH_c	
Material[a]	**OI (%)**	**Source[d]**	**Test Pressure, MPa (psia)**	**AIT, °C**	**Source[d]**	**Test Method**	**ΔH_c, J/g**	**Source[d]**
ABS	18.7	WSTF 02-37238, ASTM STP 1454 p. 25	10.3 (1 500)	243	Fire and Materials Vol. 20 p. 301–303	ASTM G72	35 588	ASTM G63-99, ASTM STP 812 p. 89
	18–39	Flamm. Handbook for Plastics p. 45					35 560	Fire and Materials Vol. 20 p. 301–303
			THERMOPLASTICS					
Fluoropolymers								
CTFE								
Kel-F 81	>99.5	ASTM STP 1454 p. 25	10.3 (1 500)	388	Fire and Materials Vol. 20 p. 301–303	ASTM G72	5 114	WSTF 87-20783
	100	ASTM STP 812 p. 61	3.4 (500)	433	ASTM STP 1040 p. 102	PDSC	6 170	Fire and Materials Vol. 20 p. 301–303, ASTM STP 1319 p. 345
	83–95	Flamm. Handbook for Plastics p. 45	10.3 (1 500)	404	ASTM STP 1319 p. 325	ASTM G72	9 630	ASTM STP 812 p. 89
			0.1 (14.7)	384[e]	ASTM STP 812 p. 61	DTA	9 627	ASTM STP 1040 p. 103
							10 701	ASTM STP 1395 p. 98
							7 859–9 785	ASTM STP 812 p. 61
Neoflon		None	10.3 (1 500)	377–382	ASTM STP 1395 p. 83	ASTM G72	5 108–5 150	ASTM STP 1395 p. 83
ECTFE (Halar)	60	Flamm. Handbook for Plastics p. 45	10.3 (1 500)	171	Fire and Materials Vol. 20 p. 301–303	ASTM G72	13 600	Fire and Materials Vol. 20 p. 301–303
							16 329	ASTM STP 812 p. 89
ETFE (Tefzel)	30	Flamm. Handbook for Plastics p. 45	10.3 (1 500)	243	Fire and Materials Vol. 20 p. 301–303	ASTM G72	14 723	WSTF 98-31929
			10.3 (1 500)	273	Wendell Hull Report WHAC1011	ASTM G72	14 813	ASTM G63-99
			10.3 (1 500)	240	WSTF 98-31929	ASTM G72	16 880	Fire and Materials Vol. 20 p. 301–303
							14 690	ASTM STP 1395 p. 98
FEP (Teflon FEP)	77	ASTM STP 986 p. 255	10.3 (1 500)	378	Fire and Materials Vol. 20 p. 301–303	ASTM G72	10 467	ASTM G63-99, ASTM STP 812 p. 89
	95	Flamm. Handbook for Plastics p. 45					10 460	Fire and Materials Vol. 20 p. 301–303
TFE (PTFE, Teflon TFE)	>99.5	ASTM STP 1454 p. 25	10.3 (1 500)	434	Fire and Materials Vol. 20 p. 301–303	ASTM G72	4 772	WSTF 92-26676
	95	Flamm. Handbook for Plastics p. 45, ASTM STP 812 p. 62, ASTM G63-99	3.4 (500)	>500	ASTM STP 1040 p. 102	PDSC	7 118	ASTM G63-99, ASTM STP 812 p. 89
			10.3 (1 500)	>425	ASTM STP 1319 p. 325	ASTM G72	6 380	Fire and Materials Vol. 20 p. 301–303
	100	ASTM STP 1111 p. 51	0.1 (14.7)	511–526[e]	ASTM STP 812 p. 61	DTA	7 116	ASTM STP 1040 p. 103
			0.1 (14.7)	524[e]	ASTM STP 1111 p. 64	DTA	6 390	ASTM STP 1395 p. 98
							6 351	ASTM STP 1319 p. 345
							5 334	ASTM STP 812 p. 61
Fluorogold (glass-fiber-reinforced PTFE)		None	3.4 (500)	484	ASTM STP 1040 p. 102	PDSC	7 118	ASTM G63-99, ASTM STP 812 p. 91
							7 116	ASTM STP 1040 p. 103

TABLE 3-12—Ignition and combustion-related properties of selected polymers. *(Cont'd)*

	Oxygen Index (downward)[b]		Autoignition Temperature[c]				Heat of Combustion, ΔH_c	
Material[a]	**OI (%)**	**Source[d]**	**Test Pressure, MPa (psia)**	**AIT, °C**	**Source[d]**	**Test Method**	**ΔH_c, J/g**	**Source[d]**
Fluorogreen E600 (glass-fiber-reinforced PTFE)	None		3.4 (500)	479	ASTM STP 1040 p. 102	PDSC	10 048	ASTM G63-99, ASTM STP 812 p. 91
							10 046	ASTM STP 1040 p. 103
TFE w/15 % graphite fill		None	10.3 (1 500)	412	WSTF 01-36030	ASTM G72	9 254	WSTF 01-36030
PVDF (Kynar)	39	ASTM G63-99, ASTM STP 986 p. 255	10.3 (1 500)	268	Fire and Materials Vol. 20 p. 301–303	ASTM G72	14 708	WSTF 01-36291
	43.7	ASTM G63-99, Flamm. Handbook for Plastics p. 45					13 720	ASTM 63-99
							14 770	Fire and Materials Vol. 20 p. 301–303
Rulon A (glass-filled PTFE)	None	3.4 (500)	484	ASTM STP 1040 p. 102		PDSC	5 862	ASTM G63-99
							6 071	ASTM STP 812 p. 91
							6 070	ASTM STP 1040 p. 103
Rulon LD (glass-filled PTFE)		None	10.3 (1 500)	>427	ASTM G63-99	ASTM G72	5 338	ASTM STP 812 p. 91
PVF (Tedlar)	22.6	Flamm. Handbook for Plastics p. 45	10.3 (1 500)	222	Fire and Materials Vol. 20 p. 301–303	ASTM G72	21 700	Fire and Materials Vol. 20 p. 301–303
PA								
Nylon 6	23–28	Flamm. Handbook for Plastics p. 45		None		None		
	24–30.1	ASTM G63-99						
	23.9	ASTM STP 812 p. 62						
Nylon 6/6	21–38	Flamm. Handbook for Plastics p. 45	10.3 (1 500)	259	Fire and Materials Vol. 20 p. 301-303	ASTM G72	31 401–33 076	ASTM G63-99
	30.5	ASTM STP 986 p. 255, ASTM G63-99	3.4 (500)	338	ASTM STP 1040 p. 102	PDSC	33 076	ASTM STP 812 p. 89
	22	WSTF 97-31456	10.3 (1 500)	178	ASTM STP 1319 p. 325	ASTM G72	32 220	Fire and Materials Vol. 20 p. 301–303
			10.3 (1 500)	246	ASTM STP 910 p. 114	ASTM G72	31 311	ASTM STP 1040 p. 103
			10.3 (1 500)	284	ASTM STP 910 p. 114	PDSC	30 794	ASTM STP 1319 p. 345
Zytel 42	31.8	ASTM STP 1454 p. 25	10.3 (1 500)	183	WSTF 93-27463	ASTM G72	31 623	WSTF 00-35847A
	36	ASTM STP 986 p. 255, ASTM G63-99					36 960	ASTM STP 1395 p. 98
	30.2	WSTF 01-36352						
PC (Lexan)	21.3–44	Flamm. Handbook for Plastics p. 45	10.3 (1 500)	286	Fire and Materials Vol. 20 p. 301–303	ASTM G72	30 949	WSTF 01-36301
	43.1	ASTM STP 1454 p. 25, WSTF 02-37236					30 960	Fire and Materials Vol. 20 p. 301–303
	22.5–39.7	ASTM G63-99					30 982	ASTM STP 812 p. 62
	27	ASTM STP 812 p. 62						

TABLE 3-12—Ignition and combustion-related properties of selected polymers. *(Cont'd)*

	Oxygen Index (downward)[b]		Autoignition Temperature[c]				Heat of Combustion, ΔH_c	
Material[a]	OI (%)	Source[d]	Test Pressure, MPa (psia)	AIT, °C	Source[d]	Test Method	ΔH_c, J/g	Source[d]
PE (unspecified density)	17.3–30.2	Flamm. Handbook for Plastics p. 45	10.3 (1 500)	185	Wendell Hull Report WHA05H07	ASTM G72	46 683	ASTM STP 812 p. 89
	17.5	ASTM STP 1454 p. 25	0.1 (14.7)	225[e]	ASTM STP 1111 p. 64	DTA	54 590	ASTM STP 1395 p. 98
	<17.5	ASTM STP 812 p. 61					46 700	ASTM STP 812 p. 61
	17.7	WSTF 01-36520						
PE, high density (HDPE)	<17.5	ASTM STP 1111 p. 51, ASTM STP 812 p. 61	10.3 (1 500)	176	Fire and Materials Vol. 20 p. 301–303	ASTM G72	46 650	Fire and Materials Vol. 20 p. 301–303
	22.5	WSTF 97-31464	0.1 (14.7)	225[e]	ASTM STP 812 p. 61	DTA		
				161	WSTF 01-36185	ASTM G72		
PEEK	35	Information supplied by manufacturer	10.3 (1 500)	305	Fire and Materials Vol. 20 p. 301–303	ASTM G72	32 500	Fire and Materials Vol. 20 p. 301–303
			10.3 (1 500)	325	Wendell Hull Report WHA05H139	ASTM G72		
PES	37–42	Flamm. Handbook for Plastics p. 45	10.3 (1 500)	373	Fire and Materials Vol. 20 p. 301–303	ASTM G72	31 440	Fire and Materials Vol. 20 p. 301–303
PEI (Ultem 1000)	47	Flamm. Handbook for Plastics p. 45	10.3 (1 500)	385	Fire and Materials Vol. 20 p. 301–303	ASTM G72	29 416	WSTF 01-36301
			10.3 (1 500)	360	WSTF 00-35266E	ASTM G72	35 220	Fire and Materials Vol. 20 p. 301–303
PET								
Mylar (unspecified grade)	20–40	Flamm. Handbook for Plastics p. 45	10.3 (1 500)	181	Fire and Materials Vol. 20 p. 301–303	ASTM G72	9 630	ASTM G63-99
	22.7	ASTM STP 812 p. 62					22 180	Fire and Materials Vol. 20 p. 301–303
							23 865	ASTM STP 812 p. 89
							22 190	ASTM STP 812 p. 62
Mylar D		None	10.3 (1 500)	260	WSTF 01-36034	ASTM G72	22 928	WSTF 01-36034
PI								
Unspecified	36.5	Flamm. Handbook for Plastics p. 45	None				None	
Vespel SP1 (unfilled PI)		None	10.3 (1 500)	328	WSTF 01-36031	ASTM G72	25 129	WSTF 01-36031
Vespel SP21 (15 % graphite-filled PI)	53	ASTM STP 812 p. 61, ASTM STP 986 p. 255, ASTM G63-99	10.3 (1 500)	343	Fire and Materials Vol. 20 p. 301–303	ASTM G72	26 456	WSTF 83-16465
			3.4 (500)	420	ASTM STP 1040 p. 102	PDSC	25 539-26 168	ASTM G63-99
			10.3 (1 500)	347	ASTM STP 1319 p. 325	ASTM G72	31 810	Fire and Materials Vol. 20 p. 301–303
			0.1 (14.7)	562[e]	ASTM STP 812 p. 61	DTA	25 535	ASTM STP 1040 p. 103
			10.3 (1 500)	322	WSTF 01-36184	ASTM G72	26 380	ASTM STP 1395 p. 98
			10.3 (1 500)	321	ASTM STP 910 p. 114	ASTM G72	26 239	ASTM STP 1319 p. 345
			10.3 (1 500)	355	ASTM STP 910 p. 114	PDSC	26 109	ASTM STP 812 p. 61

TABLE 3-12—Ignition and combustion-related properties of selected polymers. *(Cont'd)*

	Oxygen Index (downward)^{b}		Autoignition Temperature^{c}				Heat of Combustion, ΔH_c	
Material^{a}	**OI (%)**	**Source^{d}**	**Test Pressure, MPa (psia)**	**AIT, °C**	**Source^{d}**	**Test Method**	**ΔH_c, J/g**	**Source^{d}**
PMMA	17.1	ASTM STP 1454 p. 25	10.3 (1 500)	216	WSTF 01-36033	ASTM G72	26 586	ASTM STP 812 p. 89
	17	ASTM STP 986 p. 255						
	16.7–17.7	ASTM G63-99						
	17.6	ASTM STP 812 p. 57						
	17.0	WSTF 97-31457						
POM Polyacetal (Delrin)	17.2	ASTM STP 1454 p. 25, WSTF 95-36352	10.3 (1 500)	178	Fire and Materials Vol. 20 p. 301–303	ASTM G72	16 869	ASTM G63-99
	14.2–16.1	ASTM G63-99	10.3 (1 500)	175	ASTM STP 1395 p. 97	ASTM G72	16 950	Fire and Materials Vol. 20 p. 301–303
	14.7	ASTM STP 812 p. 57	10.3 (1 500)	171	WSTF 95-29363	ASTM G72	20 050	ASTM STP 1395 p. 98
							16 957	ASTM STP 812 p. 62
PP	17.0–29.2	Flamm. Handbook for Plastics p. 45	10.3 (1 500)	174	Fire and Materials Vol. 20 p. 301–303	ASTM G72	46 055	ASTM G63, ASTM STP 812 p. 61
	17.6	ASTM STP 812 p. 57	0.1 (14.7)	231–261^{e}	ASTM STP 812 p. 61	DTA	46 020	Fire and Materials Vol. 20 p. 301–303
	17.4	ASTM G63-99					46 473	ASTM STP 812 p. 89
PPO	24–33	Flamm. Handbook for Plastics p. 45	10.3 (1 500)	348	Fire and Materials Vol. 20 p. 301–303	ASTM G72	27 650	Fire and Materials Vol. 20 p. 301–303
	33.3	ASTM STP 1454 p. 25, WSTF 02-37234	10.3 (1 500)	229	WSTF 95-29347	ASTM G72	43 620	ASTM STP 1395 p. 98
PPS	43	ASTM STP 812 p. 61	10.3 (1 500)	285	Fire and Materials Vol. 20 p. 301–303	ASTM G72	30 958	WSTF 02-37153
			0.1 (14.7)	532^{e}	ASTM STP 812 p. 61	DTA	28 692	ASTM G63-99, ASTM STP 812 p. 61
			10.3 (1 500)	305	WSTF 02-37150A	ASTM G72	28 670	Fire and Materials Vol. 20 p. 301–303
PS	17.0–23.5	Flamm. Handbook for Plastics p. 45			None		41 449	ASTM G63-99, ASTM STP 812 p. 89, ASTM STP 812 p. 62
	17.8	ASTM G63-99						
	19.2	ASTM STP 812 p. 62						
	20.3	WSTF 99-33863						
PSO	30–51	Flamm. Handbook for Plastics p. 45			None		None	
PU (rigid foam)	25–28	ASTM STP 812 p. 62			None		21 771–27 214	ASTM STP 812 p. 89
	23.5–28.5	ASTM G63-99					31 401	ASTM STP 812 p. 62
PVC	20.6–80.7	Flamm. Handbook for Plastics p. 45	10.3 (1 500)	239	Fire and Materials Vol. 20 p. 301–303	ASTM G72	18 003	ASTM G63-99
	37	ASTM STP 812 p. 61, ASTM G63-99	0.1 (14.7)	402^{e}	ASTM STP 812 p. 61	DTA	20 870	Fire and Materials Vol. 20 p. 301–303
							20 934–22 609	ASTM STP 812 p. 89
							20 884	ASTM STP 812 p. 61

TABLE 3-12—Ignition and combustion-related properties of selected polymers. *(Cont'd)*

	Oxygen Index (downward)[b]		Autoignition Temperature[c]				Heat of Combustion, ΔH_c	
Material[a]	**OI (%)**	**Source[d]**	**Test Pressure, MPa (psia)**	**AIT, °C**	**Source[d]**	**Test Method**	**ΔH_c, J/g**	**Source[d]**
PVDC	60	Flamm. Handbook for Plastics p. 45, ASTM G63-99, ASTM STP 812 p. 62		None			20 934	ASTM G63-99
							18 841	ASTM STP 812 p. 89
							10 551	ASTM STP 812 p. 62
THERMOSETTING ELASTOMERS (RUBBERS)								
CR (Neoprene rubber)	26.3	Flamm. Handbook for Plastics p. 45, ASTM G63-99	10.3 (1 500)	258	Fire and Materials Vol. 20 p. 301–303	ASTM G72	26 737–27 348	ASTM G63-99
	23.9	ASTM STP 1454 p. 25	10.3 (1 500)	242	ASTM STP 1319 p. 325	ASTM G72	12 560	ASTM STP 812 p. 90
	32–35	ASTM STP 812 p. 61	0.1 (14.7)	305–317[e]	ASTM STP 812 p. 61	DTA	29 540	ASTM STP 1395 p. 98
			10.3 (1 500)	164	ASTM STP 1395 p. 97	ASTM G72	31 150	ASTM STP 1319 p. 345
			10.3 (1 500)	313	WSTF C873-B	ASTM G72	26 737–27 310	ASTM STP 812 p. 61
			10.3 (1 500)	236	ASTM STP 910 p. 114	ASTM G72		
			10.3 (1 500)	242	ASTM STP 910 p. 114	PDSC		
CSM (Hypalon rubber)	25.1	Flamm. Handbook for Plastics p. 45			None		28 470	ASTM STP 812 p. 90, ASTM STP 812 p. 62
	27	ASTM STP 812 p. 62						
	25.1	ASTM G63-99						
EPR copolymer (EPDM rubber)	21.9	ASTM STP 1454 p. 25	10.3 (1 500)	159	Fire and Materials Vol. 20 p. 301–303	ASTM G72	39 579	WSTF 82-26086
	25.5	ASTM G63-99	10.3 (1 500)	206	ASTM STP 1319 p. 325	ASTM G72	36 982	ASTM G63-99
			10.3 (1 500)	201	Wendell Hull Report WHA03H073	ASTM G72	47 260	ASTM STP 1395 p. 98
			10.3 (1 500)	187	ASTM STP 1395 p. 97	ASTM G72	39 582	ASTM STP 1319 p. 345
Fluoroelastomers								
FFKM (Kalrez)	100	ASTM STP 812 p. 61	10.3 (1 500)	355	Fire and Materials Vol. 20 p. 301–303	ASTM G72	6 552–8 750	ASTM G63-99
			0.1 (14.7)	429[e]	ASTM STP 812 p. 61	DTA	6 552	ASTM STP 812 p. 61
FKM								
Viton A	31.5	ASTM STP 1454 p. 25	10.3 (1 500)	268–322[f]	Fire and Materials Vol. 20 p. 301–303	ASTM G72	15 072	ASTM STP 812 p. 90
	57	ASTM STP 986 p. 255	10.3 (1 500)	239[f]	ASTM STP 1319 p. 325	ASTM G72	12 640	ASTM STP 1395 p. 98
	57–57.5	ASTM G63-99	10.3 (1 500)	268–322[f]	ASTM G63-99	ASTM G72	16 714	ASTM STP 1319 p. 345
	56–57.5	ASTM STP 1319 p. 355	10.3 (1 500)	290[f]	ASTM STP 1395 p. 97	ASTM G72	15 085	ASTM G63-99
			10.3 (1 500)	155[f]	WSTF 99-34391	ASTM G72		
Viton PLV 5010B		None	3.4 (500)	363	ASTM STP 1040 p. 102	PDSC	14 026–15 072	ASTM G63-99
							15 070	ASTM STP 1040 p. 103
Fluorel	73.9–93.5	ASTM STP 1319 p. 355	10.3 (1 500)	302	Fire and Materials Vol. 20 p. 301–303	ASTM G72	16 714	ASTM STP 1319 p. 345
			10.3 (1 500)	297	ASTM STP 1319 p. 325	ASTM G72		
Fluorel E2160		None	3.4 (500)	360	ASTM STP 1040 p. 102	PDSC	12 401	WSTF 01-36352
			10.3 (1 500)	297	WSTF 01-36352	ASTM G72	14 235	ASTM G63-99
			10.3 (1 500)	313	ASTM STP 910 p. 114	ASTM G72	11 514	ASTM STP 812 p. 90
			10.3 (1 500)	328	ASTM STP 910 p. 114	PDSC	14 023	ASTM STP 1040 p. 103

TABLE 3-12—Ignition and combustion-related properties of selected polymers. *(Cont'd)*

	Oxygen Index (downward)[b]		Autoignition Temperature[c]				Heat of Combustion, ΔH_c	
Material[a]	OI (%)	Source[d]	Test Pressure, MPa (psia)	AIT, °C	Source[d]	Test Method	ΔH_c, J/g	Source[d]
IIR (Butyl)	17.1	Flamm. Handbook for Plastics p. 45	10.3 (1 500)	208	Fire and Materials Vol. 20 p. 301–303	ASTM G72	39 719	WSTF 82-15073
MQ (Silicone rubber)	25.8–39.2	Flamm. Handbook for Plastics p. 45	10.3 (1 500)	262	Fire and Materials Vol. 20 p. 301–303	ASTM G72	15 491	ASTM STP 812 p. 90
	45.4	ASTM STP 1454 p. 25	10.3 (1 500)	297	Wendell Hull Report WHA05H048	ASTM G72	17 370	ASTM STP 1395 p. 98
	21–32	ASTM STP 812 p. 61	10.3 (1 500)	278	ASTM STP 1395 p. 97	ASTM G72	12 895–15 441	ASTM STP 812 p. 61
	23–29	ASTM STP 986 p. 255	10.3 (1 500)	278	WSTF 99-34756	ASTM G72		
	23–36	ASTM G63-99	0.1 (14.7)	271[e]	ASTM STP 812 p. 61	DTA		
NBR (Buna-N)	22.8	ASTM STP 1454 p. 25	10.3 (1 500)	173	Fire and Materials Vol. 20 p. 301–303	ASTM G72	30 695	WSTF 02-36743
	22	ASTM STP 812 p. 61, ASTM STP 1111 p. 51, ASTM STP 1319 p. 355	10.3 (1 500)	166	ASTM STP 1319 p. 325	ASTM G72	41 430	Fire and Materials Vol. 20 p. 301–303
	22.7	WSTF 02-37233	10.3 (1 500)	172	Wendell Hull Report WHA05H048	ASTM G72	35 588	ASTM STP 812 p. 90
			0.1 (14.7)	489[e]	ASTM STP 812 p. 61	DTA	41 460	ASTM STP 1395 p. 98
			10.3 (1 500)	358	ASTM STP 1395 p. 97	ASTM G72	26 255	ASTM STP 1319 p. 345
			10.3 (1 500)	142	WSTF 98-33191	ASTM G72	34 981	ASTM STP 812 p. 61
NR	None		None				39 775	ASTM STP 812 p. 90
PU								
Unspecified polyurethane rubber	27.8	WSTF 97-31458	10.3 (1 500)	181	Fire and Materials Vol. 20 p. 301–303	ASTM G72	21 760–27 200	Fire and Materials Vol. 20 p. 301–303
Disogren polyurethane	None		10.3 (1 500)	265	Wendell Hull Report WHA03H073	ASTM G72	None	
Orothane polyurethane		None	10.3 (1 500)	271	ASTM STP 1040 p. 248	DTA	None	
SBR (Buna-S)	16.9–19	Flamm. Handbook for Plastics p. 45	10.3 (1 500)	147	ASTM STP 1395 p. 97	ASTM G72	11 579	WSTF 98-33191
	24.9	ASTM STP 1454 p. 25	10.3 (1 500)	140	WSTF 95-29359	ASTM G72	13 560	ASTM STP 1395 p. 98
GREASES AND LUBRICANTS								
PFPE								
Fomblin fluorinated lubricant	DNI[g]	ASTM G63-99	10.3 (1 500)	>427	ASTM G63-99	ASTM G72	None	
Krytox 240AC fluorinated lubricant	DNI[g]	ASTM G63-99	3.4 (500)	>500	ASTM STP 1040 p. 102	PDSC	3 768–4 187	Modern Plastics Vol. 44 p. 141–148
			10.3 (1 500)	>427	ASTM G63-99	ASTM G72		
Silicone grease	25–27	ASTM G63-99			None		None	

TABLE 3-12—Ignition and combustion-related properties of selected polymers. *(Cont'd)*

Material[a]	Oxygen Index (downward)[b]		Autoignition Temperature[c]				Heat of Combustion, ΔH_c	
	OI (%)	Source[d]	Test Pressure, MPa (psia)	AIT, °C	Source[d]	Test Method	ΔH_c, J/g	Source[d]
THERMOSETS								
Epoxy/fiberglass composite	None		10.3 (1 500)	258	ASTM STP 1319 p. 425	ASTM G72	10 440	ASTM STP 1319 p. 425
Epoxy/aramid (Kevlar 49) Composite	None		10.3 (1 500)	217	ASTM STP 1319 p. 425	ASTM G72	26 040	ASTM STP 1319 p. 425
Epoxy/graphite composite	None		10.3 (1 500)	258	ASTM STP 1319 p. 425	ASTM G72	29 610	ASTM STP 1319 p. 425
Phenolic/fiberglass composite	None		10.3 (1 500)	155	ASTM STP 1319 p. 425	ASTM G72	10 500	ASTM STP 1319 p. 425
Phenolic aramid (Kevlar 49) Composite	None		10.3 (1 500)	265	ASTM STP 1319 p. 425	ASTM G72	27 650	ASTM STP 1319 p. 425
Phenolic/graphite composite	None		10.3 (1 500)	312	ASTM STP 1319 p. 425	ASTM G72	30 330	ASTM STP 1319 p. 425
Bismaleimide/ graphite composite	None		10.3 (1 500)	340	ASTM STP 1319 p. 425	ASTM G72	None	
Vinyl ester/ fiberglass composite	None		10.3 (1 500)	232	ASTM STP 1319 p. 425	ASTM G72	None	
MISCELLANEOUS								
Carbon black	35	ASTM STP 812 p. 60	None				None	

[a] See Table 3-13 for a description of the material designations used in this column.

[b] Percentage concentration of oxygen in a mixture of oxygen and nitrogen that will maintain equilibrium burning conditions as prescribed in ASTM D 2863.

[c] Published value in 100 % oxygen. There are several AIT methods as described in ASTM STP 1395, including ASTM G72, PDSC (Pressurized Differential Scanning Calorimetry), and DTA (Differential Thermal Analysis). Note that the AIT varies with pressure. AITs from ASTM STP 812 and STP 1111 were conducted at 101.3 kPa (14.7 psia) in pure oxygen and should be used with caution. AITs from ASTM STP 1040 p. 102–103 were conducted at 3.4 MPa (500 psia). AITs determined with the PDSC method are usually higher than those obtained by ASTM G 72 method.

[d] Sources of data include WSTF, WHA (Wendell Hull and Associates), *Flammability Handbook for Plastics* [37], *Fire and Materials* Vol. 20 [38], material manufacturers, *Modern Plastics* Vol. 44 [39], ASTM G63-99, and ASTM STPs (Refs [3], [4], and [40] through [51]). WSTF data are typically referenced by a WSTF number, and WHA data are referenced by a report number.

[e] AIT's from ASTM STP 812 and STP 1111 were conducted at 101.3 kPa (14.7 psia) in pure oxygen and should be used with caution. AIT's in STP 812 are determined by differential thermal analysis in gaseous oxygen.

[f] The AIT depends on the carbon black content in rubbers.

[g] Did not ignite in 100 % oxygen at 101.3 kPa (14.7 psia).

TABLE 3-13—Designation, chemical type, synonyms, and tradenames for materials listed in Table 3-12.

Designation	Chemical Type	Common Synonyms	Tradenames[a]
Thermoplastics			
…	acetal	polyacetal	Delrin (DuPont) Celcon (Celanese)
ABS	acrylonitrile-butadiene-styrene terpolymer	ABS	ABS (J. Gibson) Lustran (Monsanto)
CTFE	chlorotrifluoroethylene homopolymer	PCTFE; CTFE; polychlorotrifluoroethylene	Kel-F[b] (3M) Neoflon CTFE (Daikin)
ECTFE	poly(chlorotrifluoroethylene-co-ethylene)	PECTFE; ECTFE	Halar (Asimont)
ETFE	poly(ethylene-co-tetrafluoroethylene)	PETFE; ETFE	Tefzel (DuPont)
FEP[c]	fluorinated ethylene-propylene copolymer	Teflon FEP; FEP	Teflon FEP (DuPont)
HDPE	linear polyethylene; polyolefin	HDPE; high-density polyethylene	Fortiflex (Solvay) Hostalen (Celanese) Marlex (Phillips) Petrothene (Quantum)
LDPE	branched polyethylene, polyolefin	LDPE; low-density polyethylene	Petrothene (Quantum) Sclair (DuPont Canada) Tenite (Eastman)
PA	poly(hexamethylene adipamide); aliphatic polyamide	nylon	Rilson (Atochem) Zytel (DuPont)
PC	bisphenol A-based polycarbonate	PC; polycarbonate	Lexan (GE Plastics) Makrolon (Miles)
PE[d]	(see HDPE and LDPE)	(see HDPE and LDPE)	(see HDPE and LDPE)
PEEK	polyketone	PEEK (Victrex); polyether ether ketone; polyaryl ketone; amorphous polyarylether ketone	Victrex PEEK (LNP)
PES[e]	poly(ether sulfone)	PES; poly(ether sulfone); polyarylsulfone; polydiphenyl ether sulfone	Victrex PEEK (LNP)
PEI	poly(ether imide)	PEI; poly(ether imide)	Ultem 1000 (General Electric)
PET	saturated polyester	PET; polyethylene terephthalate; Dacron,[b] Fortrel[b]	Mylar (DuPont) Ektar (Eastman)
PI	aromatic polyimide, condensation-type	PI, polyimide; polypyromellitimide	Kapton (DuPont) Vespel (DuPont) Avimid (DuPont)
PMMA	polymethyl methacrylate	PMMA; polyacrylate, acrylic resin	Plexiglas (Rohm and Haas)
POM	polyoxymethylene	polyoxymethylene; POM; acetal, polyacetal, polyformadehyde	Celcon (Celanese) Delrin (DuPont)
PP	isotactic polypropylene; polyolefin	PP; i-PP; semicrystalline PP	Fortiflex (Solvay) Profax(Himont or Montell)
PPO	polyphenylene oxide	PPO, polyaryl ether, aromatic polyether	Noryl (GE Plastics)
PPS	polyphenylene sulfide	PPS; polyaryl sulfide; aromatic polysulfide	Ryton (Phillips)
PS	polystyrene, rigid	PS; ethenylbenzene homopolymer, styrene resin	Luster (Monsanto) Polystyrol (BASF)
PSO[e]	polysulfone (amorphous)	PSO; polyarylsulfone	Udel (Amoco)
PTFE	polytetrafluoroethylene	Teflon; PTFE; TFE	Teflon PTFE (DuPont) Hostaflon TF (Celanese) Neoflon TFE (Daikin)
PTFE, reinforced	reinforced polytetrafluoroethylene	reinforced PTFE; filled PTFE; glass-fiber reinforced PTFE; GFR-PTFE; GPTFE	Fluorogold (Seismic Energy Products) Fluorogreen (United Fluoro Components) Rulon (Furon)
PU	polyurethane rigid foam	PU; rigid thermoplastic urethane (RTPU)	…
PVC	polyvinyl chloride, unplasticized	PVC; polyvinyl chloride	Geon (B. F. Goodrich)
PVDC	polyvinylidene chloride	PVDC; polyvinylidene chloride; polyvinylidene dichloride	Daran (W. R. Grace) Saran (Dow)
PVDF	polyvinylidene fluoride	PVDC; polyvinylidene fluoride;	Kynar (Atochem)
PVF	polyvinyl fluoride	PVF; polyvinylidene difluoride	Tedlar (DuPont)
Thermosetting Elastomers (Rubbers)			
CR	poly(2-chloro-1,3-butadiene) elastomer	CR rubber; neoprene; chloroprene polychloroprene	Butaclor (A. Schulman) Neoprene (DuPont)
CSM	chlorosulfonated polyethylene	CSM	Hypalon (DuPont)

TABLE 3-13—Designation, chemical type, synonyms, and tradenames for materials listed in Table 3-12. *(Cont'd)*

Designation	Chemical Type	Common Synonyms	Tradenames[a]
EPR	poly(ethylene-co-propylene) elastomer	EPR; EPDM; ethylene-propylene monomer (EPM) rubber	Epcar (B. F. Goodrich) Vistolon (Exxon)
FFKM	poly(tetrafluoroethylene-co-perfluoromethylvinyl ether) elastomer	TFE-PMVE elastomer perfluoroelastomer	Kalrez (DuPont)
FKM	poly(hexafluoropropylene-co-vinylidene fluoride) elastomer	PVDF-HFP; fluoroelastomer;	Fluorel (Dyneon) Viton (DuPont)
IIR	poly(isobutadiene-co-isoprene) elastomer	fluorocarbon elastomer IIR; butyl rubber	Exxon Butyl (Exxon) Polysar Butyl (Polysar) Exxon Butyl (Exxon) Polysar Butyl (Polysar)
MQ	polydimethyl siloxane elastomer	Silicone rubber; MQ; MPQ (low-temperature copolymer); MVQ (low-compression set copolymer)	RTV (GE Silicones) Silastic (Dow)
NBR	poly(acrylonitrile-co-butadiene) elastomer	acrylonite rubber; acrylonitrile-butadiene rubber; nitrile rubber; NBR; Buna N	Chemigum (Goodyear) Hycar (B. F. Goodrich) Paracril (Uniroyal)
NR		NR; natural rubber; natural latex rubber	Hartex (Firestone)
PU	Polyurethane rubber	PU; urethane	Disogren Orothane (Eagle Picher)
SBR	natural poly(1,4-isoprene) elastomer poly(butadiene-co-styrene) elastomer	SBR; GRS, Buna S; styrene-butadiene rubber	Duradene (Firestone) Nippol SBR (Zeon) Plioflex (Goodyear)

[a] Trademarks given are for those materials for which data are provided in Table 3-12, or are representative of products that are available. Some of the tradenames may be obsolete (no longer available), but they are given because they are for the materials for which data are presented in Table 3-12.

[b] Obsolete.

[c] FEP is not polytetrafluoroethylene (PTFE).

[d] PE is a general classification and could refer to HDPE, LLDPE, LDPE, or UHMWPE.

[e] Examples of polyarylsulfones.

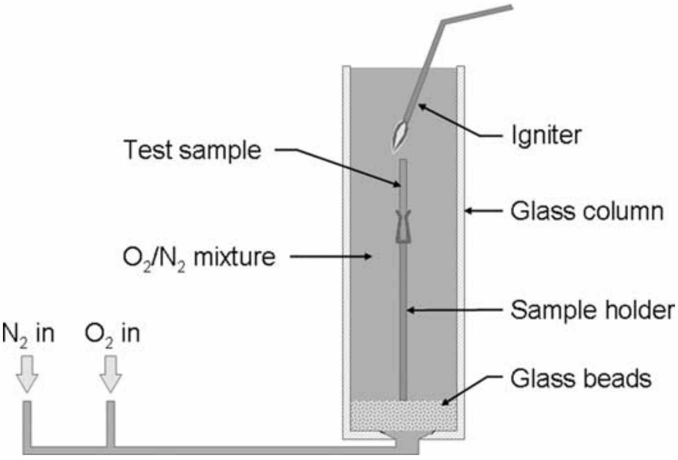

Fig. 3-8—Oxygen index test apparatus.

oxygen concentration, and heating rate. In general, as the oxygen concentration rises, the autoignition temperature of a material goes down. An increased heating rate results in a higher autoignition temperature and increased pressure results in a lower autoignition temperature.

Data

Higher autoignition temperatures are preferred. Nonmetals autoignition temperature data for 100 % oxygen are located in Table 3-12. Nonmetals autoignition temperature data for various oxygen concentrations are located in Table 3-14.

LIVE GRAPH
Click here to view

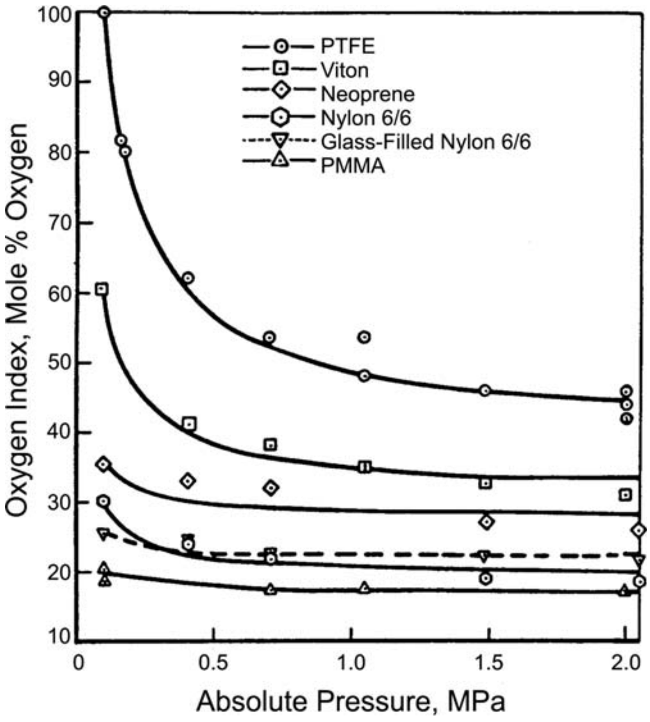

Fig. 3-9—Variability of oxygen index with pressure at 298 K (77°F) [53].

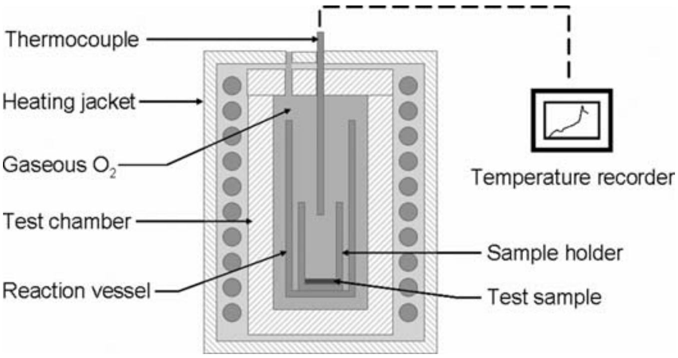

Fig. 3-10—Autoignition temperature test apparatus.

Pneumatic Impact of Nonmetals (ASTM G 74)

Test Method

The pneumatic impact test measures the relative ignitability of materials by heat of compression. The test apparatus is depicted in Fig. 3-11, and the procedure used is the *Standard Test Method for Ignition Sensitivity of Materials to Gaseous Fluid Impact* (ASTM G 74). This test can be performed at pressures up 69 MPa (10 000 psi). The standard requires that the test sample be pressurized to 95 % of the test pressure in a minimum of 10 and a maximum of 50 ms.

The test data can be used to provide a relative ranking for nonmetals, or they can be used to evaluate the use of a material in a specific application where pneumatic impact could occur. Ignition by pneumatic impact, also referred to as heat of compression or rapid pressurization, is very configuration dependent, and configurational testing or additional analysis should be conducted for specific components and systems. For instance, a certain material may fail the standard pneumatic impact test at a given pressure, but a component using the same material at a higher pressure may pass pneumatic impact testing if the material is well protected by metal surfaces.

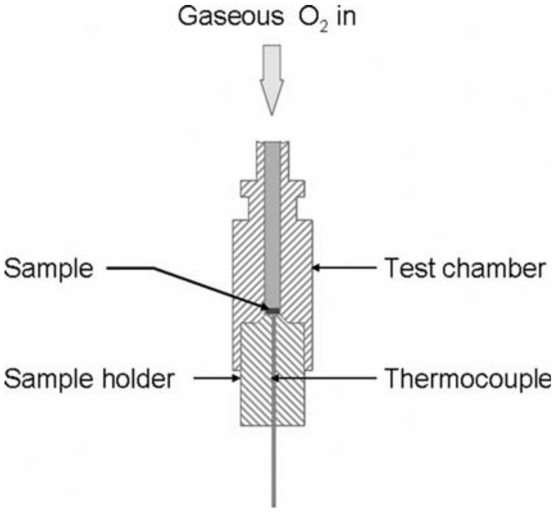

Fig. 3-11—Pneumatic impact test apparatus.

Data

Nonmetals pneumatic impact data are shown in Table 3-15. The materials listed in Table 3-15 are described in Table 3-13. Materials that require a greater impact pressure for ignition are preferred. Metals have been shown to not ignite by pneumatic impact.

Mechanical Impact (ASTM G 86)

Test Method

The mechanical impact test is used to determine the sensitivity of materials to ignition by mechanical impact in LOX or GOX at absolute pressures from 0.1 to 68.9 MPa (14.7 to 10 000 psi). The procedure used is the *Standard Test Method for Determining Ignition Sensitivity of Materials to Mechanical Impact in Ambient LOX and Pressurized Liquid and Gaseous Oxygen*

TABLE 3-14—Variability of autoignition temperature with oxygen concentration at 10.3 MPa (1 494 psi) [43].

	Oxygen Concentration (Percent Oxygen)				
	21	25	50	75	100
Material	Temperature (°C)				
Teflon TFE	438	440	441	437	435
Kel-F 81	367	370	381	382	381
Buna N	380	380	373	343	358
Vespel SP-21	397	409	356	333	338
Noryl	382	374	367	353	325
Silicone	279	278	277	268	278
Tefzel	265	266	254	249	245
Viton A	321	317	295	288	290
Zytel 42	269	267	250	205	194
EPDM	204	203	193	188	187
Polyethylene	195	185	184	180	176
Delrin	183	185	174	172	175
Neoprene	381	375	363	165	164
Buna S	338	157	149	146	146

TABLE 3-15—Pneumatic impact data for nonmetallic materials.

	Highest Passing Pneumatic Impact Pressure			Lowest Failing Pneumatic Impact Pressure		
Material[a]	**Pressure, MPa[b]**	**Reactions/Tests**	**Source[c]**	**Pressure, MPa**	**Reactions/Tests**	**Source[c]**
Thermoplastics						
CTFE Kel-F 81	3.4 3.4 3.4	0/20 0/20 0/20	MAPTIS 05521 WSTF 82-13856 WSTF 81-13856	6.89	1/20 1/2 1/20	MAPTIS 05521 WSTF 82-15670 WSTF 81-13856
CTFE Neoflon	6.9	0/20	WSTF 02-37303	10.3	19/140	WSTF 02-37303
FEP Teflon	3.4	0/20	WSTF 76-8340, MAPTIS 00649	6.89	1/16	WSTF 76-8340, MAPTIS 00649
PTFE, TFE Teflon		None		3.4	1/20	ASTM STP 1395 p. 521–528, WSTF 98-33222
Fluorogold (glass-fiber reinforced PTFE)	20.7	0/20	WSTF 84-17977	24.1	1/8	WSTF 84-17977
Fluorogreen E600 (glass fiber reinforced PTFE)	20.7	0/20	WSTF 84-17978	24.1	1/2	WSTF 84-17978
TFE w/15 % graphite fill	20.7	0/20	WSTF 01-36345	24.1	1/6	WSTF 01-36345
Rulon A (glass-filled PTFE)	6.89	0/20	MAPTIS 05300		None	
PA Nylon 6/6	3.45	0/23	MAPTIS 05298	6.89 6.89	23/94 3/23	WSTF 86-20314 MAPTIS 05298
PA Zytel 42	3.4	0/20	ASTM STP 1395 p. 521–528	6.9	8/20	ASTM STP 1395 p. 521–528
PC Lexan	0.276	0/20	MAPTIS 05197		None	
HDPE		None		3.4 3.45	2/20 1/12	ASTM STP 1395 p. 521–528 WSTF 98-33219
PET Mylar D	3.45[d]	0/20	WSTF 01-36034	6.89[d]	1/3	WSTF 01-36034
Vespel SP-1 (unfilled PI)	6.89[c]	0/20	MAPTIS 05123	8.6[e]	2/13	MAPTIS 05123
Vespel SP21 (15 % graphite-filled PI)	20.7	0/20	MAPTIS 05122	24.1	1/20	MAPTIS 05122
POM Delrin	3.4	0/20	ASTM STP 1395 p. 521–528	6.89 6.9	14/20 8/20	WSTF 98-33221 ASTM STP 1395 p. 521–528
PPO	3.4[d]	0/20	WSTF 00-35849	6.89[d]	1/4	WSTF 00-35849
PSO	3.45[f]	0/20	MAPTIS 05209	4.1[f]	1/18	MAPTIS 05209
Thermosetting Elastomers (Rubbers)						
CR Neoprene rubber	3.45	0/20	WSTF 86-20570	6.89	2/3	WSTF 86-20570
FKM Viton A	3.4	0/20	ASTM STP 1395 p. 521–528	6.89	2/20	ASTM STP 1395 p. 521–528
FKM Fluorel E2160	6.89	0/20	WSTF 01-36352	10.3	1/3	WSTF 01-36352
MQ Silicone rubber	3.4	0/20	ASTM STP 1395 p. 521–528	6.89	1/20	ASTM STP 1395 p. 521–528

TABLE 3-15—Pneumatic impact data for nonmetallic materials. *(Cont'd)*

	Highest Passing Pneumatic Impact Pressure			Lowest Failing Pneumatic Impact Pressure		
Material[a]	**Pressure, MPa[b]**	**Reactions/Tests**	**Source[c]**	**Pressure, MPa**	**Reactions/Tests**	**Source[c]**
NBR Buna-N	3.45	0/20	WSTF 02-37349A	6.89	1/2	WSTF 02-37349A
SBR Buna-S		None		3.45[g]	1/20	WSTF 98-33215
Greases and lubricants						
PFPE Krytox 240AC fluorinated lubricant	10.3	0/40	WSTF 80-12613, 80-12545	13.8	3/39	WSTF 80-12613, 80-12545

[a] See Table 3-13 for a description of the material designations used in this column.

[b] G74 standard thickness is 1.52 ± 0.13 mm (1.39-1.65 mm). All of the data falls within the standard thickness unless otherwise noted.

[c] Sources of data are include WSTF, MAPTIS, and ASTM STP 1395 [3-54]. WSTF data are typically referenced by a WSTF number, and MAPTIS data are referenced by a material code.

[d] Only data found for this material but out of range of standard thickness. Thickness is 1.27 mm.

[e] Only data found for this material but out of range of standard thickness. Thickness is 1.06 mm.

[f] Only data found for this material but out of range of standard thickness. Thickness is 3.35 mm.

[g] Only data found for this material but out of range of standard thickness. Thickness is 1.38 mm.

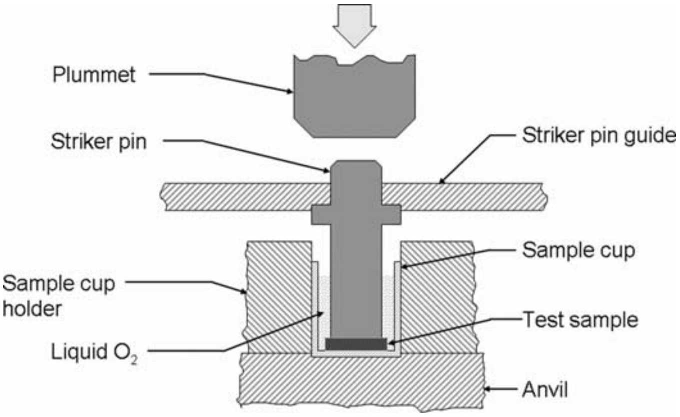

Fig. 3-12—Ambient LOX mechanical impact test apparatus.

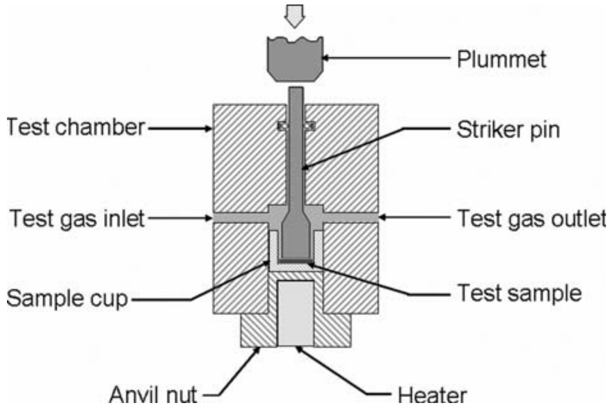

Fig. 3-13—Pressurized LOX or GOX mechanical impact test apparatus.

Environments (ASTM G 86). The test is performed by dropping a plummet onto a striker pin, which then transfers the impact energy to the test sample. The maximum impact energy is 98 J (72 ft-lb). The ambient pressure LOX and pressurized LOX or GOX test apparatus are depicted in Figs. 3-12 and 3-13, respectively. This test method is predominantly used for nonmetals.

Data

The test data can be used to rank materials for their relative ignitability by mechanical impact, or it can be used to evaluate the use of a material in a specific application where mechanical impact could occur. Ambient LOX, pressurized LOX, and pressurized GOX mechanical impact data for nonmetals are presented in Table 3-16. Although mechanical impact tests are not presently used to evaluate metals for oxygen service, data have shown that aluminum, magnesium, titanium, and lithium-based alloys, as well as some lead-containing solders, can be ignited by mechanical impact. A large body of data for mechanical impact of metals exists. Some can be found in Ref [55].

Electrical Arc

Test Method

Several nonstandardized electrical arc tests methods have been developed. These include a method for determining, with a given voltage, the current needed to produce ignition in

TABLE 3-16—Ambient and pressurized mechanical impact data for nonmetallic materials.

	Energy in LOX at Ambient Pressure (14.7 psia)			Pressure in LOX				Pressure in Ambient Temperature (75°F) GOX			
Material[a]	Reactions/ Tests	Impact Energy (J)	Source	Pressure (MPa)	Reactions/ Tests	Impact Energy (J)	Source	Pressure (MPa)	Reactions/ Tests	Impact Energy (J)	Source
NBR Buna-N	3/22[b]	20	MAPTIS 85887			None		0.1	0/20	98	ASTM STP 1395 pg 87–100
	0/20[c]	20	WSTF # 02-36743								
	1/4[c]	27	WSTF # 02-36743								
	2/20[c]	27	WSTF # 00-35084								
EPDM	0/20[c]	14	WSTF # 00-35085			None		0.1	0/20	81	ASTM STP 1395 pg 87–100
	7/20[c]	27	WSTF # 00-35085								
FEP (Teflon FEP)	0/40	98	MAPTIS 00649	6.89	0/40	98	MAPTIS 00649	0.689	0/20	98	MAPTIS 00649
				34.5	3/4	98	MAPTIS 00649	3.45	0/20	98	MAPTIS 00649
								6.89	0/20	98	MAPTIS 00649
								10.3	0/40	98	MAPTIS 00649
								40.8	0/20	98	ASTM STP 812 pg 9–42
								41.4	0/20	98	MAPTIS 00649
Kel-F 81 (CTFE)	0/60	98	MAPTIS 05521	2.78	0/80	98	MAPTIS 05521	6.8	0/20	98	ASTM STP 812 pg 9–42
	0/10	98	ASTM STP 812 pg 9–42	6.89	2/41	98	MAPTIS 05521	7.24	0/20	98	MAPTIS 05521
	0/20	98	WSTF # 84-18296	13.8	8/20	98	MAPTIS 05521	7.34	0/20	98	MAPTIS 05521
				27.6	0/20	54	MAPTIS 05521	10.3	0/20	59	ASTM STP 812 pg 9–42
				27.6	1/9	61	MAPTIS 05521	10.3	2/20	67	ASTM STP 812 pg 9–42
				34.5	33/40	98	MAPTIS 05521	13.6	0/20	54	ASTM STP 812 pg 9–42
				41.4	4/4	98	MAPTIS 05521	13.8	1/7	98	MAPTIS 05521
								17.2	1/18	98	MAPTIS 05521
								20.6	0/20	61	ASTM STP 812 pg 9–42
								20.7	1/7	98	MAPTIS 05521
								22.8	0/20	34	MAPTIS 05521
								22.8	1/6	41	MAPTIS 05521
								24.1	1/1	98	MAPTIS 05521
								25.4	0/20	47	MAPTIS 05521
								25.4	1/14	54	MAPTIS 05521
								27.6	0/20	41	MAPTIS 05521
								27.6	1/6	47	MAPTIS 05521
								31.0	1/1	98	MAPTIS 05521
								34.0	1/6	74	ASTM STP 812 pg 9–42
								34.0	0/20	54	ASTM STP 812 pg 9–42
								34.5	1/1	98	MAPTIS 05521
								37.9	1/1	98	MAPTIS 05521
								41.4	3/56	34	MAPTIS 05521
								41.4	0/50	27	MAPTIS 05521
								46.2	0/100	27	MAPTIS 05521
PA Nylon 6/6	2/20	41	MAPTIS 05298	1.72	13/20	98	MAPTIS 05298	0.0855	0/25	98	MAPTIS 05298
	0/20	34	MAPTIS 05298	3.45	20/20	98	MAPTIS 05298	0.7	0/20	98	ASTM STP 812 pg 9–42

TABLE 3-16—Ambient and pressurized mechanical impact data for nonmetallic materials. *(Cont'd)*

	Energy in LOX at Ambient Pressure (14.7 psia)			Pressure in LOX				Pressure in Ambient Temperature (75°F) GOX			
Material[a]	**Reactions/ Tests**	**Impact Energy (J)**	**Source**	**Pressure (MPa)**	**Reactions/ Tests**	**Impact Energy (J)**	**Source**	**Pressure (MPa)**	**Reactions/ Tests**	**Impact Energy (J)**	**Source**
				6.89	20/20	98	MAPTIS 05298	1.72	0/20	88	MAPTIS 05298
				10.3	20/20	98	MAPTIS 05298	1.72	14/20	98	MAPTIS 05298
								3.4	0/20	69	ASTM STP 812 pg 9–42
								3.4	1/28	98	ASTM STP 812 pg 9–42
								3.45	0/20	81	MAPTIS 05298
								3.45	10/20	88	MAPTIS 05298
								6.89	0/20	81	MAPTIS 05298
								6.89	12/20	88	MAPTIS 05298
								10.3	0/20	75	MAPTIS 05298
								10.3	14/20	81	MAPTIS 05298
								20.6	0/20	27	ASTM STP 812 pg 9–42
PEEK	1/3[c]	14	WSTF # 02-37348		None				None		
Teflon (PTFE Teflon)	0/260	98	MAPTIS 00016	0.689	0/40	98	MAPTIS 00016	0.689	0/20	98	MAPTIS 00016
	0/100	98	ASTM STP 812 pg 9–42	0.862	0/20	98	MAPTIS 00016	3.45	0/20	98	MAPTIS 00016
	0/20	98	ASTM STP 1040 pg 11–22	3.45	0/20	98	MAPTIS 00016	6.89	0/20	98	MAPTIS 00016
	1/20	111	ASTM STP 1040 pg 11–22	4.14	0/40	98	MAPTIS 00016	7.24	0/20	98	MAPTIS 00016
	1/120	111	WSTF # 87-21507	6.89	0/20	98	MAPTIS 00016	10.3	0/40	98	MAPTIS 00016
	0/120	98	WSTF # 87-21507	10.3	0/140	98	MAPTIS 00016	13.8	0/20	98	MAPTIS 00016
				10.3	0/20	98	ASTM STP 812 pg 9–42	17.2	2/6	98	MAPTIS 00016
				17.2	3/40	98	MAPTIS 00016	20.7	3/56	98	MAPTIS 00016
				20.7	4/36	98	MAPTIS 00016	24.1	1/24	98	MAPTIS 00016
				34.5	2/40	79	MAPTIS 00016	25.3	0/20	98	MAPTIS 00016
				34.5	0/20	69	MAPTIS 00016	27.6	3/29	98	MAPTIS 00016
				37.9	2/29	98	MAPTIS 00016	31.0	3/46	98	MAPTIS 00016
				41.4	2/2	98	MAPTIS 00016	34.0	4/20	98	ASTM STP 812 pg 9–42
				41.4	0/20	49	MAPTIS 00016	34.5	1/40	98	MAPTIS 00016
				55.2	2/3	98	MAPTIS 00016	37.9	1/2	98	MAPTIS 00016
				58.6	0/20	58	MAPTIS 00016	41.4	1/20	47	MAPTIS 00016
				58.6	2/43	79	MAPTIS 00016	41.4	0/20	34	MAPTIS 00016
				58.6	1/60	69	MAPTIS 00016	48.3	2/5	98	MAPTIS 00016
				68.9	2/42	98	MAPTIS 00016	55.2	1/1	98	MAPTIS 00016
				68.9	0/20	49	MAPTIS 00016	68.9	3/22	34	MAPTIS 00016
Polyvinyl chloride (PVC)	2/11	20	MAPTIS 60137		None				None		
Polyurethane rubber	None			6.89[3]	1/1	75	WSTF # 01-36381)	6.89[3]	0/20	25	WSTF # 01-36381)
								6.89[3]	1/1	41	WSTF # 01-36381)
Rulon A	0/60	98	MAPTIS 05300	0.689	0/20	98	MAPTIS 05300	0.689	0/20	98	MAPTIS 05300
	0/100	98	ASTM STP 812 pg 9–42	3.45	0/20	98	MAPTIS 05300	3.45	0/20	98	MAPTIS 05300
				6.89	0/20	98	MAPTIS 05300	6.89	0/20	98	MAPTIS 05300
				10.3	0/20	98	MAPTIS 05300	10.3	0/20	27	ASTM STP 812 pg 9–42
				10.3	0/20	98	ASTM STP 812 pg 9–42	10.3	1/1	98	ASTM STP 812 pg 9–42
				13.8	3/80	98	MAPTIS 05300	13.6	0/20	21	ASTM STP 812 pg 9–42

TABLE 3-16—Ambient and pressurized mechanical impact data for nonmetallic materials. *(Cont'd)*

Material[a]	Energy in LOX at Ambient Pressure (14.7 psia)			Pressure in LOX				Pressure in Ambient Temperature (75°F) GOX			
	Reactions/ Tests	Impact Energy (J)	Source	Pressure (MPa)	Reactions/ Tests	Impact Energy (J)	Source	Pressure (MPa)	Reactions/ Tests	Impact Energy (J)	Source
				13.8	0/20	88	MAPTIS 05300	13.6	1/3	54	ASTM STP 812 pg 9–42
				20.7	0/20	27	MAPTIS 05300	34.5	4/4	98	MAPTIS 05300
				20.7	3/20	41	MAPTIS 05300				
				35.9	2/33	49	MAPTIS 05300				
				44.1	5/5	98	MAPTIS 05300				
Silicone	2/20[c]	14	WSTF # 00-35089	None				6.9	0/20	98	ASTM STP 1395 pg 87–100
Vespel SP-1	19/112[c]	98	MAPTIS 05123	0.689	2/10	98	MAPTIS 05123	1.38	0/20	98	MAPTIS 05123
	14/40[c]	98	ASTM STP 812 pg 9–42	1.38	2/12	98	MAPTIS 05123	3.45	0/20	75	MAPTIS 05123
	0/20[c]	47	WSTF # 01-36031	1.83	2/6	98	MAPTIS 05123	3.45	1/1	81	MAPTIS 05123
	1/15[c]	54	WSTF # 01-36031	2.07	2/40	98	MAPTIS 05123	7.24	0/20	41	MAPTIS 05123
				2.76	6/17	98	MAPTIS 05123	7.24	1/27	47	MAPTIS 05123
				3.45	2/4	98	MAPTIS 05123	6.89	1/1	98	MAPTIS 05123
								7.34	0/20	41	MAPTIS 05123
								7.34	1/3	47	MAPTIS 05123
								10.3	1/1	98	MAPTIS 05123
								13.8	1/1	98	MAPTIS 05123
								17.3	1/1	98	MAPTIS 05123
								37.9	0/20	14	MAPTIS 05123
								37.9	1/14	75	MAPTIS 05123
Vespel SP-21	0/220	98	MAPTIS 05122	0.689	2/20	98	MAPTIS 05122	0.1	0/20	98	ASTM STP 812 pg 9–42
	0/100	98	ASTM STP 812 pg 9–42	1.14	0/20	98	MAPTIS 05122	0.689	0/20	98	MAPTIS 05122
	0/20	111	ASTM STP 1040 pg 11–22	1.90	1/160	98	MAPTIS 05122	0.7	1/11	98	ASTM STP 812 pg 9–42
	0/120	111	WSTF # 88-22242	2.76	3/122	98	MAPTIS 05122	0.7	0/20	67	ASTM STP 812 pg 9–42
	0/20	98	WSTF # 77-9430	3.45	15/152	98	MAPTIS 05122	1.72	0/20	98	MAPTIS 05122
	0/20	98	WSTF # 85-18863	6.89	4/42	81	MAPTIS 05122	3.45	11/86	98	MAPTIS 05122
				6.89	0/20	47	MAPTIS 05122	6.8	0/20	81	ASTM STP 812 pg 9–42
				7.24	0/40	75	MAPTIS 05122	6.89	19/62	98	MAPTIS 05122
				7.24	2/88	81	MAPTIS 05122	6.89	0/20	68	MAPTIS 05122
				10.3	1/30	98	MAPTIS 05122	6.89	0/180	14	MAPTIS 05122
				13.8	1/1	98	MAPTIS 05122	7.24	6/141	98	MAPTIS 05122
				17.2	1/5	98	MAPTIS 05122	7.24	0/80	88	MAPTIS 05122
				20.7	0/20	49	MAPTIS 05122	7.34	0/20	54	MAPTIS 05122
				22.9	0/20	81	MAPTIS 05122	7.34	1/17	61	MAPTIS 05122
				22.9	1/15	88	MAPTIS 05122	10.3	26/72	98	MAPTIS 05122
				24.1	1/3	98	MAPTIS 05122	13.8	3/36	98	MAPTIS 05122
				27.6	3/21	98	MAPTIS 05122	13.8	0/20	34	MAPTIS 05122
				31.0	1/2	98	MAPTIS 05122	17.2	1/9	47	MAPTIS 05122
				34.5	6/24	98	MAPTIS 05122	17.2	0/16	41	MAPTIS 05122
				45.6	2/5	68	MAPTIS 05122	20.7	1/1	54	MAPTIS 05122
				58.6	0/20	61	MAPTIS 05122	24.1	2/19	88	MAPTIS 05122
				58.7	1/26	61	MAPTIS 05122	27.6	5/17	98	MAPTIS 05122
				58.7	0/20	41	MAPTIS 05122	31.0	1/3	98	MAPTIS 05122
								34.0	3/20	21	ASTM STP 812 pg 9–42
								34.0	0/20	13	ASTM STP 812 pg 9–42

TABLE 3-16—Ambient and pressurized mechanical impact data for nonmetallic materials. *(Cont'd)*

	Energy in LOX at Ambient Pressure (14.7 psia)			Pressure in LOX				Pressure in Ambient Temperature (75°F) GOX			
Material[a]	Reactions/ Tests	Impact Energy (J)	Source	Pressure (MPa)	Reactions/ Tests	Impact Energy (J)	Source	Pressure (MPa)	Reactions/ Tests	Impact Energy (J)	Source
								34.5	1/4	98	MAPTIS 05122
								37.9	0/22	81	MAPTIS 05122
								37.9	1/24	88	MAPTIS 05122
								44.8	0/20	20	MAPTIS 05122
								44.8	1/7	27	MAPTIS 05122
								45.6	2/49	41	MAPTIS 05122
								46.2	0/20	88	MAPTIS 05122
								46.2	2/8	98	MAPTIS 05122
								50.0	0/20	54	MAPTIS 05122
								50.0	1/6	61	MAPTIS 05122
								62.1	1/40	98	MAPTIS 05122
								65.5	1/15	98	MAPTIS 05122
								68.9	1/16	98	MAPTIS 05122
Viton A	0/20	13.5	ASTM STP 1040 pg 11–22	None				0.1	0/20	98	ASTM STP 1395 pg 87–100
	0/100	14	WSTF # 87-21506					10.3	1/20	98	ASTM STP 812 pg 9–42
	1/120	34	WSTF # 87-21506					13.6	1/17	98	ASTM STP 812 pg 9–42
	0/20	41	WSTF # 98-33431					34	0/20	41	ASTM STP 812 pg 9–42
	1/11	47	WSTF # 98-33431								

[a] G86 standard thickness is 1.52 ± 0.13 mm (1.39 to 1.65 mm). All of the data fall within the standard thickness unless otherwise noted.

[b] Out of range of standard thickness. Thickness is 1.78 mm.

[c] Out of range of standard thickness. Thickness is 1.27 mm.

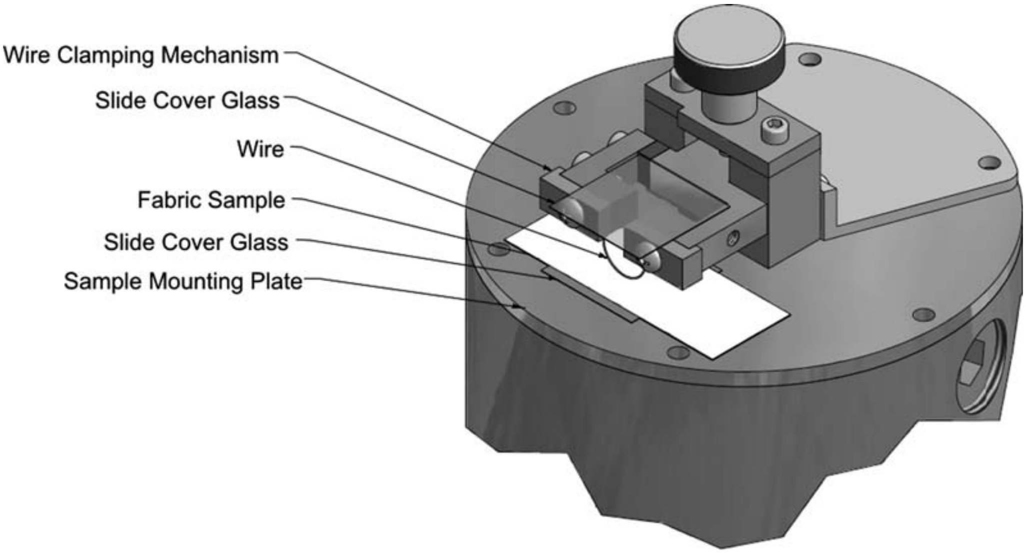

Fig. 3-14—Electrical arc test apparatus for nonmetallic materials [56].

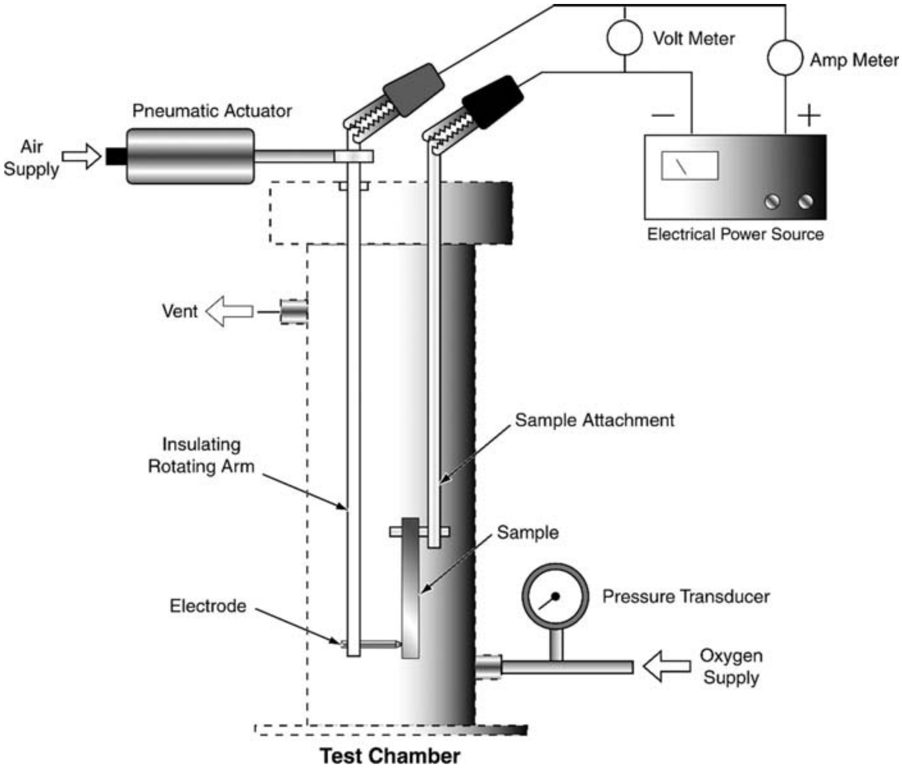

Fig. 3-15—Electrical arc test apparatus for metallic materials [57].

nonmetallic materials. This test is performed in a chamber pressurized as desired with oxygen or a gas mixture, and the apparatus includes a single strand of wire in contact with a test material sample, as shown in Fig. 3-14. Current in the wire is increased until the wire fails, producing an electrical arc. The data provide a relative ranking of which nonmetallic materials are more susceptible to ignition by electrical arc.

In addition to the electrical arc test method for nonmetallic materials, a nonstandardized electrical arc test has been developed to evaluate the ignitability of metals. This method can be used to determine either: (1) the arc energy required to ignite a metallic material at a use pressure where the material is considered flammable; or (2) the threshold pressure at which a metallic material will ignite with a specified amount of energy. This test is performed in a promoted ignition chamber pressurized as desired with oxygen or a gas mixture, and the apparatus includes an electrode positioned against the surface of a metal test sample, as shown in Fig. 3-15. The electrode is rotated away from the sample while electrically powered to draw an electric arc to the sample surface. The data provide a relative ranking of the electrical arc ignitability of metallic materials.

Data

Electrical arc test data for various nonmetallic materials are shown in Table 3-17. The test results indicate that materials

TABLE 3-17—Electrical arc ignitability of various nonmetallic materials[a] [56].

Test Materials	Wire Size (at Ignition)	Available Current (at Ignition) (A)	Power (W)	Average Next Lower Current Tested (A)	Maximum Next Lower Current Tested (A)	Minimum Next Lower Current Tested (A)
Bends treatment apparatus conditions (23.5 ± 1 psia, > 99 % oxygen, 22.5 V)						
100 % cotton t-shirt[b]	54 AWG	0.36	8.1	N/A	N/A	N/A
Moleskin[b]	54 AWG	0.3	6.8	N/A	N/A	N/A
Polyurethane-coated nylon fabric (shiny side)	52 AWG	0.70	15.8	0.53	0.66	0.43
Polyurethane-coated nylon fabric (fabric side)	47 AWG	0.97	21.8	0.82	0.94	0.72
Gore-Tex® woven PTFE fabric[c]	34 AWG	N/A	N/A	9.23	10.20	7.70
Kerlix® 100 % cotton dressing[b]	54 AWG	0.3	6.8	N/A	N/A	N/A
Polyurethane wire jacket	48 AWG	0.78	17.6	0.63	0.73	0.55
82 % nylon, 18 % spandex knit fabric	50 AWG	0.59	13.4	0.49	0.56	0.43
100 % polyester fabric	50 AWG	0.64	14.5	0.51	0.62	0.43
Neutral Buoyancy Lab conditions (50 ± 1 psia, 50 % oxygen, 15 V)						
100 % cotton t-shirt	52 AWG	0.47	7.05	0.33	0.38	0.28
Moleskin[b]	54 AWG	0.27	4.1	N/A	N/A	N/A
Kerlix® 100 % cotton dressing[b]	54 AWG	0.3	4.5	N/A	N/A	N/A

[a] Tests were performed with a single strand of silver-coated copper wire in contact with test material. Current was increased until wire failed, producing an electrical arc.
[b] This material ignited at the lowest possible current; therefore, no threshold for ignition was determined.
[c] This material was never ignited in the test conditions; however, it could be ignited in higher pressure oxygen.

that are more finely divided (fuzzy surface) are generally easier to ignite than materials that are in bulk form (smooth surface) [56].

Electrical arc test data for carbon steel and aluminum alloys with various surface treatments are shown in Table 3-18 [57].

Static Discharge

A limited number of nonstandardized tests have been performed to determine the susceptibility of materials to ignition by static discharge [58]. Tests were performed at a pressure of 0.24 MPa (35 psia) on 100 % cotton, 100 % polyester, facial tissue, cotton gauze, petroleum jelly gauze, human hair, and an alcohol prep pad. With the exception of the alcohol prep pad, none of the materials ignited in 100 % oxygen with thirty 15 000-volt sparks in the range of 15 to 20 mJ (which is the upper limit of discharges from a human). The alcohol prep pad was ignited with one 15 000-V, 15 to 20 mJ spark in air.

Resonance

A limited number of nonstandardized tests have been performed to determine the susceptibility of materials to ignition by resonance [59]. The resonance test apparatus consisted of an inlet tube, an exit tube, and a resonance tube, forming a tee. The temperatures generated at the base of the resonance tube were in excess of 811 K (1 000°F) for both GOX and nitrogen. Resonance testing data for metals are described in Ref [59].

Metallic Materials

This section contains guidelines that should be considered when selecting metals for oxygen systems. Metals are generally the bulk of the materials of construction in oxygen systems, and most metals require very high concentrations of oxygen to support combustion. Bulk metals are generally less susceptible to ignition than nonmetals; however, metal particles and thin cross-sections may be ignited more readily than bulk metals. Therefore, when selecting metals for oxygen service, situational or configurational flammability must be evaluated. Once ignited, burning metals can cause more damage than burning nonmetals because of their higher flame temperatures and because they usually produce liquid combustion products that are more likely to spread fires.

> *Note: Ignition and combustion data for metals are configuration dependent, and very little data have been generated to demonstrate the effects of nonstandard configurations. In general, metals, including those that normally exhibit high resistance to ignition, are more flammable in oxygen when they have thin cross-sections, such as in thin-walled tubing, or when they are finely divided, such as in wire-mesh or sintered filters. Special care should be taken to avoid ignition sources in locations where thin cross-sections or finely divided metals are used.*

Nickel and Nickel Alloys

Nickel and nickel alloys are very resistant to ignition and combustion and are therefore suitable for use in oxygen systems at all pressures. Nickel 200 (commercially pure nickel) is the only material that has been shown to not support combustion even at pressures as high as 69 MPa (10 000 psia) when configured as a wire mesh (Table 3-2). Thus, Nickel 200 is suitable for use as a filter element. In addition, nickel alloys usually have high strengths with significant low-temperature toughness.

Nickel-Copper Alloys (such as Monel)

Nickel-copper alloys, such as Monel, are among the least ignitable alloys commonly used as structural materials. Monel alloys used in bulk configurations have a successful history of

TABLE 3-18—Electrical arc ignitability of carbon steel and aluminum alloys with various surface treatments[a] [57].

Pressure, MPa (psia)	1100 Aluminum	6061 Aluminum	Acid-Washed 6061 Aluminum	Acid-Washed 7060 Aluminum	Shot-Peened 7060 Aluminum	
5.6 (800)					░ 1	
5.3 (750)						
4.9 (700)						
4.6 (650)					░ 1	
4.2 (600)					░ 1	
3.9 (550)						
3.5 (500)					░ 1	░ 1
3.2 (450)						
2.8 (400)				░ 1	▓ 3	▓ 4
2.5 (350)	░ 2	░ 1	░ 1	░ 1		▓ 2
2.1 (300)	▓ 3	▓ 3	░ 1			▓ 1
1.8 (250)						
1.4 (200)	▓ 1	▓ 1				
░	Indicates complete burn					
▓	Indicates no ignition					

[a] Numbers indicate number of tests for that result at that pressure.

use in oxygen at pressures up to 69 MPa (10 000 psia). When configured as 0.32-cm (0.125-in.)-diameter rods, Monel 400 and K-500 do not support self-sustained combustion in upward flammability tests at pressures as high as 69 MPa (10 000 psia) as shown in Table 3-1. Monel alloys have not been ignited in particle impact tests, although some surface melting and burning have been observed. Monel alloys have unusually high coefficients of friction, and they ignite in friction tests at higher *Pv* products than stainless steels. However, configuration has a strong effect on the flammability and ignition characteristics of Monel alloys. Monel and Monel alloys in thin cross sections and finely divided configurations, such as filter elements and thin-walled tubing, are flammable in oxygen at near-ambient pressures (Tables 3-2 and 3-3). Therefore, care should be taken to minimize ignition hazards when using Monel configured as a filter element or thin-walled section.

Monel alloys in bulk form can be used extensively in oxygen systems. Monel K-500 can be used for valve stems, and 400-series Monels can be used for valve bodies. In addition, springs can be wound from Monel wire. Monel alloys are recommended for manually operated systems and systems where the consequences of a fire are high. In industrial piping installations, Monel is often used in high-velocity gas applications such as control valves and bypass valves where burn-resistant alloys are required to minimize particle impact ignition. Monel is also commonly used as a strainer mesh for pipeline applications.

Monel alloys traditionally have not been materials of choice for flight systems because of the perception that components constructed of Monel weigh more than those of aluminum and other lightweight alloys. However, Monel alloys can often be obtained in the range of necessary hardnesses and strengths and, because of the greater strength-to-weight ratio of Monel compared to aluminum, Monel components can sometimes be made smaller and lighter. In aerospace systems when weight is a constraint, the use of Monel sections or linings in key areas can provide extra protection from ignition and fire propagation without increasing weight.

Nickel-Iron alloys (such as Inconel)

Nickel-iron alloys, such as Inconel MA754, have been used successfully at absolute pressures as high as 69 MPa (10 000 psia). The ignition resistance of Inconel varies with the specific alloy. Inconel alloys appear to have particle impact ignition resistance similar to 440C stainless steel, which is better than most other stainless steels. Inconel MA754 has exceptional resistance to ignition by friction and, when configured as a 0.32-cm (0.125-in.)-diameter rod, does not support self-sustained combustion in upward flammability tests at pressures as high as 69 MPa (10 000 psia). Known as a good structural material, Inconel 718 has a successful history of use in some high-pressure oxygen applications. However, promoted ignition data indicate that the flammability of Inconel 718 is approximately equivalent to 300-series stainless steels. Friction tests indicate that Inconel 718 is only marginally less ignitable than stainless steels (Table 3-5).

Other Nickel-Based Alloys (such as Hastelloy)

Some Hastelloys, such as C-22 and C-276, are much more ignition resistant than stainless steels and Inconel 718.

Copper and Copper Alloys (such as Brass and Bronze)

Copper and copper alloys, such as brass and bronze, in bulk form are very ignition resistant and, when configured as

0.32-cm (0.125-in.)-diameter rods, do not support self-sustained combustion in upward flammability tests at pressures as high as 69 MPa (10 000 psia). Copper and copper alloys are particularly useful for resisting ignition by particle impact and therefore can be used in high-velocity gas applications for which burn-resistant alloys are required (see Chapter 5). However, copper also has a low ductility oxide that is not tenacious and can slough off, leading to contamination in oxygen systems [60]. Configuration has a strong effect on the flammability and ignition characteristics of copper and its alloys. Copper and copper alloys in finely divided configurations, such as wire mesh, are flammable in oxygen at near-ambient pressures (Table 3-2). Therefore, care should be taken to minimize ignition hazards when using finely divided or thin-walled copper or its alloys. Recent testing has shown that sintered bronze is less flammable than sintered Monel 400 and stainless steel for filter element material [19]. Aluminum-bronzes containing greater than 5 % aluminum, although containing a high amount of copper, are not recommended for use in oxygen systems because the presence of aluminum increases their flammability and ignitability [22].

Stainless Steels

Stainless steels have been used extensively in high-pressure oxygen systems but are known to be more flammable and more easily ignited than copper and copper-nickel alloys. In contrast, however, they are still far more ignition and burn resistant than aluminum alloys. However, stainless steels have high heats of combustion compared with copper-nickel alloys, are considered flammable in relatively low pressure oxygen, and are ignited easily in high pressures by friction and particle impact. Few problems have been experienced with the use of stainless steel storage tanks and lines, but ignitions have occurred when stainless steels were used in dynamic locations of high-velocity, high-pressure, or high-flow rates, such as in valves and regulators. In addition, when configured as a wire mesh or thin-walled tube, stainless steels are flammable in ambient pressure oxygen. Therefore, care should be taken to minimize ignition hazards when using stainless steel in dynamic locations or thin cross-sections. Stainless steel particulates have been shown to ignite materials [22]; however, they are far less hazardous than aluminum particulates.

Aluminum and Aluminum Alloys

Aluminum and its alloys are known to be difficult to ignite, yet they burn in oxygen at very low pressures. Aluminum and its alloys have been used extensively in aerospace oxygen systems and small medical devices where weight is of paramount importance [24,61]. In industrial oxygen systems, however, aluminum is generally avoided except in applications that benefit from its conductivity and heat transfer capability, like heat exchangers. When configured as 0.32-cm (0.125-in.)-diameter rods, aluminum and its alloys support self-sustained combustion in upward flammability tests at near-ambient pressures. In general, caution should be exercised in using alloys containing even small percentages of aluminum.

Aluminum's tough, tenacious oxide, which has a melting point of 2 315 K (3 708°F), protects the base metal from ignition under static conditions even above the melting point of aluminum (933 K [1 220°F]). However, aluminum and its alloys have high heats of combustion and can be ignited very easily by friction and particle impact because these ignition mechanisms damage the protective oxide layer.

Aluminum should not be used in applications where frictional heating is possible (see data in Tables 3-5 and 3-6). Particle impact tests on anodized aluminum targets have indicated that anodizing the surface dramatically increases the resistance to ignition by particle impact [62]. However, aluminum that has not been anodized should not be used in applications where particle impact is possible. In mechanical impact tests, 6061-T6 aluminum has been ignited when it was contaminated with cutting oil, motor-lubricating oil, or toolmaker's dye as a result of the promoted ignition of the aluminum by the contaminant [63].

Aluminum alloys are attractive candidate materials for pressure vessels and other applications where no credible ignition hazards exist because of their high strength-to-weight ratios. However, the use of aluminum alloys in lines, valves, and other dynamic components should be avoided whenever possible because of their poor ignition and combustion characteristics.

In addition, aluminum particulate is a very effective ignition source for particle impact. High-pressure oxygen systems fabricated from aluminum must be designed with extreme care to eliminate particulates. Filters should be fabricated of materials less ignitable than aluminum such as nickel, bronze, or Monel alloys. For more information on designing to avoid particle impacts, see Chapter 5.

Iron Alloys

Iron alloys generally are not good candidates for aerospace oxygen systems because they ignite easily and offer little weight savings. However, iron alloys are used extensively in compressed gas cylinders and oxygen pipeline applications where no credible ignition hazard exists. Alloy steels (iron-nickel) suitable for use in oxygen systems include 5 % nickel (but not at temperatures below 129 K [−227°F] because of low-temperature embrittlement), 9 % nickel, and 36 % nickel (Invar). The threshold pressure for Invar 36 is similar to most stainless steels, and in frictional heating tests the Pv product for ignition is comparable to that of stainless steels (Table 3-5).

Restricted Alloys

In oxygen systems, the use of certain metals, including titanium, cadmium, beryllium, magnesium, and mercury, must be restricted. Titanium alloys are generally avoided because they exhibit very undesirable flammability and ignition characteristics. Tests have indicated that titanium, α-titanium, and α_2-titanium alloys can be ignited and sustain combustion in oxygen at absolute pressures as low as 7 kPa (1 psi). A reaction of titanium and LOX or GOX may propagate and completely consume the metal [11,64–66]. Various titanium alloys tested (α, α–β, β alloys) have shown very high sensitivity to mechanical impact in oxygen [55]. Frictional heating tests conducted on titanium and titanium alloys indicate that the Pv product for ignition is extremely low (Table 3-5). Recent tests indicate that titanium and its alloys also can be ignited in air in frictional heating tests. In addition, titanium particulates are extremely flammable and are exceptional as particle impact ignition sources.

Cadmium's toxicity and vapor pressure restrict its use. Systems containing breathing oxygen must not include cadmium if temperatures will exceed 322 K (120°F) at any time.

Beryllium must not be used in oxygen systems or near oxygen systems where it could be consumed in a fire. Beryllium metal and its oxides and salts are highly toxic.

Magnesium and its alloys are flammable in air and, therefore, should not be used in oxygen systems. In promoted combustion tests in 100% oxygen, magnesium and its alloy AZ-91 have shown the ability to sustain combustion even at absolute pressures as low as 7 kPa (1 psi).

Mercury must not be used in oxygen systems in any form, including amalgamations. Mercury and its compounds can cause accelerated stress cracking of aluminum and titanium alloys. Toxicity further limits its use.

Other Metals and Alloys

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. The ignitability of these metals and alloys in high-pressure oxygen and their ability to propagate fire after ignition must be compared to the flammability properties of the common structural materials previously described before determining how suitable they are for use in high-pressure oxygen systems. Before a new alloy is used in an oxygen system, its flammability and resistance to the ignition mechanisms present in the proposed application must be determined based on applicable test data.

Metal Oxides

Metals, with the exception of gold and platinum, tend to oxidize to a nonmetallic (ceramic) form in the presence of oxygen (including air). The rate of oxidization depends primarily on the rate of diffusion through the oxide film that is formed on the metal surface when it is exposed to oxygen. Thus, the rate of oxidization is largely independent of the concentration of oxygen that the metal is exposed to if the amount of oxygen is sufficient to keep the outside of the layer saturated. The mechanical properties of a metal may be deleteriously affected by oxidization. Consequently, the effects of oxidization on the mechanical properties of metals used in an oxygen environment, especially when used for structural and pressure containment, should be considered. The Pilling and Bedworth ratio[†], which establishes whether or not an oxide is protective, indicates that nickel, chromium, aluminum, and iron should form a protective oxide layer (*ASTM Standard Guide for Evaluating Metals for Oxygen Service* [ASTM G 94]).

Nonmetallic Materials

This section contains guidelines that should be considered when selecting nonmetals for oxygen systems. The use of nonmetals in oxygen systems is often necessary for purposes such as valve seats and seals. Nearly all nonmetals are flammable in oxygen at absolute pressures greater than 101.3 kPa (14.7 psi). Nonmetals, such as polymers, are generally easier to ignite and generally ignite at lower temperatures and pressures than metals. Therefore, the use of nonmetals should be limited and their quantity and exposure to oxygen should be minimized. Some damage that might result from the ignition of nonmetals includes propagation of the fire to metallic components, loss of function arising from system leaks, and toxic combustion products entering the oxygen system.

Nonmetals that are preferred for use in oxygen systems meet the following criteria: (1) a high autoignition temperature[†], (2) a low heat of combustion[†], and (3) a high oxygen index[†]. The ignitability of polymers varies considerably [67], but the risks associated with polymer flammability can be minimized through proper selection combined with proper design. Should ignition occur, the material's heat of combustion, mass, and flame propagation characteristics affect the ability of the material to damage adjacent construction materials [68]. Filler, char formation, and polymer shape stability have also been shown to affect a burning polymer's propensity to ignite surrounding materials [69].

Material Types

The nonmetals used in oxygen service are usually polymers (including plastics and elastomers), composites, and lubricants. Ceramics and glasses are not often used in oxygen systems and, as they are considered to be inert in use, they are not discussed in this manual. In general, fluorinated materials are preferred for use in oxygen systems because of their oxygen compatibility characteristics. Fully fluorinated nonmetals tend to have high autoignition temperatures, low heats of combustion, and high oxygen indices.

Elastomers

Elastomers typically are used for O-rings and diaphragms because of their flexibility. They have glass transition temperatures (T_g)[†] below room temperature and are generally useful to approximately 520 K (475°F) above their T_g. Fluorinated elastomers, such as polyhexafluoropropylene-co-vinylidene fluoride (Viton and Fluorel), are commonly used in oxygen systems.

Silicone rubbers have been used in oxygen systems because of their extremely low T_g; however; they are not as ignition resistant as fully fluorinated compounds. Therefore, when using silicone rubbers, extra care should be taken to minimize ignition sources, especially in high-pressure systems. In some applications, silicone rubbers have been successfully replaced with Kalrez. In addition, extra care must be taken to minimize ignition mechanisms when using Buna-N, neoprene rubber, polyurethane rubbers, and ethylene-propylene rubbers as a result of their poor ignition and combustion characteristics. If ignited in oxygen, these hydrocarbon-based materials burn energetically and can more easily kindle ignition to surrounding materials. Furthermore, several catastrophic fires have resulted from the use of these hydrocarbon-based elastomers instead of fluorine-based compounds.

Plastics

Plastics are typically used for seat and seal applications. The most frequently used plastics in oxygen systems are fluorinated and can be amorphous in structure, such as polyimides (Vespel), or semicrystalline in structure, such as polytetrafluoroethylene (PTFE), fluorinated ethylene-propylene (FEP), and polychlorotrifluoroethylene (PCTFE). PTFE is commonly used in oxygen systems because of its good oxygen compatibility. Unfortunately, PTFE has poor creep resistance; therefore, it is sometimes necessary to replace it with polymers that are less compatible with oxygen. Nylon has been used in oxygen systems when its superior mechanical properties are needed; however, caution should be used with nylon because its ignition and combustion characteristics are not as favorable as the fully fluorinated materials.

Composites

Composites include the previously mentioned polymer groups that have nonpolymer reinforcement, such as glass and graphite. Caution should be exercised when incorporating a reinforcement material into a polymer, because the addition of the reinforcement can lower the ignition resistance of the material. For example, glass-filled Teflon is more vulnerable to ignition by mechanical impact than unfilled Teflon.

Lubricants

Lubricants and greases used in oxygen systems are mainly based on CTFE, PTFE, or FEP. These include fluorinated or halogenated chlorotrifluoroethylene (CTFE) fluids thickened with higher-molecular-weight CTFEs, such as Fluorolube, and perfluoroalkyl ether fluids thickened with PTFE or FEP telomers (short-chain polymers), such as Braycote and Krytox. These materials are preferred as a result of their good oxygen compatibility. Some PTFE-based products use additives to increase lubricity, but the oxygen compatibility of these products may be compromised as a result of the additives. CTFE fluids thickened with silicon oxide (SiO_2) have been found to allow moisture to penetrate the film and cause severe corrosion. Thus, they should not be used in oxygen service.

Effects of Physical and Thermal Properties on Ignition and Combustion

Although not fully understood, the thermal and physical properties of nonmetals have an important role in ignition and combustion. For instance, a material's specific heat determines the amount of heat necessary to bring a polymer to its autoignition temperature. For polymers of comparable autoignition temperatures, the more heat required to reach the autoignition temperature, the less likely it is to ignite and combust. Physical properties also play an important role in kindling chain ignition of metals from burning polymers [69].

Effects of Diluents

The presence of diluents (gases mixed with the oxygen) can make it more difficult to ignite nonmetals. This is because of the decreased availability of oxygen, as well as differences in the thermal conductivity, specific heat, and diffusivity of the gas mixture [70]. However, increased pressure can negate the effects of the diluents. For instance, some materials that are not flammable in oxygen at ambient pressure can become flammable in air at pressures greater than 20.7 MPa (3 000 psi). Therefore, in air systems at pressures greater than 20.7 MPa (3 000 psi), materials selection should be similar to that for an oxygen system.

Toxicity Considerations

In breathing gas systems, the toxicity of the combustion products of the nonmetal components should be considered when selecting materials. The level of risk of breathing toxic combustion products from fluorinated materials is currently under investigation. In general, however, fluorinated nonmetals have a much greater resistance to ignition and burning than the alternative materials for these applications. Furthermore, the fluorinated materials, if ignited, are less likely to lead to a burn-out of the component because of their low heats of combustion.

Materials Control

Designers and maintenance personnel must keep control of the materials used in oxygen systems. Each application must be evaluated to determine the proper level of materials control. In general, materials procured for use in oxygen systems require a material certification[†] from the manufacturer. It is also good practice to verify the manufacturer-supplied information.

Experience has shown that some materials exhibit such manufacturing variability that different batches are not always satisfactory for use. One form of control criteria that may be used is batch lot testing. A batch, or lot, is a collection of material that has been made under the same conditions and at the same time using the same starting materials (ANSI/ASQ Z1.4). In batch lot testing, a sample is drawn from a batch of material and tested to determine conformance with acceptability criteria. The acceptability criteria can be based on the material's structural integrity and ignition and flammability characteristics. It is recommended that for critical applications, materials should be controlled at the batch lot level to ensure compliance with structural requirements as well as ignition and combustion design criteria.

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4

Oxygen Compatibility Assessment Process

Introduction

THE FOCUS OF THE OXYGEN COMPATIBILITY assessment process is fire hazards†[1], and there is great emphasis placed on evaluating ignition mechanisms (presented in Chapter 2) and applying materials test data (presented in Chapter 3). This process is a systematic approach that can be used as both a design guide and an approval process for materials, components, and systems. The necessity for conducting an oxygen compatibility assessment is directly tied to minimizing the risk† of fire and the potential effects of fire on personnel safety and the system. This chapter begins with a brief description of the risk management approach that is recommended for handling the fire hazards associated with oxygen systems, followed by a description of the oxygen compatibility assessment process. This chapter concludes with a description of how the oxygen compatibility assessment process can be usedv to select materials for oxygen service.

Fire Risk Management

Fires occur in oxygen systems because at least three elements are present—heat, fuel, and oxygen. This concept has often been presented in terms of the fire triangle, as shown in Fig. 4-1. The three sides of the triangle are formed by the three elements necessary to create a fire. If any one of three sides—heat, fuel or oxygen—is taken away, a fire cannot occur. The classic approach to managing the risk of fire in most environments is to prevent fires by removing one of the three elements of the fire triangle.

However, this fire-prevention method is not possible in oxygen systems. The oxygen side of the triangle is always present, and the presence of oxygen increases the ignitability and flammability of almost all materials used to construct oxygen systems. Thus, the materials of construction for an oxygen system can be considered as fuel, preventing the removal of the fuel side of the triangle. Furthermore, the operation of oxygen systems involves energy. Pressurized oxygen systems have potential energy and flowing oxygen has kinetic energy, both of which can be converted to heat energy. Consequently, it is difficult to remove the heat side of the triangle because the generation of at least some heat is inherent in the operation of most oxygen systems. Therefore, a risk management approach must be used to manage the risk of fire in oxygen systems. This approach focuses on limiting the three elements of the fire triangle.

By definition, oxygen will be present in an oxygen system. However, oxygen pressure and concentration can have sizeable effects on material flammability and ignitability. In general, materials are easier to ignite and will burn more readily as either oxygen pressure or concentration increases. Hence, wherever possible, oxygen systems should be operated at the lowest possible pressure and oxygen concentration. Limiting either may be enough to ensure that a fire does not occur.

Likewise, poor material choice can greatly increase the likelihood of a fire occurring in an oxygen system. Some materials are harder to ignite than others and, when ignited, are resistant to sustained burning. Materials also vary in the amount of energy they release when they burn. Therefore, careful selection of materials can enhance the ignition and burn resistance of a system and limit the amount of damage resulting from a fire. Chapter 3 provides data that can be applied in choosing materials for oxygen service.

Despite the fact that heat sources may be inherent to an oxygen system or its surroundings, design elements, such as those discussed in Chapter 5, can limit the amount, or dissipate altogether, the heat generated within an oxygen system. If the temperatures generated by the heat sources within the system are below the ignition temperatures of the system materials in that environment, ignition cannot occur.

In summary, *the risk-management approach should focus on limiting the amount of oxygen available, using ignition and burn resistant materials where practical, limiting the amount of heat generated within oxygen systems, and limiting the exposure of personnel and equipment*. The oxygen compatibility assessment approach is recommended as a risk-management tool that can be used to evaluate the fire risks associated with materials and components intended for use in oxygen systems.

Oxygen Compatibility Assessment Process

The oxygen compatibility assessment process outlined in this section meets the requirements and guidelines set forth in the *ASTM Guide for Evaluating Nonmetallic Materials for Oxygen Service* (G 63), the *ASTM Guide for Evaluating Metals for Oxygen Service* (G 94), and *Oxygen Pipeline Systems* [1].

The oxygen compatibility assessment process is designed to be applied to individual components. To analyze an entire system, the process may be applied to each component in a system, or techniques can be applied to quickly evaluate the severity of system components and piping so that the most severe components are identified and analyzed by this method [2]. The suggested oxygen compatibility assessment procedure is as follows:

1. Determine the worst-case operating conditions.
2. Assess the flammability of the oxygen-wetted materials at the use conditions.
3. Evaluate the presence and probability of ignition mechanisms.
4. Evaluate the kindling chain, which is the potential for a fire to breach the system.
5. Determine the reaction effect, which is the potential loss of life, mission, and system functionality as the result of a fire.
6. Document the results of the assessment.

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[1] The † indicates a term defined in the Glossary (Appendix G).

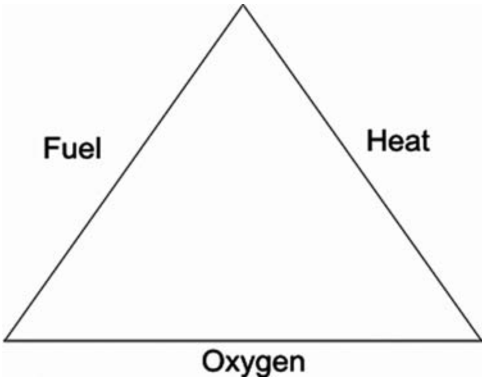

Fig. 4-1—Fire triangle.

The analyst who performs the oxygen compatibility assessment should be a person or, ideally, a group of people, trained specifically in recognition and mitigation of oxygen hazards. Training in oxygen hazards is offered through the ASTM G-4 Committee on Compatibility and Sensitivity of Materials in Oxygen Enriched Atmospheres.

Worst-Case Operating Conditions

Increasing oxygen concentration, temperature, pressure, flow rate, and contamination can intensify flammability and ignition risks. Therefore, it is necessary to quantify the worst-case operating conditions before analyzing each component. A system flow schematic, process flow diagram, or piping and instrumentation diagram is generally required for determining the worst-case operating conditions for each component. In general, the analyst should determine the conditions that may exist as a result of single-point failures and minimize reliance on procedural controls to regulate the conditions within the oxygen system. In addition to environmental factors such as oxygen concentration, temperature, and pressure, the analyst should determine the worst-case cleanliness level of each component.

Flammability Assessment

As pressure increases, most common engineering materials become flammable in 100 % oxygen. This includes metals, plastics, elastomers, lubricants, and contaminants. Almost all polymers are flammable† in 100 % oxygen at near-ambient pressure.

The flammability of materials is very dependent upon their configuration. For instance, metals, including those that normally exhibit high resistance to ignition, are more flammable in oxygen when they have thin cross-sections, such as in thin-walled tubing, or when they are finely divided, such as in wire mesh or sintered filters. Therefore, when assessing flammability, it is important to reference a cross-sectional view of each component that shows the configuration of the materials of construction. An example of a cross-sectional view is shown in Fig. 4-2.

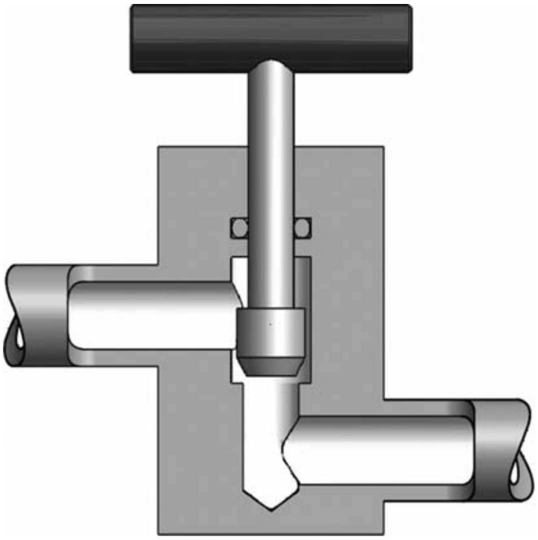

Fig. 4-2—Example of cross-sectional view.

Once there is an understanding of the configuration of the materials of construction, the analyst should reference the test methods and data described in Chapter 3. The test method relating to metals flammability is promoted ignition (ASTM G 124), and the test method relating to nonmetals† flammability is oxygen index (ASTM G 125). A conservative approach to applying metals flammability data is to use a 1-in. (2.54-cm) burn criterion, as shown in Table 3-1 in Chapter 3. Using this approach, if the metal is being used at or above the highest "no-burn" pressure, the metal is considered "flammable" in its application. Conversely, if the metal is being used below the highest "no-burn" pressure, and its thickness is greater than or equal to 0.125-in. (3.2 mm), the metal is considered "nonflammable." For nonmetals, oxygen index data show that all polymeric materials used in pure oxygen at elevated pressure are considered "flammable."

If the flammability of the materials is unknown, or the materials of construction have not been selected, then the materials should be considered to be flammable. Material flammability is affected by many factors, and absolute flammability thresholds are difficult to establish without testing the actual use configuration. Therefore, much of the oxygen compatibility assessment process focuses on the presence and probability of ignition mechanisms.

Ignition Mechanism Assessment

Ignition mechanisms in oxygen systems are simply sources of heat that, under the right conditions, can lead to ignition of the materials of construction or contaminants. The most effective way to analyze the ignition risk in a component is to perform a systematic analysis of known ignition mechanisms. The following list includes some potential ignition mechanisms, which are described in detail in Chapter 2:

- Particle impact
- Heat of compression
- Flow friction
- Mechanical impact
- Friction
- Fresh metal exposure
- Static discharge
- Electrical arc
- Chemical reaction
- Thermal runaway
- Resonance
- External heat

For ignition mechanisms to be active, certain "characteristic elements" must be present. These characteristic elements are unique for each ignition mechanism, and represent the current understanding of what is typically required for each ignition mechanism to be active. Therefore, to assess ignition mechanisms, the analyst should focus on evaluating the presence of the characteristic elements and applying materials test data related to the ignition mechanisms (Chapter 3). Knowledge of the system layout and a system flow schematic, process flow diagram, and/or piping and instrumentation diagram are generally required in performing this assessment.

The analyst should assign a subjective probability rating for each ignition mechanism, which is based on the assessment of the characteristic elements and the flammability of the materials of construction. These ratings provide a basis for determining which ignition mechanisms are most prevalent in each component. An example of a probability rating logic that may be used is shown in Table 4-1.

When the ignition mechanism assessment indicates that there are fire hazards present, the analyst should make recommendations for mitigation of the fire hazards. These recommendations assist the system owner, user, and approval authority in making the system safe to use. The recommendations can encompass topics such as changes in materials, replacement of components, and the implementation of procedural controls.

Kindling Chain Assessment

Kindling chain is defined as the ability of ignition to propagate within a component or system, potentially leading to burn-out. A kindling chain reaction can occur if the heat of combustion and specific configuration of the ignited materials are sufficient to ignite or melt the surrounding materials, leading to a burn-out. The analyst should assess the kindling chain based on the presence of ignition mechanisms and the ability of the materials of construction to contain a fire. If ignition of one material can promote ignition to surrounding materials and lead to burn-out, then a kindling chain is present.

Reaction Effect Assessment

The reaction effect assessment is performed to evaluate the effects of a fire on personnel, mission, and system functionality. The analyst should evaluate whether an ignition mechanism and kindling chain are present that could lead to burn-out of the component. The reaction effect rating for each component is based upon the degree of fire propagation expected if ignition occurs, and the potential effect on personnel safety, mission, and system functionality. Because it is difficult to conceive of all possible fire scenarios that could result in injury and damage, reaction effect ratings should be applied conservatively; i.e., the worst-case scenario should drive the reaction effect assessment. Reaction effect ratings provide a basis for determining which components have the potential for causing the greatest damage and injury. An example of a reaction effect rating logic that may be used is shown in Table 4-2 (based on ASTM G 63 and G 94).

Document Assessment Results

It is strongly recommended that the results of the oxygen compatibility assessment are documented in a written report. This report can facilitate communication and dissemination of results to interested parties, and serves as a record of the findings for future reference. The report should include system schematics, drawings for each component, references to data, and notes to document the rationale used in determining the various ratings. In addition, the report should identify the components with the highest probability of fire, and also recommend changes to design, materials, and procedures that mitigate the fire hazards identified. For large systems, reports should include a concise listing of the most severe hazards and suggested mitigations for those hazards.

Using the Oxygen Compatibility Assessment Process to Select Materials

The oxygen compatibility assessment process can be used in selecting materials for use in oxygen systems, as shown in Fig. 4-3. The material selection process begins with defining the application for the material, followed by performing an oxygen compatibility assessment, and locating or generating test data relevant to the credible ignition mechanisms. In defining the application for the material, designers should ensure that the materials selected have the proper material properties, such as strength, ductility, and hardness, to operate safely under all use conditions. Furthermore, it is important to consider each material's ability to undergo specific cleaning procedures to remove contaminants, particulates†, and combustible materials without damage (see Chapter 6 of this manual, *ASTM Standard Practice for Cleaning Methods for Material and Equipment Used in Oxygen-Enriched Environments* (G 93), *Cleaning Equipment for Oxygen Service* [3], and Refs [4] and [5]). In addition to the material requirements for GOX service, materials used for LOX service should have satisfactory physical properties, such as strength and ductility, at low operating temperatures. One additional consideration is that there may be increased pressure and ignition risks as a result of LOX vaporization around heat sources, such as ball bearings.

The oxygen compatibility assessment process allows the designer to identify credible ignition mechanisms, and then focus on locating or generating relevant data (Chapter 3).

TABLE 4-1—Ignition mechanism probability rating logic.

Rating	Code	Criteria	
		Characteristic Elements	**Material Flammability**[a]
Not possible	0	Not all present	Nonflammable OR Flammable
Remotely possible	1	All present and some are weak	Nonflammable OR Flammable
Possible	2	All present	Flammable
Probable	3	All present and some are severe	Flammable
Highly probable	4	All are present and all are severe	Flammable

[a] Data used to assess material flammability must be applicable to the specific configuration of the parts, as described in the "Flammability Assessment" section.

TABLE 4-2—Reaction effect rating logic, based on ASTM G 63 and G 94.[a]

Rating	Code	Effect on Personnel Safety	System Objectives	Functional Capability
Negligible	A	No injury to personnel	No unacceptable effect on production, storage, transportation, distribution, or use as applicable	No unacceptable damage to the system
Marginal	B	Personnel-injuring factors can be controlled by automatic devices, warning devices, or special operating procedures	Production, storage, transportation, distribution, or use as applicable is possible by utilizing available redundant operational options	No more than one component or subsystem damaged. This condition is either repairable or replaceable within an acceptable time frame on site
Critical	C	Personnel may be injured operating the system, maintaining the system, or by being in the vicinity of the system	Production, storage, transportation, distribution, or use as applicable impaired seriously	Two or more major subsystems are damaged—this condition requires extensive maintenance
Catastrophic	D	Personnel suffer death or multiple injuries	Production, storage, transportation, distribution, or use as applicable rendered impossible—major unit is lost	No portion of system can be salvaged—total loss

[a] Because it is difficult to conceive of all possible fire scenarios that could result in injury and damage, reaction effect ratings should be applied conservatively; i.e., the worst-case scenario should drive the reaction effect assessment.

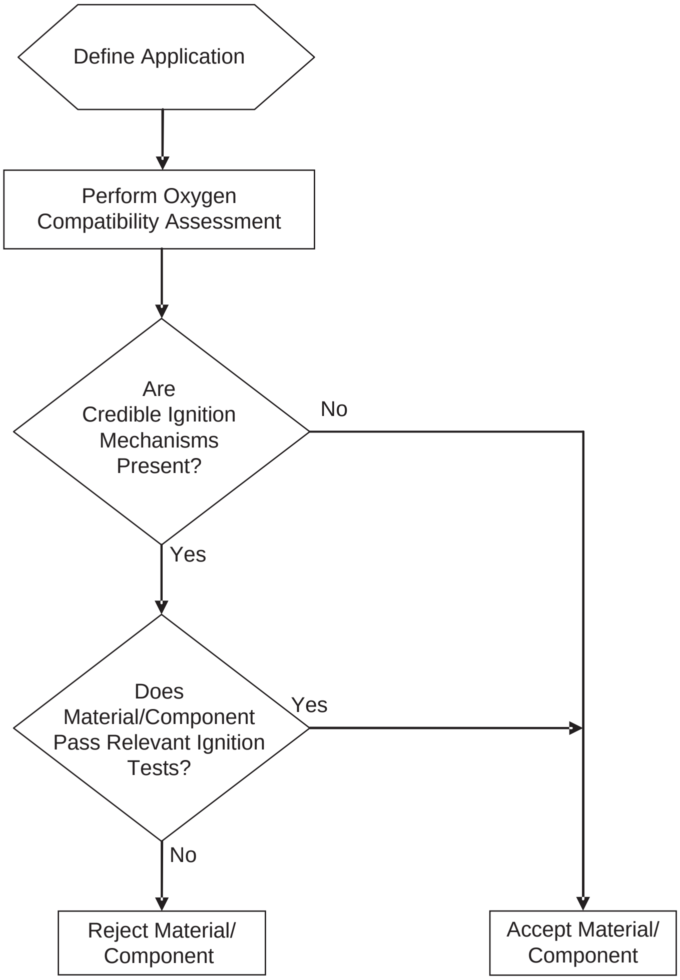

Fig. 4-3—Material selection process.

Whenever possible, materials should be used below their ignition thresholds for the applicable ignition mechanisms. Up to 20.7 MPa (3 000 psi), there is a large base of experience and test data that may be used when selecting materials. However, limited experience exists at pressures greater than 20.7 MPa (3 000 psi). When selecting materials where little use experience exists, application-specific material tests and configuration tests should be performed.

Additional information relating to the selection of materials for oxygen service can be found in the *ASTM Guide for Evaluating Nonmetallic Materials for Oxygen Service* (G 63) and *ASTM Guide for Evaluating Metals for Oxygen Service* (G 94). For selecting metals for pipeline applications, further guidance may be found in *Oxygen Pipeline Systems* [1], which focuses on reducing the likelihood of particle impact ignition by controlling allowable gas velocities for specific engineering alloys.

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5

Design Principles

Introduction

PROPER DESIGN IS A CRUCIAL STEP IN ENSURING the safe use of oxygen. This chapter begins with a section describing the design approach. The following sections deal with design guidelines for oxygen systems and the code design requirements associated with oxygen systems.

Specific design details and examples are given in this chapter. The *ASTM Guide for Designing Systems for Oxygen Service* (ASTM G 88) and *CGA/EIGA Oxygen Pipeline Systems* (CGA G-4.4-2003 (4th Edition)/IGC doc 13/02) are examples of other common industry references that provide guidance in designing systems for use in oxygen service. Both can be used alongside this manual as an initial design guideline for oxygen systems and components but also can be used as a tool to perform safety audits of existing oxygen systems and components.

Design Approach

The generally accepted steps in the oxygen system design process include risk†[1] training, design specifications, design reviews, oxygen compatibility assessment, and component and system testing. These steps are described herein.

Risk Training

Before embarking on a new design task, it is important that all personnel interfacing with the oxygen system understand the risks associated with oxygen systems. Experience with inert fluids, fuel gases, or other oxidizers does not qualify one to safely design and operate oxygen systems. Oxygen safety training should be provided for all personnel working with oxygen or oxygen-enriched components or systems, including design, cleaning, assembly, operations, and maintenance as applicable to personnel. In the United States, federal requirements for training on hazardous materials are listed in the Code of Federal Regulations. 29 CFR 1910.1200(h) and 49 CFR 172.702(a) mandates that employers provide training for all employees using hazardous materials, which includes oxygen. This chapter addresses some of the design concerns specific to oxygen systems. Additional information on training of personnel and on related policies and procedures is given in Appendix F.

Design Specifications

Each new design project must begin with specifications that define the requirements for the oxygen system or component. These specifications may include items such as function, weight, cost, and material compatibility. It is important to ensure that the design specifications do not create an unnecessary risk for personnel or equipment. Many materials are combustible in oxygen-enriched environments, and reactivity is generally increased with increasing temperature and pressure. Therefore, materials selection criteria are critical to achieving a successful final product. Designers also should take care to ensure that their specifications are accurate and not overly rigorous. For example, requesting higher temperature and pressure ratings than are necessary requires more expensive and heavier materials.

Companies or entities may create internal design specifications for their oxygen systems. This allows the standardization of systems for their specific applications to allow tighter control of design, materials selection, and cleaning. Such design specifications would be periodically reviewed to ensure compliance with applicable standards.

Design Reviews

Before initiating construction, the design of components, equipment, systems, or facilities that involve the use of oxygen should be reviewed in accordance with procedures approved by the authority having jurisdiction. The design review ultimately needs to address all design aspects down to the individual part level because all parts may pose potential hazards in oxygen service. Furthermore, the design review should address all safety and hazards† involved in the component, equipment, system, or facility, and compliance with applicable standards, codes, and regulations. The design review process should consist of formal reviews at various stages of a project beginning with the conceptual stage, continuing through the fabrication and construction stages, and ending with a final review of the assembled system. A summary of these reviews and their relationship with other reviews and the life-cycle phases of a project is given in Appendix F.

Oxygen Compatibility Assessment

Because of the inherent risk of fire, oxygen systems require a unique level of analysis separate from typical design reviews to assess the risk of fire in oxygen systems and components. Often referred to as an Oxygen Compatibility Assessment (OCA) or an Oxygen Hazards and Fire Risk Assessment (OHFRA), these analyses consider the specific system or component operating conditions, the oxygen-wetted materials of construction, the active ignition mechanisms, and the specific system or component configuration to assess both the risk of fire and the reaction effect of a fire in a given component or system. Further details on OCAs and OHFRAs are provided in Chapter 4 and Appendix F.

Component and System Testing

The intent of component and system testing is to ensure the integrity of equipment for its intended use. A wide variety of tests may be required, depending upon the critical nature of the equipment. Some of the various tests that may be performed for pressure vessels are discussed in Appendix C. Compliance with approved requirements of the authority

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[1] The † indicates a term defined in the Glossary (Appendix G).

having jurisdiction is required. Qualification testing† and acceptance testing† should be performed on components, systems, or both to verify that they meet specification requirements and to identify defects that may exist in the component or system. Acceptance tests of the final hardware configuration should be conducted with clean oxygen and parts cleaned for oxygen service. Testing with oxygen should begin only after an OCA has been performed on the specific test hardware (see Chapter 4 and Appendix F). The OCA often defines the testing required to further evaluate specific ignition mechanisms.

Design Guidelines for Oxygen Systems

By themselves, the use of ignition- and burn-resistant materials for components in oxygen systems will not eliminate oxygen fires. Design features, such as the physical design of components and the component location within a system, must be effectively coupled with proper materials selection to achieve safe operations. This section presents some guidelines for oxygen systems related to the following:

- overall design,
- materials,
- cleanliness,
- minimizing ignition mechanisms,
- design of components,
- low-pressure oxygen systems,
- cryogenic systems, and
- managing fires.

These guidelines can be used as a checklist for any oxygen system. It may not be possible to implement all of the guidelines, but the designer should implement as many as possible. Evaluation of such design features should begin with the preliminary design reviews.

In real design situations, the designer often will face risk optimization. Many times, task constraints dictate the use of specific materials, hardware, or features. When these features introduce new ignition hazards, the hazards must remain minimal. Often, the designer will be able to minimize risks by adding filters, reducing pressurization rates, or ensuring that the best (and possibly more expensive) materials are incorporated into the design. It is beyond the scope of this document to describe all possible compromises for risk optimization; the designer must assess each situation separately.

Overall Design Guidelines

Overall oxygen system design guidelines include the following. Refer to *ASTM G 88* and to *CGA G-4.4-2003* (4th Edition)/ IGC doc 13/02 for additional system design guidelines.

1. Design, fabricate, and install in accordance with applicable codes (see the Code Design Requirements section in this chapter).
2. Minimize pressure in all parts of a system. The pressure should be reduced near the oxygen source rather than at the use point so that the pressure is minimized in intermediate equipment.
3. Avoid unnecessarily elevated temperatures and locate systems a safe distance from heat or thermal radiation sources (such as furnaces).
4. Ensure proper system pressure relief protection.
5. Components and systems should be pretested in controlled situations to verify they are safe for use in the intended oxygen service.
6. Use inert gases for pneumatic gas actuators to eliminate oxygen hazards in locations where the use of oxygen is not necessary.
7. Provide monitoring equipment and automatic shutdown devices where practical for heat sources such as heaters and bearings.
8. Avoid thin walls. Thin sections are more prone to ignition and can increase the likelihood of a kindling chain to bulk materials. Care should be taken to ensure that the walls between inner cavities or passageways and the outer surface of component housings does not become so thin that stress concentrations result when pressure is introduced. If such walls become too thin, they may rupture under pressure loading and the exposed bare metal may oxidize rapidly and generate enough heat to ignite and burn. Furthermore, thin walls increase the risk of kindling chain ignition of bulk materials. Thin walls can generally be eliminated through design and manufacturing forethought. Fig. 5-1 illustrates a thin-wall condition.
9. Be cautious of single-barrier failures that introduce oxygen into regions not normally exposed to it, such as failure of seals and leaks in which only the primary containment structure is breached. The materials or configuration of parts in this region may not be compatible with oxygen. Any situation in which a single barrier may fail should be analyzed during the design phase. The purpose of the analysis should be to determine whether a barrier failure is credible and if exposure of incompatible materials could create a hazard.
10. Eliminate burrs and avoid sharp edges. Although the elimination of burrs and sharp edges should be the goal of all designers and machine shops, it becomes especially important in oxygen systems in which small, thin portions of metal can become the site for kindling chain ignition. If an ignition source such as particle impact is able to ignite a burr, this may promote the combustion of the bulkier material surrounding it, which would otherwise have been substantially more difficult to ignite. Removal of this material before oxygen service should be standard practice and is essential to avoiding ignition as a result of particle impact. Fig. 5-2 shows an example of a design with a sharp edge, and the steps needed to eliminate the sharp edge. In Fig. 5-2(*a*), insufficient drill-point penetration in the drilled hole creates a sharp edge at the intersection of the bore and drilled hole. As shown in Fig.5-2(*b*), the sharp edge can easily be eliminated by extending the drill-point penetration, thereby making the part much less susceptible to ignition.
11. Ensure adequate ventilation to avoid creating an oxygen-enriched environment as a result of leaks. Further discussion of the hazards of oxygen-enriched environments can be found in Chapter 1.
12. Limit fluid-induced vibrations over all operating ranges. Vibrations can cause fretting, galling, impacting, and particle generation in components and systems. Valve-poppet chatter and vibration are examples of this phenomenon.
13. Design for component directionality and verify flow direction after installation. Many components can be used in assorted orientations that may seem similar in function but can be widely different in terms of ignition mechanisms. The severity of a given oxygen component, such as a globe valve, can be affected simply by changing the flow direction through the component, in that impingement

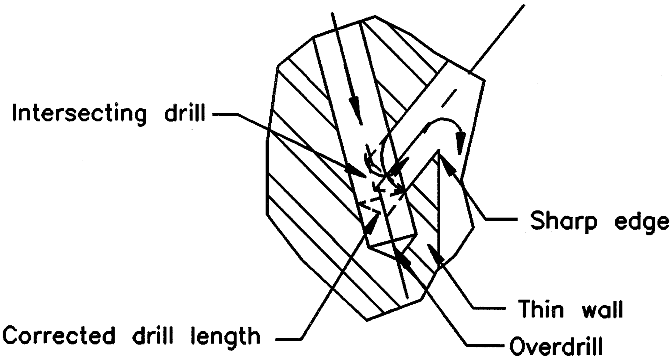

Fig. 5-1—Design resulting in thin walls.

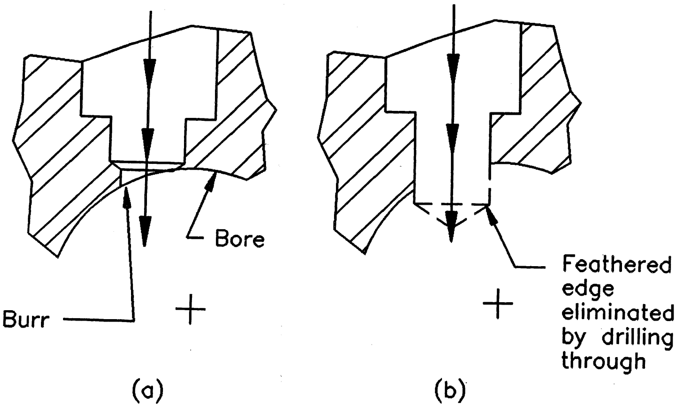

Fig. 5-2—Design with sharp edge.

surfaces are changed. Although many components have the intended flow direction stamped on the component body to ensure proper installation, many others do not have this feature. Component directionality should always be verified after system installation. When in doubt, the component manufacturer should always be consulted regarding intended flow direction.

14. Design equipment so that power losses or other loss of actuation sources return the equipment to a fail-safe position to protect personnel and property.
15. Consider the effects of thermal expansion and contraction, especially at the interface of dissimilar materials.
16. Unlike fuel gas systems, oxygen systems generally do not require inert gas purges after use, before “breaking into” the system for maintenance. The bulk materials of construction often are considered situationally nonflammable at ambient conditions (even with commercially pure oxygen in the system), and the energies required to ignite these materials under these conditions are very high. If there exists a possibility of fuel gases or other ignitable contaminants being present, inert gas purges prior to maintenance are generally required.

Materials Guidelines

Materials guidelines for oxygen service include the following. Refer to Chapter 3 and Appendix B of this manual, *ASTM G 63*, *ASTM G 94*, and *CGA G-4.4-2003* (4th Edition)/IGC doc 13/02 for materials use guidelines.

1. Although it is not always possible to use materials that do not ignite under any operating condition, it is generally understood that the most ignition-resistant materials are preferred for any design.
2. Ensure that there are proper certifications for all materials in contact with oxygen. For more information, see Chapter 3 under “Materials Control.”
3. Use caution with surface preparations, such as coatings and platings. The designer should first attempt to meet all functional requirements without coatings, platings, or hardfacings to avoid failure mechanisms as a result of the failure of such techniques. In most applications, surface preparations can be avoided. When a surface preparation cannot be avoided, designers should consider and understand the effects of the specific surface preparations on material properties, such as strength and ductility, and on material ignitability and flammability. In addition, designers should consider the effect of cleaning procedures on the surface preparation.
4. Prefer the use of nonmetallic materials whose autogenous ignition temperature in oxygen (in accordance with Test Method G 72) exceeds the maximum use temperature by at least 100 K (100°C) (in accordance with Guide ASTM G 63). A greater temperature differential may be appropriate for high use pressures or other aggravating factors.
5. Although the design of sealing interfaces is a necessary compromise, the design should use standard shapes as much as possible. Past experience has shown that elastomeric O-rings are successful in static environments but can be poor choices in dynamic environments. In some instances, polytetrafluoroethylene (PTFE) Teflon with Viton as a backup (which exposes the most compatible materials preferentially to oxygen) has been used for seals in which elastomers must be used and cannot be limited to static applications. Rigid plastics, such as Vespel, have been used as seats in valves and regulators; however, the noncompliance of the material requires a small contact area with a hard (metal or sapphire) mating surface to achieve a seal. An alternative to rigid plastics is to use a coined metal seat if precautions are taken to eliminate galling (metal deterioration that involves smearing and material transfer from one surface to another).
6. Consider the effects of long-term operation, including the following:
   a. Cold flow of seals. Cold flow is a concern, especially for soft goods with little resiliency such as PTFE Teflon. With applied loads, such materials become permanently deformed, usually resulting in a loss of sealing.
   b. Seal extrusion. Seals with low hardnesses are typically used because they tend to provide better sealing. However, high temperatures and pressures as well as pressure and thermal cycles may result in extrusion of soft seals. Such extrusion may increase ignition hazards.
   c. High-temperature excessive oxidation of copper**.** Copper is often used as a sealing material in oxygen systems and 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 can then become particulate in the system.
   d. Silicone embrittlement and degradation. Although silicone seals should be used with caution, they are used in some oxygen systems. A careful examination of silicone seals is recommended during maintenance because

embrittlement and degradation of silicone can occur in oxygen environments.

7. In applications where weight is important, take advantage of specific strength, which often allows the use of the most oxygen-compatible materials to improve performance and decrease ignition hazards. Specific strength is the ratio of the material strength to density, and this is the critical parameter for determining the weight of hardware. For example, Monel alloys are rarely materials of choice for flight systems because of the perception that components constructed of Monel weigh more than those of aluminum and other lightweight alloys. However, Monel alloys often can be obtained in the necessary range of hardnesses and strengths and, because of the greater strength-to-weight ratio of Monel compared with aluminum, Monel components can sometimes be made smaller and lighter.
8. Use fluorinated lubricants that have been analyzed according to the guidelines in Chapter 4 and that have been shown to be compatible with oxygen usage.

Design for Cleanliness and Maintaining Cleanliness

System cleanliness is one of the most important fire-prevention methods. Information regarding system cleanliness can be found in *ASTM G 93*, *ASTM G 88*, and Chapter 6. The following guidelines will aid in the design of a system that can be properly cleaned and maintained clean to mitigate the fire hazard.

1. Design a system that is easy to clean and easy to maintain clean. It should be possible to disassemble the system into components that can be thoroughly cleaned.
2. Avoid the presence of unnecessary sumps, blind passages, crevices, dead-ends, and cavities that are likely to accumulate debris. Design necessary sumps, cavities, dead-ends, or remote chambers carefully to exclude or minimize the accumulation of contaminants. Stagnant areas at the end of drilled passages tend to collect debris either from manufacturing or from normal use. Drill points can collect particulate at their center and significantly increase the chance of ignition. Blind passages and dead-end cavities also increase cleaning difficulty, requiring that the part be turned during soaking to eliminate air pockets. Special nozzles or extensions must be used to flush such areas. Fig. 5-3(*a*) depicts a blind passage created by plugging a drilled passage. The blind passage could be eliminated by making the counterbore for the plug much deeper and installing the plug closer to the stem. The cavity may not be completely eliminated, but the total dead volume would be significantly reduced. Fig. 5-3(*b*) depicts a dead-end cavity created by overdrilling an intersecting passage. This dead-end cavity can be eliminated by paying careful attention to dimensions and tolerances or, preferably, by redesigning to eliminate the intersecting holes. Inspection with a borescope can be conducted to verify that passageway lengths are within tolerance.
3. Systems that are free draining and smooth surfaced internally and that have a general downward flow direction will tend to retain less debris and deposits.
4. Design bypass lines to exclude or minimize the accumulation of contaminants. Bypass lines often are used for system start-up scenarios or to facilitate cleaning or maintenance. A compatible bypass valve is typically a small economical copper-base alloy or nickel-base alloy valve that can be installed directly across a rapid-opening valve for use in pressure equalization to minimize particle impact ignition. The associated piping upstream and downstream of the bypass valve also should be designed to mitigate particle impact ignition. When used on horizontal piping, bypass lines should be added off the top of the piping. Related tactics may be used on vertical piping. Although bypass piping off the top is preferred, construction at or above the horizontal center line is acceptable [1].
5. Use filters to limit the introduction of particles and to capture particles generated during service. Guidance for the use of filters and strainers in oxygen systems includes the following:
    a. *Location*: Consider the use of filters at sites of oxygen entry into a system, downstream of points where particles are likely to be generated, and at points where the presence of particles produces the greatest risk. Place filters in locations where they can be removed and inspected. Furthermore, place filters where there is no possibility of back flow that could cause the particulate captured by the filter to be blown back out of the filter. Examples of appropriate filter placement include:
        - Gas supply points;
        - Disconnect points; and
        - Upstream of valves, regulators, and other high-velocity-producing components.
    b. *Size*: Use the finest (i.e., smallest) filtration for a system that meets system flow requirements. Ensure that the filtration level corresponds to the system cleanliness level to lessen the likelihood of clogging the filter. Common strainer mesh sizes for larger industrial gas applications range from 30 to 100 mesh (600 to 150 μm). For smaller, higher-pressure applications, such as aerospace or welding, filters commonly range from 2 to 50 μm.
    c. *Strength*: Filter elements should not be fragile or prone to breakage. If complete blockage is possible, the elements should be able to withstand the full differential pressure that may be generated.
    d. *Maintenance*: Filters must have preventive maintenance that is adequate to limit the hazard associated with flammable debris collected on a filter element. Such provision may include pressure gauges to indicate excessive pressure drop and a method of isolating the filter from the system to perform maintenance. If the system cannot be shut down to change filter elements, consider parallel, redundant filter configurations with upstream and

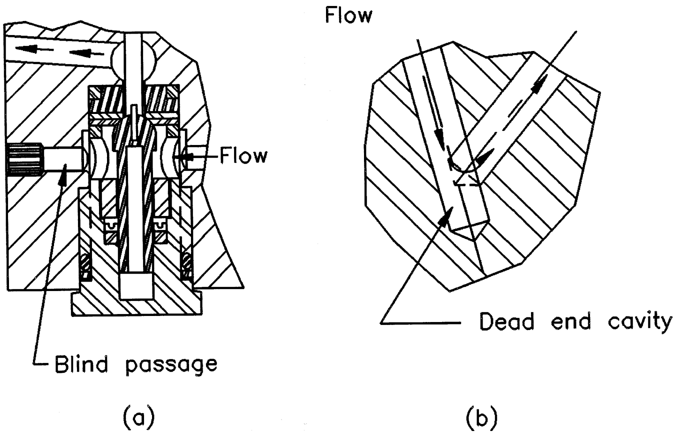

Fig. 5-3—Contaminant entrapping configurations.

downstream shutoff valves (with pressure equalization if required).

e. *Materials*: Use burn-resistant materials for filter elements because filter elements generally have greater flammability as a result of their high surface area/volume ratios. See Chapter 3 for information regarding filter material selection.

6. After assembly, purge systems with clean, dry, oil-free filtered inert gas to remove assembly-generated contaminants.
7. Design to minimize the generation of particulate during assembly, operation, and maintenance. Component designs should purposely minimize particulate generation through the normal operation of valve stems, pistons, and other moving parts. This can be accomplished by using bearings and bushings, or by using configurations that will keep particulate away from oxygen-wetted regions.
8. Design to minimize contamination during assembly, cleaning, and maintenance. Implement good practices to minimize contamination.
9. Consider the locations and effects of operationally generated contaminants in oxygen systems. Components that, simply by their function, generate particulates include compressors, pumps, check-valves, rotating-stem valves, and quick-disconnect fittings.
10. Ensure vent line terminations are protected from contamination. This protection can include the use of tees and screens to prevent contaminants, insects, and animals from entering the system.

Guidelines for Minimizing Ignition Mechanisms

The designer should avoid ignition mechanisms wherever possible, but the designer also must consider the relative importance of the various ignition mechanisms when designing new or modified hardware. This means that certain designs may be more vulnerable to specific ignition mechanisms than others simply by their function (such as components which produce high velocities) or because of the size and exposure of soft goods. Most designs can be optimized to minimize ignition if emphasis is placed upon minimizing the characteristic elements of a particular ignition mechanism inherent in the design.

The following guidelines are grouped by the ignition mechanisms they work to minimize. For descriptions of these ignition mechanisms, see Chapter 2.

Particle Impact

An ideal design to eliminate particle impact ignition sources, according to the characteristic elements, limits fluid velocities, minimizes contamination, reduces the potential for particle impacts on blunt surfaces, and avoids burrs and small parts susceptible to kindling chain ignition and combustion. A best-case example of a design minimizing particle impact ignition is particle-free, low-velocity flow through a straight section of piping. A worst-case example of a design highly vulnerable to particle impact ignition may be found in Fig. 5-4, which illustrates several design problems:

i. Particles entrained in the flow stream are accelerated through the orifice and impact on a blunt surface downstream.

ii. On impact, the particles are at near-sonic velocity and the kinetic energy is efficiently converted to heat.

iii. The drill point exaggerates the problem by concentrating the heat from multiple burning particles, and the sharp edge from the intersection of drilled holes allows a kindling chain that could promote the combustion of the bulkier portion of the housing.

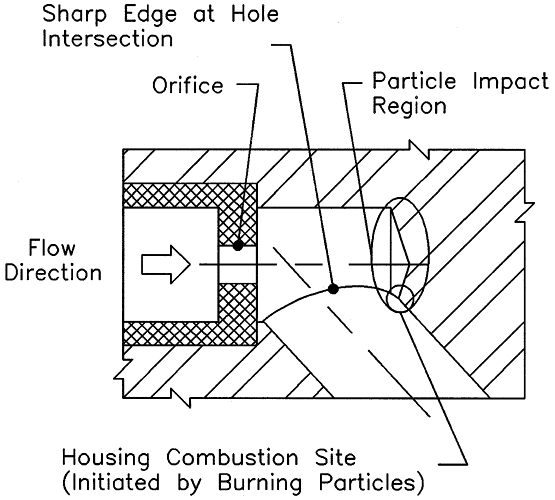

Fig. 5-4—Design highly susceptible to particle impact ignition.

The following guidelines should be applied to minimize particle impact ignition.

1. Limit the nominal gaseous oxygen (GOX) flow velocity. Limiting the flow velocity minimizes erosion, reduces particle energy, and reduces the risk of particle impact ignition. Although each material and configuration combination must be reviewed individually, gas velocities above approximately 30.5 m/s (100 ft/s) should receive special attention, especially at flow restrictions (see *Industrial Practices for GOX Transmission and Distribution Piping Systems* [CGA G-4.4-2003 (4th Edition)/IGC doc 13/02]). For pipelines, *Oxygen Pipeline Systems* [1] may be consulted for an industry approach to limiting oxygen gas velocities for given materials and pressures. In liquid oxygen (LOX) systems, high gas velocities that could be present during cooldown should also be considered. See also Refs [2–4].
2. High-velocity and turbulent gas streams may be present in systems in which the average cross-sectional velocity is calculated to be acceptable. For example, flow through a throttling valve or from small-bore piping into large-bore piping may create localized high velocity jets, eddies, and turbulence. Traditional practice [1] has been to assume that the flow velocites within the pipe will approach the average velocity within a distance of about eight to ten internal pipe diameters. Therefore, burn-resistant alloys are often used for a minimum of eight inside pipe diameters (based on the smallest diameter that would produce an acceptable average velocity) downstream of high-velocity flow disturbances. In some applications, the required length of burn-resistant alloy also may be determined using computational fluid dynamics to model areas of high velocity and impingement. Consider that even small pressure differentials across components can generate gas velocities in excess of those recommended for various metals in oxygen service, as shown in Fig. 5-5. Consider that system start-ups or shut-downs can create high transient gas velocities. These velocities often are orders of magnitude higher than those experienced during steady-state operation.

LIVE GRAPH
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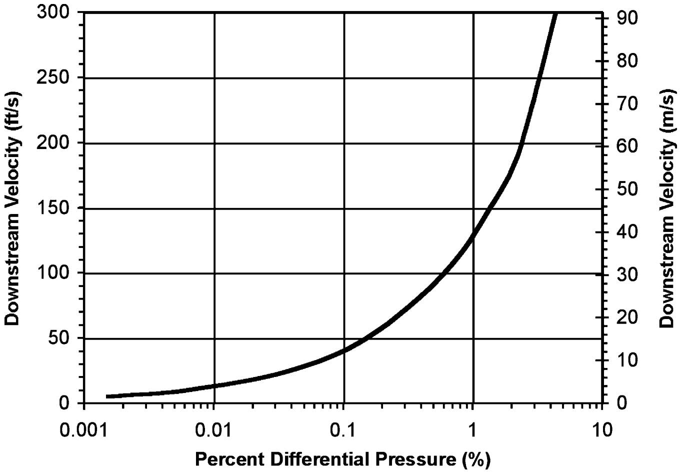

Fig. 5-5—Maximum oxygen gas velocity produced by pressure differentials, assuming isentropic flow.

3. In areas in which high velocities will be present, such as internal to and immediately upstream and downstream of throttling valves, for ten diameters downstream of uncontrolled velocities:
   a. Design to avoid particle impingement,
   b. Use materials that are resistant to ignition by particle impact, and
   c. Use filters to limit particulate immediately upstream of the high-velocity areas.
4. Use materials that are resistant to ignition by particle impact at particle-impingement points, such as short-radius elbows, tees, branch connections, orifices, and globe-style valves.
5. Minimize blunt flow-impingement surfaces. The risk of particle impact ignitions can be reduced if potential impact surfaces are designed with small oblique impact angles to reduce the kinetic energy absorbed by the impact surface [5].
6. Use filters and strainers to capture system particulates. Guidance for the use of filters and strainers in oxygen systems is found in the section “Design for Cleanliness and Maintaining Cleanliness.”
7. Design to allow a blowdown of the system with filtered, dry, oil-free inert gas at the maximum possible system flow rates and pressures. This serves to purge or capture assembly-generated particulate. An inert gas blowdown should be performed after initial assembly as well as anytime the system is broken into for maintenance.
8. Design to minimize the generation of particulate during assembly, operation, and maintenance. Component designs should purposely minimize particulate generation through the normal operation of valve stems, pistons, and other moving parts. This can be accomplished by using bearings and bushings, or by using configurations that will keep particulate away from oxygen-wetted regions. However, some components generate particulate simply by their function. These include compressors, pumps, check-valves, rotating-stem valves, and quick-disconnect fittings. Consider the locations and effects of the operationally generated particulates from these components.
9. Threaded connections can generate contaminants in oxygen systems as they are engaged and tightened (Fig. 5-6(*a*)). This problem can be minimized by redesigning the threaded members so the smooth portion of the plug interfaces with the seal before the threads engage (Fig. 5-6(*b*)). However, this solution involves rotating a part against its seal and may cause seal damage. Alternatively, the in-line threaded connection can be replaced with a flanged and bolted connection where the threaded portions are outside the fluid stream (Fig. 5-6(*c*)). The function of the threaded connection also can be performed by a separate locking nut and sealing plug; the locking nut is inserted after the sealing plug has been pushed into the seal (Fig. 5-6(*d*)). Another option is to install a barrier ring to block the particulate (Fig. 5-6(*e*)).

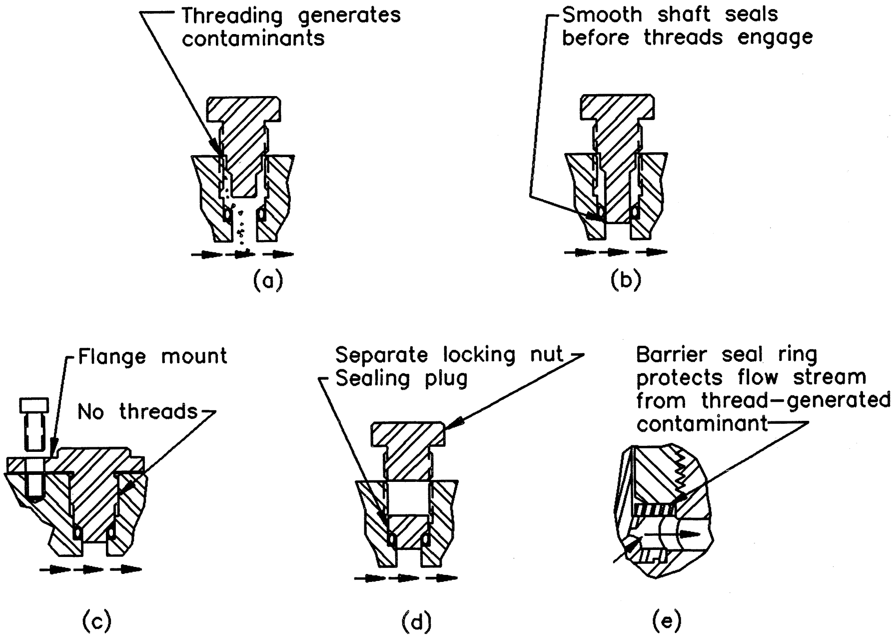

Fig. 5-6—Designs showing various fitting and particulate generation configurations.

10. Design to minimize contamination during assembly, cleaning, and maintenance. Design a system that is easy to clean and easy to maintain (see *ASTM G 93* and Ref [1]). It is preferred to disassemble the system into components that can be thoroughly cleaned. Implement good practices to minimize contamination.
11. Avoid rotating valve stems and sealing configurations that require rotation on assembly, rotation of seals, and rotation against seats. Rotating valve stems and seals can gall and generate particulate. Sealed parts that require rotation at assembly, such as O-rings on threaded shafts, can generate particles that may migrate into the flow stream. Although ball valves are commonly used as isolation valves in oxygen systems, particle generation can occur where valve operation rotates the ball on its nonmetallic seal.
12. Eliminate burrs and avoid sharp edges as described in the section "Overall Design Guidelines."
13. Internal weld surfaces should be smooth and free of slag, beads, or loose debris.
14. Design dynamic seals to minimize particle generation by minimizing coefficients of friction, using surface finishes, and choosing appropriate seal configurations.
15. Design bypass lines to minimize the accumulation of particulates, as described in the section "Design for Cleanliness and Maintaining Cleanliness."
16. Design captured vent systems to minimize particle impact hazards and reduce pressure buildup. An example of a captured vent is a relief valve or burst disk that is not open directly to the atmosphere, but rather has a tube or pipe connected to the outlet. When using captured vents, they should be designed in such a way that there are no bends closely coupled to the outlet of devices that will create high velocities, such as valves or burst discs. Alternatively, highly burn-resistant materials, such as Monel and copper, can be used.
17. Design for component directionality and verify flow direction after installation, as described in the section "Overall Design Guidelines."

Heat of Compression

Ideal designs to eliminate heat of compression ignition, according to its characteristic elements, limit pressurization rates, minimize the amount of soft goods, and use metallic parts to protect soft goods from fluid flow. Manifold designs that allow fluid hammer to occur during flow transients are to be avoided. Small, drilled holes or crevices that are difficult to clean and can accumulate nonmetallic contaminants that can be easily ignited with compressive heating are also to be avoided. Fig. 5-7 illustrates soft goods that are minimized and protected from the flow by metallic parts. Furthermore, there is a tortuous flow path that reduces the pressurization rate and compressive heating of the seals.

The following guidelines should be applied to minimize heat of compression ignition.

1. Limit GOX pressurization rates to prevent the ignition of soft goods such as seats, seals, coatings, and lubricants. Typical pressurization rates should be on the order of seconds, not fractions of a second, for small, high-pressure oxygen systems. Large industrial gas systems require even slower pressurization rates, generally on the order of minutes, as a result of the large volume of gas being pressurized. The opening time of valves and regulators should be controlled to limit downstream pressurization rates. In some applications, flow-metering devices such as orifices are required to limit pressurization rates downstream of high flow components such as quarter-turn ball valves.

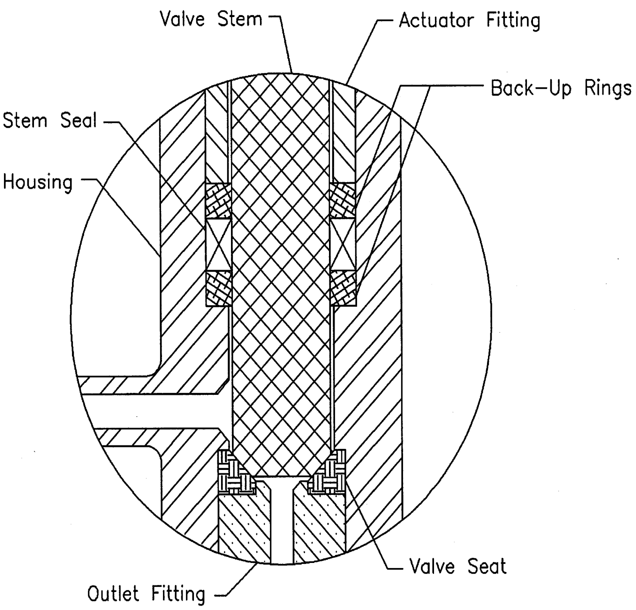

Fig. 5-7—Design showing minimization of soft good exposure to fluid flow.

2. Do not compress GOX against soft goods such as exposed valve seats, lubricants, and seals.
3. Avoid the use of fast-opening valves in which downstream system volumes can be quickly pressurized. Fast-opening valves (such as quarter-turn ball valves) may be used if specifically designed to enable slow pressurization or used strategically for isolation only and never opened with a differential pressure across the valve.
4. Use distance/volume pieces to protect soft goods at end points that experience heat as a result of rapid compression. For example, PTFE-lined flexible hoses are sensitive to ignition by heat of compression and have been shown to ignite at pressures as low as 3.45 MPa (500 psi) when pressurized in 150 ms. A distance/volume piece is a section of fire-resistant metal that can be implemented at the end of a polymer-lined hose to contain the hot compressed-gas slug that can form during pressurization and to safely absorb its heat of compression. The required size of the distance/volume piece can be calculated by ensuring that the compressed volume of gas in the system downstream of the pressurization point is completely contained in the distance/volume piece. Further information on distance/volume pieces can be found in *ASTM G 88*.
5. Minimize the amount of soft goods and their exposure to flow. Soft goods exposed to flow can be readily heated through rapid compression or from burning contaminants [6]. Soft goods may be ignited through kindling chain reactions and can promote the ignition of nearby metals. Minimizing the exposure of soft goods by shielding with surrounding metals can significantly reduce ignition hazards. Materials used for shielding around soft goods should be selected to stop a kindling chain reaction.
6. Design to minimize contamination during assembly, cleaning, and maintenance. Design a system that is easy to clean and easy to maintain (see *ASTM G 93* and Ref. 1). It is

preferred to disassemble the system into components that can be thoroughly cleaned. Implement good practices to minimize contamination.

7. Provide for pressure equalization across rapid-opening industrial gas valves. Use slow-opening compatible bypass valves for pressure equalization where applicable. Design bypass lines to preclude or minimize the accumulation of contaminants, as described in the section "Design for Cleanliness and Maintaining Cleanliness."
8. Design for component directionality and verify flow direction after installation, as described in the section "Overall Design Guidelines."
9. Avoid rotating valve stems and sealing configurations that require rotation on assembly. Rotating valve stems and seals can damage the soft goods and make them more susceptible to ignition by heat of compression.
10. Use metal-to-metal seals when possible to limit the amount of soft goods. Unless seals are thermally isolated from high temperatures, polymeric materials cannot be used as seals in valves that seal or control the flow of oxygen at high temperatures because they lose sealing properties, are easily ignited, and wear too rapidly. Metal-to-metal stem seals are generally not leak tight, and some leakage should be expected.

Flow Friction

An ideal design to eliminate flow friction ignition uses redundant seals to prevent leaking, limits the amount and size of soft goods, and is purposefully designed to prevent damaging the soft goods during assembly, operation, and maintenance.

The following guidelines should be applied to minimize flow friction ignition.

1. Avoid "weeping" flow configurations around nonmetals. These configurations can include external leaks, such as past elastomeric pressure seals, or internal flows or leaks, such as on or close to plastic seats in components.
2. Avoid rotating valve stems and sealing configurations that require rotation on assembly, rotation of seals, and rotation against seats. Such configurations can damage soft goods and render them more susceptible to flow friction ignition.
3. Avoid oxygen flow over nonmetal[†] surfaces that are highly fibrous, such as materials that have been chafed, abraded, or plastically deformed.
4. After assembly or maintenance, perform leak checks using dry, oil-free, filtered, inert gas.
5. Promptly repair leaks or replace components that persistently leak.
6. Design for thermal expansion and contraction. Leaks are commonly caused by the disparity of thermal expansion coefficients between polymers and metals. Upon cooling, polymer shrinkage will exceed that of metals, and seals will lose the compression required for sealing.
7. Be aware of seat shape and seal design. Designs in which an O-ring seals against a seat in such a way that it may cause increased wear and accelerated extrusion of the O-ring should be avoided.
8. Design properly to avoid cold flow and extrusion of seals. Standard manufacturers' dimensions and tolerances should be incorporated into designs unless an unusual overriding design constraint demands the change. Additionally, all valve assembly part dimensions should be carefully inspected. Cold flow and extrusion of seals can often be minimized by using springs to provide an external shape memory for the seal, by reinforcing the materials with various types of fibers, and by supporting the seals with stiff back-up rings. Additionally, seal extrusion can be avoided by minimizing pressure and thermal reversal cycles.
9. Avoid "feathering" of soft goods, which occurs when valve stems are rotated against some nonmetallic seat materials. The mechanical properties of such materials allows a thin, feather-like projection of material to be extruded from the seat. The feathered feature is more ignitable than the seat itself. Materials prone to feathering should not be used for seals and seats in rotating configurations.

Mechanical Impact

Special caution should be exercised where large or repeated impacts could occur on nonmetallic materials to ensure mechanical impact ignition is not a concern. For instance, seats of components such as relief valves, shut-off valves, solenoid valves, and regulators may be susceptible to ignition by mechanical impact if the impact energy is large enough (on the order of foot-pounds as opposed to inch-pounds) or if the components operate in a mode where repeated impacts could occur. Refer to Fig. 5-8, which illustrates that mechanical impact can occur between the valve seat and valve stem.

The following guidelines should be applied to minimize mechanical impact ignition.

1. Minimize mechanical impact. Mechanical impact ignitions can ignite contamination and soft goods entrapped by the impact. Components such as relief valves, shutoff valves, and regulators, whose configuration leads to impact and possible chatter on nonmetallic parts, should be especially reviewed for this hazard.
2. Design component and system combinations to avoid chatter that can result from mechanical or fluid vibrations, flow resonance, or valve instability. This hazard is commonly associated with regulators, relief valves, and check valves.
3. Perform inert-gas flow checks of regulators, relief valves, and check valves in their use configuration and environment to ensure chatter does not occur. These flow checks must replicate the range of flow rates and pressures the component will be exposed to during opertaion.

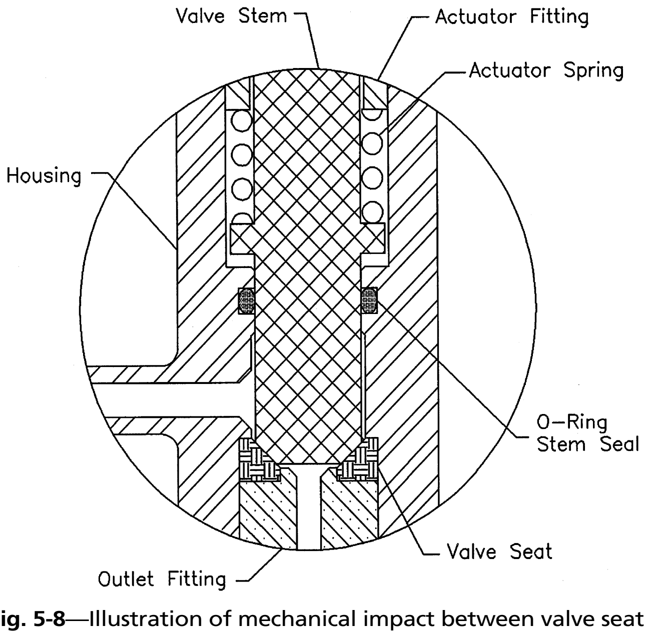

Fig. 5-8—Illustration of mechanical impact between valve seat and stem.

Friction

Rotational or translational sliding contact between two parts has the potential to generate enough heat to ignite parts at the interface in GOX as well as LOX. Common configurations in which frictional heating might be observed are components with bearings and pistons. Any contamination near the heated region, such as lubrication or particulate generated by seal wear, also can be ignited. Frictional ignition hazards can be reduced by careful control of surface finishes, coefficients of friction, alignment, and flow-induced cooling. Rubbing of metallic parts should be avoided unless the design has been carefully analyzed.

The following guidelines should be applied to minimize ignition as a result of friction.

1. Burn-resistant materials should be used if frictional heating cannot be eliminated or sufficiently limited.
2. Rotating machinery should be designed with adequate clearances that can be verified.
3. Rotating machinery may be equipped with sensors to shut down the equipment if rubbing or instabilities develop.
4. Avoid galling, which is a form of surface damage arising between sliding solids, and is distinguished by macroscopic roughening and creation of protrusions above the original surface. Galling often includes plastic flow or material transfer or both and is generally encountered when identical or similar hardness materials are in sliding or rotating contact with each other. The use of materials with dissimilar hardnesses, lubricants, or surface finishes that provide lubrication will reduce problems with galling. The use of 300 series stainless steel on itself or aluminum is particularly prone to galling. Combinations of 300 series stainless against hardened 400 series stainless or 15-5 PH stainless will inherently have fewer problems with galling.
5. Avoid fretting, which is surface fatigue of a material during high loading with very small motion between parts. Use of higher-strength materials or plating with hard material, such as nickel, will reduce problems with fretting.
6. High pressures and high flow rates can cause metal deterioration by fretting or galling as a result of side loads and oscillations on stems, poppets, or stem seals. To minimize the possibility of ignition, poppet, stem, and bore designs that have close clearances should be made of materials that are relatively resistant to ignition by frictional heating. One surface may be hardened by nitriding or a similar process to minimize material loss by fretting or galling. Where possible, the valve poppet or stem should be designed for symmetrical flow so oscillatory side loads are reduced. The symmetrical flow tends to center the poppet or stem in the bore and maintains design clearances between the poppet and bore surfaces. Another option is to reduce the volumetric flow rate, and thus the magnitude of oscillations and side loads, by installing an orifice downstream of the poppet or seal to minimize the pressure differential across the poppet.

Static Discharge

Static discharge poses an ignition hazard in dry, oxygen-enriched environments. Precautions should be taken whenever people are exposed to oxygen-enriched environments, such as in hyperbaric chambers, during LOX filling operations, and near oxygen leaks.

The following guidelines, should be applied to minimize ignition as a result of static discharge. See Ref [7] for more information.

1. Provide low-resistance paths to ground.
2. Increase the relative humidity to reduce the likelihood of static charge buildup. To be effective, the humidity should be a minimum of 50 %.
3. Use conductive flooring to reduce static charge buildup.
4. In instances in which increased humidity is not possible, consider the use of metal-impregnated textiles.

Electrical Arc

Electrical arcs in oxygen-enriched environments can lead to heating and subsequent ignition. An example of good design practice is found in Fig. 5-9, which demonstrates the proper method to insulate electrical components and reduce the possibility of arcing. Ignitions caused by electrical malfunction can be prevented by using double-insulated heater wire with a differential current sensor and a temperature sensor to monitor off-limit operating conditions.

The following guidelines should be applied to minimize ignition as a result of electrical arcing.

1. Electrical wiring should not be exposed to oxygen-enriched environments. In areas in which such exposure is necessary, the electrical wiring should be enclosed in hermetically sealed conduits or in conduits purged with an inert gas such as nitrogen or helium.
2. Instruments, switches, flow sensors, and electrical devices that are directly in an oxygen environment should be designed in a modular structure and hermetically sealed. Inerting with nitrogen or helium is recommended.
3. Bulk oxygen installations are not categorized as “hazardous” (“classified”) locations as defined and covered in 29CFR1 910 Subpart S–Electrical. Consequently, general purpose or weatherproof types of electrical wiring and equipment are acceptable depending on whether the installation is indoors or outdoors. Such equipment shall be installed in accordance with the applicable provisions of 29CFR1 910 Subpart S–Electrical [29CFR1 910.104].
4. Electrical wiring and equipment shall be in accordance with the requirements of 29CFR 1 910 Subpart S–Electrical, and NFPA 70, including Article 505 [NFPA 55].
5. Electrical arcing should be prevented with the proper grounding of components and component parts.
6. No part of an oxygen system should be used for electrical grounding [NFPA 55].
7. All oxygen system components should be located so they cannot become part of an electrical circuit [NFPA 55].
8. Electrical terminals should not turn or loosen when subjected to service conditions. Terminal points should be protected from shorting by eliminating foreign objects and contaminants.

Resonance

The following guidelines should be applied to minimize ignition as a result of resonance.

1. Minimize contamination, which can be easily ignited by resonance.
2. Eliminate blind passages, which may form resonant cavities and are difficult to clean and inspect for cleanliness. Additionally, they can provide a location for particulate to accumulate during operation of the equipment.
3. Avoid crevices for particulate entrapment and resonant cavities [8]. Cavities formed at the intersection of mating parts in assemblies create a location where contamination can accumulate and increase ignition risks.

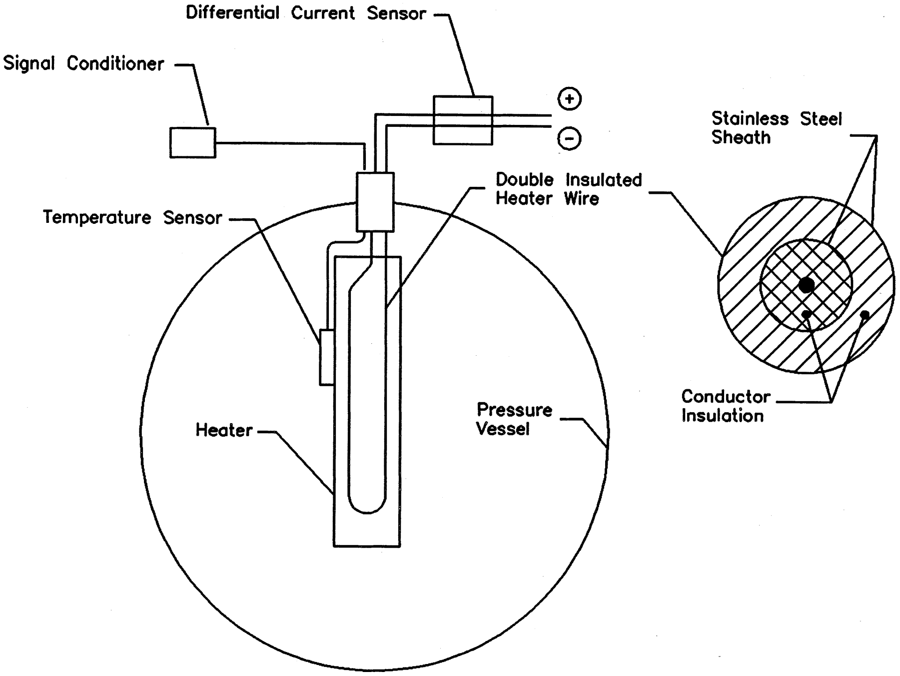

Fig. 5-9—Design minimizing electrical arcing.

4. Avoid sumps, dead-ends, or cavities in LOX and oxygen-enriched cryogenic systems in which the liquid is stagnant and can vaporize, allowing dissolved low-boiling-point hydrocarbons to concentrate and eventually precipitate. Various names have been applied to this vaporization and precipitation process including: fractional vaporization, LOX boil-off, dead-end boiling, boiling-to-dryness, and dry boiling [9,10].
5. GOX components should be designed so that jets will not impinge on or flow across stagnant cavities. Jets should be gradually expanded and stagnant cavities should be eliminated or kept as shallow as possible.

Component Design Guidelines

The following sections should assist component and system designers during the design process. These guidelines include design requirements from various codes the designer must consider.

> *Note: This section does not attempt to give all code requirements. It is the responsibility of the designer to refer to the appropriate codes. Additional requirements noted below were specified from extensive experience and can be found in other documents, such as* Oxygen (CGA G-4.0).

Piping, System Connections, and Joints

The following guidelines should be applied to piping, system connections, and joints in oxygen systems.

1. Piping and pressure-containing components should be consistent with the accepted design philosophy, substantiated by the following:
   - Stress analysis to predict safe and reliable operation per codes,
   - Pressure testing per codes to verify predicted performance, or
   - Extensive, successful service experience under comparable design conditions with components that are similarly shaped and proportioned.
2. All piping systems should be designed in accordance with specifications of the authority having jurisdiction. *ASME Process Piping* (ASME B31.3) is typically specified for pressure piping. The design should be based on the pressure and temperature of the system and the pressure and temperature limitations of the materials selected. All local, state, and federal codes shall be considered (Appendix D).
3. Material used in pressure-containing piping systems and piping elements should conform to listed or published specifications covering chemical, physical, and mechanical properties; method and process of manufacture; heat treatment; and quality control. It should otherwise meet the requirements of the authority having jurisdiction.
4. Piping, tubing, and fittings should be suitable for oxygen service and for the pressures and temperatures involved [11]. Materials are described in Chapter 3 and Appendix B.
5. The primary concern with high-velocity flow conditions is the entrainment of particulates and their subsequent impingement on a surface, such as at bends in piping. The effects of extremes in flow velocity and pressure are also concerns. Material erosion or ignition can be caused by entrained particulate impact and abrasion, erosive effects of the fluid flow, or by both.
6. All factors must be considered when establishing safe velocity limits. A safe piping system, in addition to being designed and installed in accordance with all applicable codes and regulations, should further meet the special requirements for oxygen services. These special requirements include certain velocity restrictions and material specifications; special criteria for design and location; correct location and specification of joints, fittings, safety devices, and filters; and thorough and adequate cleaning of the components and system for oxygen service. Factors

that primarily affect velocity in oxygen piping systems are pipe material, gas-operating temperature and pressure, and restrictive configurations such as valves or orifices.

7. Until a more quantitative limit can be established, the following practices are recommended:
   a. Where practical, avoid sonic velocity in gases; where impractical, use materials resistant to ignition by particle impact.
   b. If possible, avoid the use of nonmetals at locations within the system where sonic velocity can occur.
   c. Maintain fluid system cleanliness to limit entrained particulates, and perform blowdown with filtered, dry gaseous nitrogen at maximum anticipated pressure and flow before wetting the system with oxygen.
8. Piping systems should be designed to ensure the GOX in the system does not exceed specified velocities. Places where fluid velocities approach 30 m/s (100 ft/s) should be reviewed for particle impact ignition sensitivity (Chapter 2 and Ref [1]).
9. The selection of piping material on the inlet and outlet of the bypass valves should be given special consideration because this piping is often exposed to both high velocities and turbulent flow during pressurization. The piping should be designed to mitigate particle impact ignition.
10. Design bypass lines to minimize the accumulation of particulates, as described in the section "Design for Cleanliness and Maintaining Cleanliness."
11. Piping downstream of throttling or process control valves experiences high velocities and highly turbulent gas flow. Therefore, the piping should be designed to mitigate particle impact ignition.
12. Wherever possible use piping with long-radius bends instead of sharp bends to reduce the likelihood of particle impingement.
13. Piping upstream of vents and bleeds should be designed as bypass piping.
14. Piping downstream of vent valves and safety relief valves should be designed to mitigate particle impact ignition.
15. Consideration must be given to the location of vent outlets to minimize risks as a result of the oxygen-enriched atmosphere in the surroundings, including a consideration of height, direction, adequate spacing, etc.
16. Vent lines should be constructed of corrosion-resistant material because they are open to atmosphere and invite condensation with daily temperature fluctuations.
17. Underground piping cannot be inspected for leaks, corrosion, or other defects as readily as visible piping. Therefore, oxygen piping and equipment shall be installed at a distance from electrical power lines or electrical equipment far enough so that power line or electrical equipment failure precludes contact with oxygen piping and equipment. All oxygen piping must be adequately supported to avoid excessive vibration and to prevent deterioration by friction.
18. Welded, brazed, or silver-soldered joints are satisfactory for oxygen systems. Such joints, however, if left in the as-formed condition, may have slag or surfaces that can trap contaminants. Welds shall be specified as full penetration so that the contracting surfaces are joined to limit particulate entrapment.
19. The use of fittings, such as socket fittings, that leave a gap exposed to oxygen are permitted by standards such as *Standard for Bulk Oxygen Systems at Consumer Sites* (NFPA 50). However, the use of such fittings must be given careful consideration. Factors that must be considered in the use of this type of fitting include the potential for contaminant entrapment in the gap and the difficulty of removing cleaning fluids from the gap.
20. Exposed weld surfaces should be ground to a smooth finish for ease of cleaning. With brazed and soldered joints, special care must be taken to ensure surface cleanliness, close and uniform clearance, and full penetration of the joint.
21. Materials used should be documented for compatibility with the total environment of pressure, temperature, flow rates, and exposure time profiles. Material for joints and fittings should be similar to the piping metal to avoid developing electrical couples. When the use of different metals cannot be avoided, considerable care must be taken when removing the fitting or connection so any grit or contaminant resulting from the electrical couple is not left in the piping.
22. Piping should be assembled by welding, except at connections to valves, where flanged joints are required. Welding procedures, welder qualification tests, welding operations, and weld testing should be in accordance with ASME Boiler and Pressure Vessel Code, Section IV, "Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators" and ASME B31.3. Backup rings should not be used because of the difficulty of recleaning the system.
23. The oxygen gas trailers and transfer connections must use a unique design configuration to prevent or minimize connecting with incompatible gaseous fluids or similar fluids at different pressure levels. The connectors and fittings to be disconnected during operations should be provided with tethered end plates, caps, plugs, or covers to protect the system from contamination or damage when not in use.
24. Acceptable flexible links for connecting compressed gas cylinders are as follows:
   a. Stainless steel tubing formed into loops to provide enough flexibility for easy hookup is the preferred method.
   b. Flexible metal tube or pipe, such as a bellows section, is also recommended. PTFE-lined flexible hoses may be used if particular care is exercised to ensure that heat of compression ignitions cannot occur. The risks may be minimized if procedures preclude operator error and the design incorporates a long, nonignitable metallic tubing at the downstream end of the flexible hose. Proper restraining cables and anchoring cables are required for flexible hoses. All-metal bellows, although recommended, will trap contaminants and are difficult to clean, and the cleaning fluids cannot be completely rinsed off or removed from the bellows, which may lead to corrosion. Therefore, it is recommended that special attention be given to the cleaning of metal bellows to ensure that they are properly cleaned and that the cleaning fluid is completely removed.

Valves

The following guidelines apply to various types of oxygen system valves.

1. Avoid valves with rotating stems. A manual, screw-type valve with a rotating stem (Fig. 5-10(*a*)) might seem desirable in a high-pressure oxygen system because such a valve can provide a slow actuation rate. However, actuation of

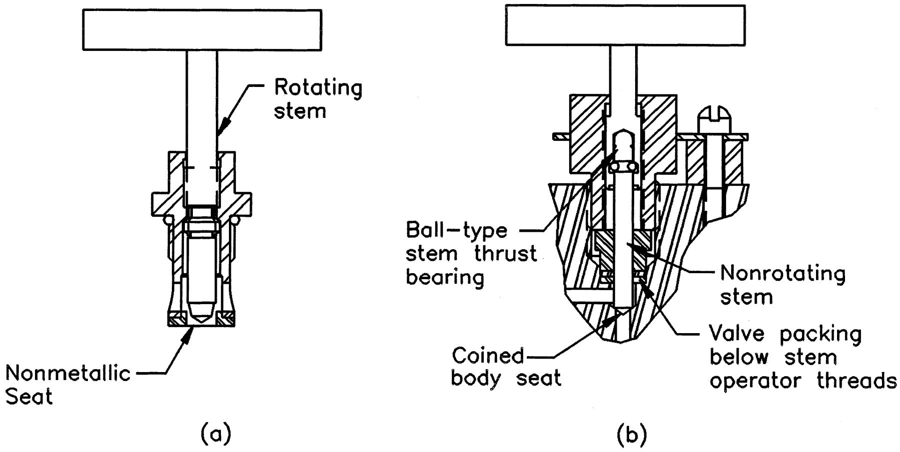

Fig. 5-10—Designs illustrating rotating and nonrotating stem configurations.

valves with rotating stems creates particulate in the threads and at the point of contact with the seat. A nonmetallic seat can easily be damaged by excessive closing torque, shredding, or gas erosion during opening and closing. Furthermore, solid contaminants can become embedded in soft seat material. If the seat is made of metal, it must be hardened to prevent galling when the valve stem rotates against the seat. Such hardened materials can fracture or even fragment as a result of excessive closing torque or closure onto hard contaminants such as silica.

2. Manual valves with a nonrotating stems and metallic seats (Fig. 5-10(*b*)) can be used to achieve slow actuation rates. In this case, the metal seat can be made of a much softer material and the seat can be formed by "coining" (pressure molding by the stem to create a perfect match). Contaminants will not cause fragmentation of such a seat. Galling cannot occur unless the nonrotating feature is compromised, and care should therefore be exercised when cleaning). The seat and body of such a valve can be fabricated from many metals that are comparatively unreactive with oxygen. Particle contamination can be minimized as shown in Fig. 5-10(*b*) by placing stem seals below the valve stem threads to isolate them from oxygen and by making the stem a nonrotation configuration. Axial stem movement without rotation will minimize particulate generation, and the hazard of particle impact ignition is reduced.
3. Avoid rotating valve stems and sealing configurations that require rotation on assembly, rotation of seals, and rotation against seats. Rotating valve stems and seals can gall and generate particulate. Sealed parts that require rotation at assembly, such as O-rings on threaded shafts, can generate particles that may migrate into the flow stream. Particle generation also occurs in ball valves in which valve operation rotates a ball on a nonmetallic seal. Fig. 5-11(*a*) shows a configuration in which particulate generated by the threads at assembly can enter the oxygen-wetted valve regions, because the seal is not engaged during the threading operation. Fig. 5-11(*b*) shows one of many configurations that can be used to isolate assembly-generated particles from the contained oxygen and reduce wear and feathering of the seal or assembly.
4. The material and physical design of valves should be carefully selected considering both normal and unusual operating conditions.
5. Bypass valves are normally piped from immediately upstream to immediately downstream of manual isolation valves for use in pressure equalization to minimize ignition as a result of particle impact and heat of compression. Compatible bypass valves are typically small, economical copper-base alloy or nickel-base alloy valves.
6. Throttling or process control valves are considered to be the most critical components in gaseous-oxygen systems because of the presence of active ignition mechanisms. These valves include those for pressure control, flow control, emergency shut-off, venting, bypass, and safety relief. The function of such valves is to regulate flow. They operate with high differential pressure that is associated with high velocity and turbulent impingement flow. The turbulence and impingement is not only present in the trim and body of the valve but is considered to extend to the downstream piping for a length of a minimum of eight pipe diameters. To mitigate the hazard of heat of compression and particle impact, special consideration must be given to process control valves and components downstream of process control valves.
7. Ball, butterfly, and plug valves are inherently quick opening. This leads to concerns about heat of compression for any nonmetallic material downstream of the valve.
8. Globe valves have a tortuous path with many impingement sites, and care must therefore be taken to mitigate the particle impact ignition hazard.
9. Manual bypass valves should be provided around manual pipeline valves to equalize pressure in a controlled manner for configurations or systems where it is necessary to reduce heat of compression, pressure surge, or high flow velocity across controlling elements.
10. Valves should include an electrical ground connection between the stem and body to prevent static electric charge from accumulating on internal components from the fluid flowing through the valve.
11. Vessels used as test facility components should have remotely operated fail-safe shutoff valves located close to the loading vessel. All large-capacity storage vessels should have remotely operated fail-safe shutoff valves. A manual override should be considered in case of a power failure.
12. Isolation valves
    a. Isolation valves should be used as needed to isolate portions of a piping system for operation, maintenance,

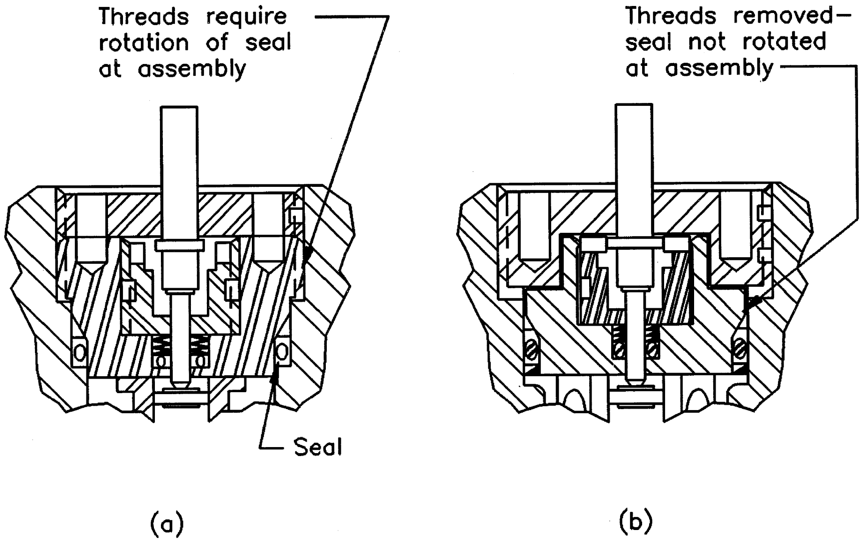

Fig. 5-11—Designs illustrating seal configurations.

and emergencies. All valves should be accessible for operation and maintenance and should be protected from accidental damage by nearby activities, such as vehicle movement.

b. Valves in oxygen distribution systems should be kept to a minimum and should be of good quality because they have mechanical joints that are susceptible to leaks. All valve materials must be suitable for oxygen service, and material selection must meet velocity criteria. Stems, packing glands, and other parts vital to proper valve operation should be of materials that will not readily corrode. The stem packing should be an oxygen-compatible material as listed in approved sources, such as Refs [5–12].

c. Isolation valves should be operated either fully open or fully closed and never in a throttling or regulating mode. Where required, a bypass valve should be provided around an isolation valve, especially one of large size. The bypass valve must be of suitable materials because of the high velocity involved. If a remotely operated bypass valve is used, the valve should close in case of power loss or from a system emergency shutdown signal.

d. GOX tube trailers should be equipped with normally closed safety shutoff valves that require power to remain open and automatically return to full closed when the power is removed. These safety shutoff valves should never be used for flow control. Manually operated main shutoff valves should also be used to isolate the trailers and to control flow, if required.

13. Check valves

a. Check valves should not be used when bubble-free tightness is required. If bubble-free tightness is required, two isolation valves with a bleed valve between them, an arrangement commonly referred to as a double block and bleed configuration, should be used rather than a check valve.

b. Check valves might be completely tight at the start of service but develop leaks later. A single check valve is often more leak tight than multiple check valves because the larger pressure drop closes it more tightly. The pressure on the upstream side of a check valve must be maintained at a pressure higher than the pressure downstream of the check valve.

c. The safety of laboratory operations requires that bottled gases not be contaminated. Suppliers of bottled gases specifically prohibit contaminating gases in their bottles. However, bottled gases have become contaminated as a result of leaking check valves in interconnected systems. Therefore, system maintenance should include regular inspection of the check valves and analysis of the contents of the pressure vessels.

d. Heat of compression ignition should be assessed when the downstream side of a check valve may be exposed to rapid pressurization with oxygen. One example of such a scenario is the use of a check valve to prevent oxygen from entering an inert gas system.

Pressure Relief Devices

The following guidelines apply to pressure relief devices.

1. When pressure relief valves are located indoors, captured vents should be used to allow venting to occur outside.
2. Pressure relief devices shall comply with national or international standards, such as *ASME Boiler and Pressure Vessel Code*, Section VIII, "Pressure Vessels."
3. Relief valves, rupture disks, or both shall be installed on tanks, lines, and component systems to prevent overpressurization. The capacity of a pressure-relief device should be equal to that of all the vessel and piping systems it is protecting. These devices must be reliable and the settings must be secured against accidental alteration.
4. Relief valves and similar devices should not be considered to be secondary or passive components in the test hardware design. It should be assumed that they will function at some time. Personnel safety and protection of hardware from damage should be primary design considerations.
5. Relief valves shall be functionally tested to verify that design requirements are satisfied, including testing in both the static and dynamic states. Relief valves shall be functionally tested to verify design requirements are satisfied.
6. Relief valve riser pipes on high-pressure oxygen systems shall be analyzed for resonant tuning.

7. All sections of a pipeline system and all equipment in an oxygen system that may be removed for inspection, maintenance, or replacement shall be adequately protected by pressure-relief devices and should have vent and purge valves to allow for blow-down and purging.
8. Relief valves and associated piping should be constructed entirely of approved materials.
9. Inherent ignition hazards are associated with self-activating relief devices in oxygen systems; therefore, relief devices and any vent lines connected just downstream should be built from the most ignition-resistant materials available and positioned in remote locations or isolated from personnel by barriers or shields.
10. Vent and relief valves should be located outdoors to discharge in a safe area. If they cannot be located outdoors, the discharge should be piped outdoors. Lines leading to and from relief devices should be of sufficient size to ensure the system will not be overpressurized. Piping and component orientation is critical, and consideration must be given to water aspiration or rain entering a system and thereafter freezing out against relief devices. Bug screens, thrust balancing, and the potential to backstream contaminated water into systems should also be addressed. Discharge lines should be fabricated from ignition-resistant materials. Outlet ports should be checked to ensure they cannot inadvertently become plugged. Resonant frequency or coupling in captured vent systems, which can aggravate a failure, should also be considered.
11. The calculations that form the basis for pressure relief system design shall be maintained. Such data should include:
    - maximum operating pressure under both normal and abnormal operating conditions,
    - location and condition of relief devices,
    - suggested methods of installation,
    - testing frequency,
    - possible hazards caused by system operation, and
    - materials of construction.
12. Relief devices should be checked before use to prevent possible installation of incorrect pressure-rated devices.
13. Caution should be used when captured relief vents are connected in a common manifold. The manifold and the vent line must be capable of handling the total flow from all of the relief valves that are connected to the manifold. In addition, resonance, flow oscillations, water hammer, etc. could be issues in a common manifold and vent line.
14. The minimum relieving capacities of the relief devices should be as determined by the flow formulas in applicable codes and specifications, such as *ASME Boiler and Pressure Vessel Code,* Section VIII, Division, "Pressure Vessels," ASME B31.3, and Refs [4] and [13]. Safety relief valves and frangible disks shall be designed and installed in accordance with applicable codes and specifications, such as DOT regulations, especially 49 CFR [14]; *Pressure Relief Device Standards—Part 1—Cylinders for Compressed Gases* (CGA S-1.1); *Pressure Relief Device Standards—Part 2—Cargo and Portable Tanks*† for Compressed Gases (CGA S-1.2); and *Pressure Relief Device Standards—Part 3—Compressed Gas Storage Containers* (CGA S-1.3).

Filters and Strainers

In addition to the guidelines in the section "Design for Cleanliness and Maintaining Cleanliness," the following guidelines should be applied to filters and strainers in oxygen systems:

1. Filter elements should not be fragile or prone to breakage. If complete blockage is possible, the elements should be able to withstand the full differential pressure that may be generated.
2. Burn-resistant materials, such as nickel, bronze, or Monel, should be used for filter elements because they typically have high surface-area/volume ratios. The use of materials with relatively low combustion resistance, such as stainless steel mesh, is not recommended.
3. Conical strainers in gaseous-oxygen service are normally designed as a perforated cone with a mesh-screen overlay. The strainer should be positioned in the piping system such that the mesh will be on the outside of the cone with the cone projecting upstream. The mesh of a conical strainer is regarded as an area of high risk because it experiences direct impingement and also captures and accumulates debris and particles.
4. Conical-strainer cones should be designed with a high buckling or collapse pressure, preferably 100 % of the system maximum allowable working pressure as determined by the setting of the pressure relief valve. If the buckling pressure is less than 100 %, a pressure differential indicator with an alarm should be installed to warn operating personnel that the element is approaching a failure condition and that corrective action is required. These precautions work to avoid collapse of the cone and the passage of fragments through the piping system that create a potential fire hazard.

Electrical Wiring and Equipment

Electrical equipment and fittings used in oxygen-enriched atmospheres should be designed for use at the maximum proposed pressure and oxygen concentration. Further guidelines for the installation of electrical wiring and equipment for use in oxygen-enriched atmospheres are found in NFPA 53 and may be applied with appropriate engineering discretion and approval of the authority having jurisdiction.

Design for Low-Pressure Oxygen Systems

Although the design still requires a high level of attention to hazards, the ignition hazards are lessened in low-pressure oxygen systems. Particle impact ignition is less likely to occur as a result of the reduced flammability of many system metals. In addition, the heat of compression ignition hazard is greatly decreased as a result of reduced pressure ratios and subsequent heat energy available in the gas when it is compressed. In some instances, this decrease in the heat of compression hazard may lead to cleanliness requirements that are not as stringent as for higher-pressure oxygen systems.

Design for Cryogenic Oxygen Systems

In addition to the oxygen system design guidelines previously discussed, specific considerations for cryogenic applications are described as follows. Liquid cryogens† can easily vaporize and produce high-pressure regions in systems assumed to be at low pressure, a phenomenon known as liquid lockup. If these potentially high-pressure conditions are not considered when designing the system, serious hazards can exist. Refer to Chapter 8 for tankage considerations.

Design Considerations for System Installations

Design considerations relating to system installations are noted below.

1. Thermal conditioning, or controlling the rate of temperature change, of cryogenic systems is highly recommended during cool down and, possibly, during warm-up operations. LOX

system components are subjected to a large temperature change and may undergo excessive thermal gradients when they are cooled from ambient to LOX operating temperature[†]. This temperature change, and possibly high thermal gradients, also exist when components are warmed from LOX to ambient temperature; however, this process usually occurs more slowly and large thermal gradients are less likely to occur. Large thermal gradients can result in high thermal stresses and possibly even rupture. Consequently, the rate of cooling (and possibly warming) is usually controlled between the lower and the upper flow rate limits to prevent thermal shock, bowing of lines, overstressing, pressure and flow surges, and high velocity boil-off gases. Thermal conditioning can be performed with either cold gaseous or liquid nitrogen or oxygen.

The largest circumferential temperature gradients, and consequently the highest added stresses, occur during stratified two-phase flow. Stratified two-phase flow occurs when liquid flows along the bottom or outer radius of a pipe or bend and gas flows along the top or inner radius. Such conditions have caused significant pipe bowing in large cryogenic systems. Stratified flow has been found to decrease with increasing flow rate. During cooldown, a minimum flow rate, such as shown in Fig. 5-12, should be maintained to avoid pipe bowing. However, cooling too rapidly can cause large radial temperature gradients by quickly cooling the inner wall of thick-wall sections, such as flanges, while the outer wall remains near ambient temperature. An example of the maximum cooldown flow rate limits for a 304 stainless steel flange for liquid hydrogen and liquid nitrogen is shown in Fig. 5-13. The upper and lower estimates shown in Fig. 5-13 represent the range of variables involved in calculating the flow rate limit. The limits for liquid nitrogen may be used as an initial estimate for LOX flow rate limits; however, specific calculations for LOX should be made. It is prudent, and may be necessary, to design the components to be able to sustain the loads created if the cooldown rate is not, or cannot be, controlled [15-17].

2. The startup of LOX pumps and pressure let down valves should be carefully analyzed and accomplished because cavitation from improper cooldown can increase fluid pressures and damage parts, leading to premature failure or fretting of components. It can also create startup instabilities, leading to frictional ignition.
3. Condensation on external surfaces should be avoided because cryogenic temperatures can freeze water and other vapors and create falling ice or other hazards.
4. Condensation on internal surfaces should be avoided because the cryogen can freeze water and other vapors.
    a. Long-term storage of LOX and extended cyclic fill operations may concentrate low volatile impurities in the storage container[†] as a result of the loss of oxygen by boil-off. Therefore, the oxygen may not be satisfactory on the basis of the original specifications. Pressure relief valves or other means should be designed to prevent the back aspiration of volatile impurities into storage systems.
    b. The contents of vessels should be periodically analyzed at low spots to ensure conformance to the specifications. To limit the accumulation of contaminants from cyclic fill-and-drain operations, an inspection and system warmup cycle should be established based on the maximum calculated impurity content of the materials going through the tank or system. This should allow frozen water and

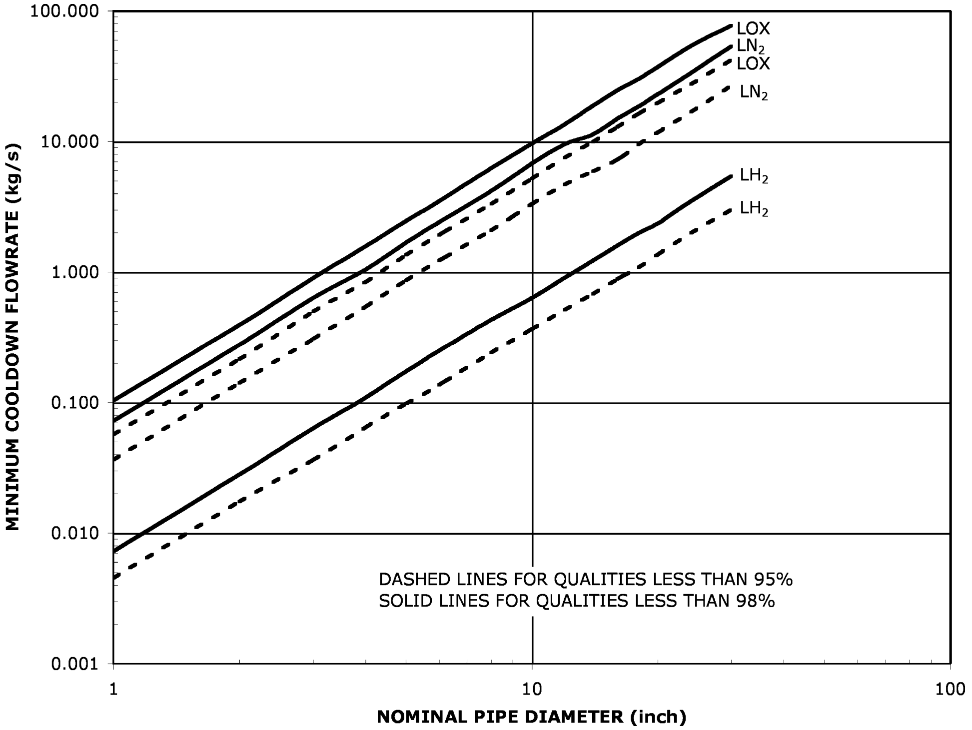

Fig. 5-12—Minimum flow rate for nonstratified, two phase hydrogen, nitrogen, and oxygen flow for pipeline fluid qualities of 95 % and 98 %. The liquid and gas phases in the two-phase flow are assumed to be saturated at the normal boiling point [15,16].

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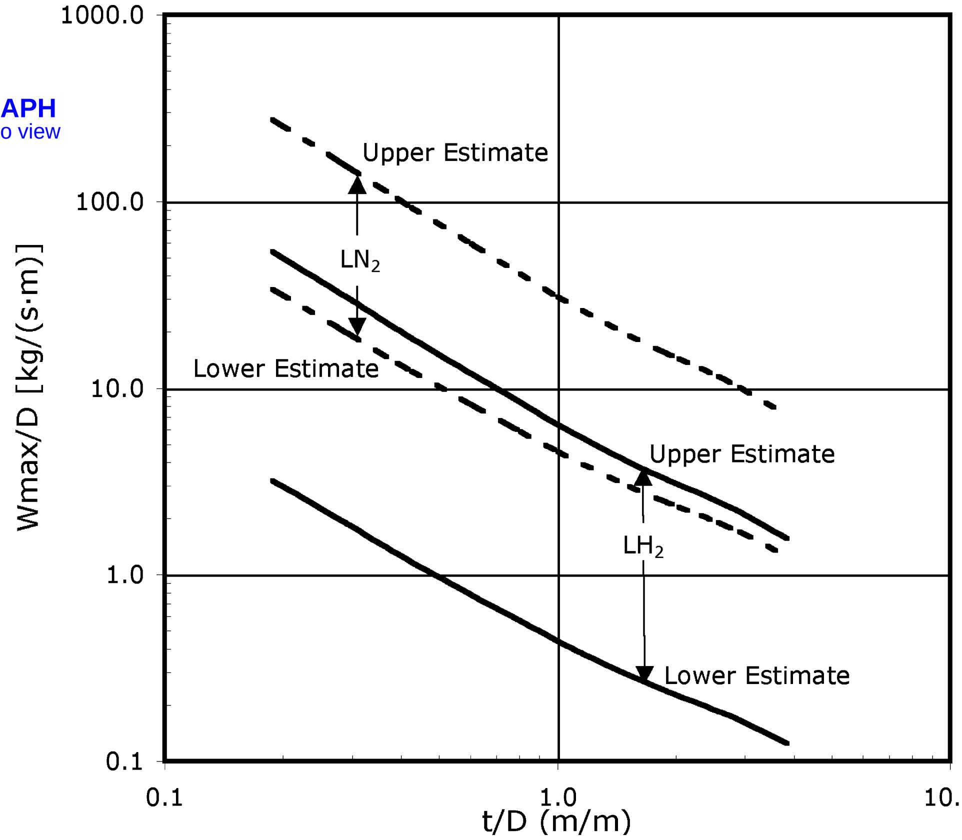

Fig. 5-13—Liquid hydrogen and liquid nitrogen flow rate limits to avoid excessive cooldown stresses in thick-wall 304 stainless steel piping sections, such as flanges. Upper and lower estimates represent difference in variables, such as heat transfer correlation and limiting stress values. t = maximum radial thickness of the flange wall (m); D = inside diameter of the flange (m); and Wmax = cooldown flow rate limit (kg/s) [15].

gas contaminants to vaporize and be purged from the vessels. Where practical, a mass balance of measurable contaminants should be made for all fluids entering or leaving the system or the component.

Design Specifications

The concerns are similar to those for other oxygen systems with the addition of material embrittlement because of the low temperatures. Cracking and fractures of soft goods and metals can cause premature failures.

Hazard Considerations

Cryogenic hazards, such as cold injuries from exposure when handling equipment with LOX, should be considered. Additionally, LOX-containing equipment should not be operated over asphalt pavement because of spill hazards and the potential for ignition of oxygen-enriched asphalt. LOX spills on pavements such as asphalt have resulted in impact-sensitive conditions that caused explosions from traffic or dropped items [18]. When use of LOX systems over asphalt cannot be avoided, all asphalt areas under uninsulated piping should be protected to prevent contact with oxygen.

Combustion and even detonation hazards can also exist with the contact of liquid oxygen and hydrocarbon fuels. Hydrocarbon fuels have broad flammability limits and very low minimum ignition energies in oxygen. Fuels such as methane can be completely miscible in liquid oxygen. Systems in which oxygen is produced through pressure swing adsorption of air and then liquefied should be assessed for the presence of hydrocarbon contaminants in the air source. This is critical in air separation technology to minimize explosion and detonation hazards.

LOX Vessel Considerations

The safe containment of LOX requires particular attention to design principles, material selection and fabrication, inspection, and cleaning procedures. The operation and maintenance of LOX vessels must be sufficiently detailed to ensure safe and reliable performance.

LOX storage vessels typically include an inner tank to contain the LOX and an outer jacket. The space between the inner tank and the outer jacket provides thermal insulation to reduce heat transfer from the outside of the outer jacket to the LOX inside the inner tank. A variety of thermal insulation techniques may be used, such as powders, vacuum, and multilayer paper/foil.

The construction, installation, and testing of LOX storage vessels should conform to requirements established by the authority having jurisdiction and to applicable codes and standards. Typical oxygen storage vessel specifications are given in Appendix C.

The tank outlet should be clearly marked and should indicate whether the contents are gaseous or liquid. The hazard potential of opening the system will differ significantly between pressurized gases and liquids. Emergency isolation valves that function to stop liquid flow from the tank in case of a line failure downstream should be provided as close to the tank annulus as possible. The emergency valve should be quick-acting and must be operable under conditions of maximum flow through a ruptured pipe. A label shall be provided listing the content, capacity, operating pressures†, direction of flow, dates of proof tests†, and dates of in-service inspection and recertification†.

Tank truck specifications for LOX are described in Chapter 9 of this manual, *CGA Standard for Insulated Cargo Tank† Specification for Nonflammable Cryogenic Liquids* (CGA 341), *49 Code of Federal Regulations (CFR) 171-180* [14], and Ref [19]. The vibration and sloshing of LOX should be minimized by careful selection of running gear and placement of inner tank baffles and supporting systems. Vibration can be reduced by controlling unwanted expansion and contraction.

The tank pressure or liquid should not open the isolation valves. The valves should fail closed on loss of power or control signal. The emergency isolating valve should be in addition to any normal isolating valve required for operation. Top-entry connections that extend into the liquid should also be protected by emergency valves.

For more information, see *ASME Boiler and Pressure Vessel Code*, "Alternative Rules" Section VIII, Division 2.

LOX Piping System Design Considerations

Considerations applicable to LOX piping systems include the following:

1. Many LOX lines are vacuum-jacketed or insulated to reduce heat input. Jacket design should allow the jacket to follow natural thermal displacement of the inner line. Piping systems should be sufficiently flexible to prevent thermal expansion or contraction from causing piping failures or leaks. Piping systems that are used infrequently or that are short may be uninsulated. Long pipe runs should be vacuum-insulated. Bellows sections in vacuum jackets should be used to compensate for contraction and expansion.
2. Horizontal pipelines may experience cryogenic bowing because of stratified flow or because a single liquid layer exists only on the bottom of the pipe. The large forces normally generated by bowing should be considered when designing pipe-guide supports for bellows expansion joints. The design of pipe-supporting systems should be based on all concurrently acting loads transmitted into such supports. These loads should include weight, service pressure and temperature, vibration, wind, earthquake, shock, and thermal expansion and contraction. All supports and restraints should be fabricated from materials suitable for oxygen service.
3. Each section of liquid-oxygen piping capable of being isolated should be considered a pressure vessel with a source of heat into the line. A heat leak can cause the pressure to increase significantly as trapped fluid warms to atmospheric temperature. Therefore, each such section must be equipped with protective devices for overpressure† control, particularly from overpressures caused by insulation failures. The overpressure protection devices must be located in such a manner that all parts of the system are protected from overpressure.
4. Low points (traps) on liquid discharge piping are to be avoided to prevent accumulating contaminants and trapping liquid. If traps are unavoidable, low-point drains should be provided and designed so that all fluids drain on oxygen-compatible surfaces. All tubing ends, fittings, and other components used in oxygen systems should be protected against damage and contamination.
5. Where practical, avoid cavitation in LOX; where impractical, use the preferred materials listed in Ref [4].
6. Transition joints, such as aluminum to stainless steel, should not be used in LOX transportation system piping. Large temperature cycles and severe mechanical jolts have frequently caused failure of such joints.
7. The connection of a LOX vessel to rigidly mounted facility piping should use a flexible metal hose that is properly supported and anchored, insulated for low-temperature service, and rated for use at the MAWP of the fill line. Recommendations for flexible hoses include a maximum allowable slack of approximately 5 % of the total length. For greater safety, the hose restraints should be at least 50 % stronger than the calculated impact force on an open line moving through the flexure distance of the restraint.
8. Fill connections for loading and transfer from transportation systems shall terminate in the fixed ends of hose unions that use a unique design configuration (for example, keyed) to prevent filling oxygen tanks with other fluids. Standard cryogenic fluid transfer connections, such as those described in *CGA Standard Cryogenic Liquid Transfer Connections* (CGA Pamphlet V-6), should be used whenever possible to prevent cross connection of filling systems for oxygen and other fluids.

Component and Systems Design Considerations

The following are some component and systems design considerations for LOX systems.

1. Overpressure protection by rupture disk, relief valve, or both should be installed in any section of a storage vessel or piping where LOX or cold gas can be trapped or otherwise isolated. This condition exists most often between two valves in series.
2. Avoid fluid expansion regions where the fluid can vaporize. If expansion is allowed to occur, the resulting fluid downstream will have two phases, gas and liquid, and the following situations could occur:
   a. Increased pressure caused by vaporization.
   b. High surge pressures caused by liquid hammer effects; mechanical damage as well as rapid compression heating and ignition of soft goods can occur if fluid hammer against gas pockets is not eliminated in oxygen systems.
   c. Decreased performance of metering valves and other components sensitive to fluid properties.
3. Avoid cavitation of rotating equipment because the high pressures generated by rapid vaporization during cavitation can exceed the hardware rated capability. Additionally, dynamic instabilities can be created that allow rotating shafts and impellers to wear against housings, leading to failures from frictional heating.
4. Avoid geysering† of LOX and GOX, caused by gas bubble formation in flowing liquid systems, because this can create heat of compression on soft goods. Geysering can create a fluid hammer condition with rapid overpressurization of components, leading to bursting of pressure-containing components.
5. Prevent hydrostatic overpressurization of tanks and dewars during filling operations by using an overfill protection method to maintain an adequate ullage volume.
6. Valves that, from a safety viewpoint, are suitable for high-pressure GOX service may also be suitable for high-pressure LOX service. The selection of a valve for liquid service should include consideration of possible mechanical problems such as contraction strains, icing, and glass transition temperatures of polymers. Extended-stem gate, globe, or

ball valves are satisfactory. Valves must be provided with venting features to prevent trapping cryogenic liquid or cold gases. Valves, particularly ball and gate valves, used in LOX service should be designed to eliminate a trapped volume between the upstream and downstream seats when in the closed position. Liquid trapped between the seats of a valve will expand when heated and can rupture the valve and piping system.

7. A check valve should be placed in a LOX tank fill line to prevent the tank from draining in the event of a fill line failure or improper operation of the fill line isolation valve.
8. For protection against rupture hazards, all enclosures that contain liquid or that can trap liquids or cold vapors should have rupture disks or relief valves installed.

Electrical Design Guidelines

The following electrical design guidelines apply to LOX systems.

1. Whenever possible, electrical wiring inside LOX tanks should be encased in hermetically sealed conduits or conduit inerted with helium or nitrogen gas. If possible, the instruments, switches, flow sensors, and electrical devices should be designed in modular structures, hermetically sealed, and inerted with nitrogen or helium.
2. If electric heaters are used to provide the primary heat source in a LOX vaporizer, the vaporizing system shall be electrically grounded [29CFR1 910.104, NFPA 50].

Thermal Insulation

The following guidelines apply to thermal insulation for LOX systems.

1. Thermal insulation should be installed on LOX and cryogenic temperature GOX components of oxygen systems to prevent condensation and ice on their external surfaces and to reduce heat input into the LOX.
2. Thermal insulation used in an oxygen system shall be of noncombustible material. Insulation that is enclosed in a pressure-tight casing shall be equipped with suitable safety pressure relief devices [29CFR1 910.104, NFPA 50].
3. Oxygen system components subject to cryogenic temperatures should be insulated or guarded to prevent personnel from contacting cold surfaces.

Pressurization and Purge Gases

Gases such as nitrogen that are used for pressurization or purging in an oxygen system should not contribute to system contamination. Contaminants such as hydrocarbons and gases that could condense or freeze should be eliminated to the extent possible. The authority having jurisdiction should establish appropriate specifications for the gases used for pressurization and purging.

Space Applications and Considerations

The first use of LOX as a propellant was by Robert Hutchings Goddard in the early 1920s in conjunction with gasoline as the fuel. The system was self-pressurizing by LOX expansion. These concepts and designs were later used in German V-2 rockets. Aside from its use as an important oxidizer, the primary purpose of LOX in space applications is to support environmental control and electrical power systems such as fuel cells. Cryogenic storage of the oxygen is especially useful in space applications because of the high density and low storage pressure that results in the use of smaller containers, lower container strength requirements and, therefore, lower associated tank weights. These considerations made the use of cryogenic oxygen, stored within dewars, highly effective in many successful missions including the spacecraft of the Gemini and Apollo programs.

The difference in the design factors for a LOX system for use in space versus terrestrial use is primarily dictated by the reduced temperature, pressure, and gravity environment of space, the often adverse environment of operation (thermal, pressure), and the inability to service or maintain the equipment. These factors will often dictate system design changes to normal terrestrial systems to ensure that a given amount of liquid is properly drawn from the dewar when required from a system that will often have a disorderly orientation of the liquid phase and vapor phase present.

Other specific considerations for these systems include the following:

1. Mission considerations:
   - Reliability,
   - Operational pressure of system [resulting in single-phase (supercritical) or two-phase (subcritical) conditions],
   - Quantity determination and accuracy, and
   - Pressure control.
2. LOX storage considerations:
   - Reproducibility (of system performance),
   - Shelf-life,
   - Weight,
   - Materials, and
   - Envelope constraints by spacecraft.
3. Performance considerations:
   - Standby time from fill to deployment,
   - Fluid quantity,
   - Fluid usage rate,
   - Power requirements, and
   - Environmental conditions.

Design to Manage Fires

In conjunction with the use of good design practices to reduce the likelihood of ignition in oxygen systems, designers should provide for the management of fires in the system. The following guidelines will help ensure the safety of personnel and equipment in case of a fire.

1. Provide for accessible or remote shutoff, or both, of the oxygen supply. Shutting off the oxygen supply is one of the most important procedures to limit the damage from a fire.
2. When possible, design for automatic source isolation in the event of a downstream fire or system failure. For example, a device may be used that will stop flow as a result of the high flow that occurs because of a fire or system failure. Such devices are known as autostop valves, excess flow valves, or flow fuses.
3. Ensure easy access and escape for personnel in the area. It should be easy for people to escape from the fire, and their natural path of egress should be to a safe location away from the oxygen system.
4. Reduce personnel exposure by minimizing hands-on operation and using barriers to protect personnel.
5. Use remote operation for the first oxygen exposure of a system or component.
6. Design for fire containment using methods such as fire break, fire blow out, or remote operation. Fire breaks and fire blow outs are both methods to prevent an existing fire from propagating further in the system. An example of a fire break is an ignition-resistant component, such as a sintered

bronze filter, which could prevent the fire from propagating further. An example of a fire blow out is a fitting, such as an elbow, that would cause the fire to breach the system and not propagate further downstream. It is appropriate to use fire-resistant materials that may serve as a barrier at the locations of fire blow outs.

7. Ensure fire extinguishers are available to fight secondary fires once oxygen source has been isolated.
8. Minimize flammables near oxygen systems. This includes good housekeeping to ensure that the areas near oxygen systems are clean and free from unnecessary flammable† materials such as gloves, wipes, and oils.
9. Separate bulk oxygen storage from the system and flammable materials.

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6

Cleaning

Introduction

SCRUPULOUS CLEANING IS THE MOST FUNDAMENTAL fire safety measure that can be applied to oxygen systems. The presence of contaminants in otherwise-robust oxygen systems can lead to catastrophic fires. To reduce the hazard†[1] of ignition, components and systems should be initially clean and should be maintained clean during assembly and maintenance. The intent of this chapter is to provide a general overview of cleaning for oxygen systems that can be used alongside other cleaning standards. This chapter begins with an overview of cleaning, followed by descriptions of cleanliness levels, cleaning safety, cleaning methods and aids, and cleaning procedures. This chapter is concluded with guidelines for maintaining cleanliness during the assembly and maintenance of components and systems.

General

Components used in oxygen systems should always be reasonably clean before initial assembly to ensure the removal of contaminants that could potentially cause mechanical malfunctions, system failures, fires, or explosions. Visual cleanliness alone is not a sufficient criterion when dealing with oxygen systems because of the hazards associated with contaminants that cannot be detected with the naked eye. Visual inspection should be preceded by a verified cleaning process. Cleaning is a specialized service that must be performed by properly trained and qualified individuals at approved facilities. In many cases a facility certification is required.

Effective cleaning will:

- remove particulates, films, greases, oils, and other unwanted matter, which are more easily ignited than bulk material, and
- prevent loose scale, rust, dirt, mill scale, weld spatter, and weld flux from clogging flow passages and interfering with component function.

Cleaning should be performed in accordance with procedures established and approved by the authority having jurisdiction. In addition, regulatory authorities may have established cleanliness level requirements for specific components in oxygen systems. For instance, 49 CFR 173.302(5) establishes cleanliness level requirements for aluminum oxygen cylinders.

Cleaning procedures may be based on *Practice for Cleaning Methods for Material and Equipment Used in Oxygen-Enriched Environments* (ASTM G 93), *Cleaning of Equipment for Oxygen Service* (CGA G-4.1/ EIGA IGC 33/06/E), *Oxygen System and Component Cleaning and Packaging* (SAE ARP 1176), and Refs. 1–8. Cleaning procedures, desired cleanliness levels, and cleaning intervals must be established for each system or component based on the materials of construction, design configurations, and operating parameters. The most practical cleaning method for each application should be determined by:

- the types, locations, and quantities of the contaminants to be removed,
- an understanding of the configuration of each part or component, such as dead-end ports, to ensure that cleaning operations can be adequately performed, and
- the required cleanliness level, which may vary depending on industry, application, and system conditions.

Any supplier responsible for cleaning or supplying clean equipment or components for oxygen service should be evaluated. This evaluation should include a review of the following by a knowledgeable person:

- cleaning methods, equipment, and fluids,
- methods used to evaluate cleanliness,
- training and experience of operators,
- methods used to ensure cleanliness during testing,
- records of inspections for cleanliness witnessed or subsequently carried out by the purchaser, and
- methods used to maintain cleanliness up to and during storage.

Cleanliness Levels

Items that should be considered when establishing the cleanliness level include, at a minimum, the flammability of the materials of construction, the presence of ignition mechanisms (evaluated as described in Chapter 4), the use of filters, and the effects of contaminants on downstream components. It has been shown that oil films in the range of 2.5 to 6.5 mg/ft^2 (27 to 70 mg/m^2) are vulnerable to ignition by heat of compression [9], and that as little as 10 mg of particulate has ignited components [10]. The level of contamination necessary to markedly increase the ignition hazard has not been established. Therefore, a good practice is to be conservative by specifying a cleanliness level equal to or better than the level experience has shown to be acceptable for the application.

Cleanliness levels typically are specified with a number and letter, such as 100A. The letter corresponds to the allowable level of nonvolatile residue (NVR), which gives an indication of the amount of oils, greases, and hydrocarbons present on the parts. As shown in Table 6-1, “Level A” corresponds to several different amounts of allowable NVR, depending on what cleaning specification is used. Therefore, it must be ensured that the desired level of NVR is obtained by paying close attention to what specification is used. The number corresponds to the maximum allowable particle size, and for any given level there is a distribution allowed according to the size of the particulate, as shown in Table 6-2.

Typical NASA, ASTM, and CGA cleanliness levels are given in Tables 6-1 and 6-2. The maximum allowable NVR on parts

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[1] The † indicates a term defined in the Glossary (Appendix G).

TABLE 6-1—Typical NVR level specifications.

	NASA Specifications [3] Maximum Quantity NVR		ASTM G 93 Specifications NVR Remaining		EIGA IGC 33/06 Specifications Acceptable Contamination Level				CGA G-4.1 Specifications Acceptable Contamination Level	
					Systems Below 3 MPa (345 psi)		Systems Above 3 MPa (345 psi)			
Level	mg/m^2	mg/1.08 ft^2	mg/m^2	mg/ft^2	mg/m^2	mg/ft^2	mg/m^2	mg/ft^2	mg/m^2	mg/ft^2
A	10[a]	1	<11	<1	...	...	...	...	...	...
B	20	2	<32	<3	...	...	...	...	...	...
C	30	3	<65	<6	...	...	...	...	...	...
D	40	4	<215	<20	...	...	...	...	...	...
E	...	...	<538	<50	...	...	...	...	...	...
F	...	...	Specified by user or supplier		...	...	...	...	...	...
...	...	...	...	...	500[b]	46[b]	200[b]	19[b]	500[c]	47.5[c]

[a] NVR level commonly specified for NASA oxygen systems.

[b] EIGA IGC 33/06 also notes that no drops of water can be visible. Further, it states that "lower figures could be requested depending on the specific application (type of fluid, temperature, pressure, flow, velocity, product purity), or effects like migration."

[c] CGA G-4.1 states that this value "could be more or less depending on specific application (state of fluid, temperature, and pressure."

used for oxygen service is normally 1 mg/ft^2 (~10 mg/m^2) for aerospace applications and 50 mg/ft^2 (~538 mg/m^2) for industrial applications. Particulate requirements for specific components and systems depend on the application; levels 50, 100, and 300 are most common. In some cases, cleanliness requirements may be loosened for low-pressure systems.

Cleaning Safety

Cleaning Operations

Cleaning operations should be directed by an experienced individual. All operators should be instructed in the safe use of the cleaning agents and all applicable hazard communication standard requirements such as Material Safety Data Sheets (MSDSs). Operators should also be given written standard operating procedures that identify safety considerations wherever special safety considerations are involved.

The use of hazardous cleaning chemicals should be kept to a minimum. Appropriate spill response training and spill control equipment must be provided for the chemical types used. Used cleaning solutions should be disposed of in accordance with appropriate federal, state, and local hazardous waste regulations.

Cleaning of oxygen components intended for breathing systems requires special consideration in the selection of cleaning agents. Cleaning agents that are toxic should be avoided whenever possible. If toxic cleaning agents must be used, it should be purposefully ensured that the cleaning agent residue is removed.

Ventilation

All areas where cleaning compounds and solvents are used should be adequately ventilated to protect operators from hazardous airborne contaminants. Local exhaust ventilation, together with enclosures, should be used whenever feasible. General dilution and general ventilation provide much less protection for personnel and may result in contamination of clean room atmospheres. Outdoor cleaning operations should be located so operators can work upwind of solvent vapor accumulations. Chemical containers should be clearly identified, labeled, and sealed when not in use.

Care should be exercised to ensure that parts to be welded are free of cleaning chemicals. Appropriate respiratory protection must be used when performing operations involving personnel exposure to heated chemicals. Respiratory protective equipment should be used as a supplement to engineering controls as necessary to prevent or control exposures of personnel to airborne contaminants. Engineering controls, such as enclosures, local exhaust ventilation, or vapor degreasers, should be used as the primary means of exposure control. Atmospheric monitoring (area and/or personal, as applicable) may be required to evaluate exposures to hazardous airborne contaminants or to detect otherwise dangerous levels of hazardous materials in the atmosphere.

Personal Protective Equipment

Personal protective equipment, such as face shields, gloves, respiratory protection, and lab aprons, should be worn in accordance with applicable safety guidelines as specified by the authority having jurisdiction, Occupational Safety and Health Administration (OSHA) regulations, and MSDSs. Operable emergency eyewash units and deluge showers must be provided in the immediate areas where chemicals are used. Fire suppression equipment appropriate for the fire hazard (e.g. fire extinguishers, sprinkler systems, etc.) must be provided and operational.

Cleaning Methods and Aids

Cleaning methods generally may be classified as chemical or mechanical. In a given cleaning process, a combination of both chemical and mechanical cleaning methods may be used. When selecting cleaning methods, multiple factors should be considered, including:

- initial condition of the parts to be cleaned,
- cleanliness requirements,
- cleaning ability of the agent,
- oxygen compatibility of the agent,
- effect of the cleaning procedure on the parts to be cleaned,

TABLE 6-2—Typical particulate specifications for various oxygen cleaning standards.

	NASA Specifications [3]		ASTM G 93 Specifications		EIGA IGC 33/06 Specifications		CGA G-4.1 Specifications[a]	
Cleaning Test Level	Particle Size Range µm	No. Particles per 0.1 m^2 (1 ft^2)	Size Range µm/100 mL	No. Particles allowed per 0.1 m^2 (1 ft^2)	Particulate Allowed for Systems Below 3 MPa (435 psi)	Particulate Allowed for Systems Above 3 MPa (435 psi)	Particle Size Range µm	No. Particles per 1 m^2 (11 ft^2)
…					Single small chips or fibers[c]	Single very small chips or fibers[c]	1 000 (maximum allowable size) Fibers no longer than 2 000[d]	
							500 through 1 000	≤ 215
1 000	<500	Unlimited[b]						
	500 through 750	34						
	>750 through 1 000	5						
	>1 000	0						
500	<100	Unlimited[b]	× <100	No limit				
	100 through 250	1 075	100< × <175	100				
	>250 through 500	27	175< × <300	20				
			300< × <500	5				
	>500	0	× >500	0				
			fibers	100				
300	<100	Unlimited[b]	× <100	No limit				
	100 through 250	93	100< × <175	20				
	>250 through 300	3	175< × <300	5				
	>300	0	× >300	0				
			fibers	25				
200	<50	Unlimited[b]						
	50 through 100	154						
	>100 through 200	16						
	>200	0						
175			× <50	20				
			50< × <100	5				
			100< × <175	1				
			× >175	0				
			fibers	5				
100	<25	Unlimited[b]						
	25 through 50	68						
	>50 through 100	11						
	>100	0						
50	<10	Unlimited[b]						
	15 through 25	17						
	>25 through 50	8						
	>50	0						
25	<5	Unlimited[b]						
	5 through 15	19						
	>15 through 25	4						
	>25	0						

[a] CGA G-4.1 lists these specifications as "typical" and not as a requirement.

[b] "Unlimited" means particulate in this size range is not counted; however, if the accumulation of this silt is sufficient to interfere with the analysis, the sample shall be rejected.

[c] Clusters of fibers, other particles, and dust must not be visible.

[d] There shall be no accumulation of lint fibers.

- cost effectiveness, including disposal,
- safety of the cleaning agents, and
- availability of the cleaning agents.

Mechanical Cleaning

Mechanical cleaning methods use mechanically generated forces to remove contaminants from components. Sensitive surfaces must be protected before mechanical cleaning methods are applied. It should be ensured that any mechanical cleaning process used does not cause the parts or components to become noncompliant with required standards or specifications. If physical alteration of parts or components occurs, the parts or components should be checked to verify that they meet required standards or specifications. If there is any concern about the effects of mechanical cleaning on parts or components, the recommendations of the manufacturer should be followed. Various mechanical cleaning methods are described herein.

Ultrasonic Cleaning

Ultrasonic energy can be used with a variety of chemical cleaning agents to effect intimate contact between the part and the cleaning agent. Ultrasonic agitation aids removal of lightly adhered or embedded particles from solid surfaces. It is generally used in solvent cleaning of small parts, precious metal parts, and components requiring a very high degree of cleanliness. See *ASTM Practice G 131* for an ultrasonic cleaning procedure.

Abrasive Blast Cleaning

Abrasive blast cleaning involves the forceful impingement of abrasive particles against surfaces to be cleaned to remove scale, rust, paint, and other foreign matter. Abrasive blast cleaning can affect dimensions, tolerances, and surface finishes. The abrasive may be either dry or suspended in liquid. Typical abrasive particle materials include metallic grit and shot, natural sands, manufactured oxide grit, carbide grit, walnut shells, and glass beads. The specific abrasive particle material used should be suitable for performing the intended cleaning without depositing contaminants that cannot be removed by additional operations, such as high-velocity blowing, vacuuming, and purging. Various systems are used to propel abrasives, including airless abrasive blast blades or vane-type wheels, pressure blast nozzles, and suction blast nozzles. Propellant gases should be verified as oil-free.

Wire Brush or Grinding Cleaning

Wire brushing or grinding methods are used to remove excessive scale, weld slag, rust, oxide films, and other surface contaminants. These methods generally incorporate a power-driven wire, nonmetallic fiber-filled brush, or an abrasive wheel. Wire brushes may be used dry, or wet as when the brushes are used in conjunction with alkaline cleaning solutions or cold water rinses. Wire brush and grinding cleaning methods may imbed brush or grinding material particles in the cleaning surface, and they can affect dimensions, tolerances, and surface finishes. Cleaning brush selection depends on the component or system parent material. Nonmetallic brushes are suitable for most materials to be cleaned. Carbon steel brushes should not be used on aluminum, copper, and stainless steel alloys. Any wire brushes previously used on carbon steel components or systems should not be subsequently used on aluminum or stainless steel.

Tumbling

Tumbling, sometimes called barrel or mass cleaning, involves rolling or agitation of parts within a rotating barrel or vibratory tubs containing abrasive or cleaning solution. The container action, rotation, or vibration imparts relative motion between the components to be cleaned and the abrasive medium or cleaning solution. This method may be performed with dry or wet abrasives. The part size may vary from a large casting to a delicate instrument component; however, mixing different components in one barrel should be avoided, as damage may occur from one component impacting on another of a different type. Barrel cleaning may be used for descaling, deburring, burnishing, and general washing. Some factors to consider in barrel cleaning are component size and shape, type and size of abrasive, load size, barrel rotational speed, and ease of component/abrasive separation.

Swab, Spray, and Dip Cleaning

Swab, spray, and dip cleaning are methods of applying cleaning solutions to component surfaces, and each method has its particular advantages. Swabbing is generally used on parts or components to clean small select areas only. Spraying and dipping are used for overall cleaning. These methods are generally used with alkaline, acid, or solvent cleaning methods discussed in later sections.

Vacuuming and Blowing

Vacuuming and blowing remove contaminants with the use of currents of clean, dry, oil-free air or nitrogen. These methods may be used to remove loose dirt, slag, scale, and various particles, but they are not suitable for removing surface oxides, greases, and oils.

"Pig" Cleaning

Pigs are piston-like cylinders with peripheral seals that can be pushed through pipelines using compressed gas pressure, typically nitrogen. Pigs may be used to clean long, continuous pipelines in situ. Pigs may be equipped with scrapers or wire brushes, and pairs of pigs may carry slugs of liquid cleaning agents between them. Hence, a train of four pigs can transport three isolated slugs of solution through a pipeline to produce various levels of cleaning and rinsing.

Chemical Cleaning

There are various types of chemical cleaning agents, including, but not limited to, aqueous-based, solvent-based, and chemical-based. Chemical cleaning agents should ideally have good degreasing properties, be noncorrosive, not leave behind any residue, and be compatible with oxygen and commonly used materials of construction. Corrosion, embrittlement, or other surface modifications are potentially harmful side effects of chemical cleaning agents. The use of chemicals can alter the microstructure of some materials, and may compromise the mechanical properties of the material. Several ASTM standards that may assist in selecting cleaning agents are *Standard Practice for Preparation of Contaminated Test Coupons for the Evaluation of Cleaning Agents* (G 121), *Standard Test Method for Evaluating the Effectiveness of Cleaning Agents* (G 122), *Standard Guide for Selection of Cleaning Agents for Oxygen Systems* (G 127). In addition, *Cleaning of Equipment for Oxygen Service* (CGA G-4.1/ EIGA IGC 33/06/E) includes information that may be helpful in selecting cleaning agents. Various chemical cleaning methods are described below.

Aqueous and Semiaqueous Cleaning

Aqueous systems have few problems with worker safety compared with most other solvents. They are not flammable† or explosive, and toxicity is low for most formulations. Aqueous cleaning methods are based on achieving an interaction between the cleaning solution and the contaminant or component surface to effect easy removal of contaminant by subsequent or concurrent mechanical methods. Aqueous systems can be designed to remove particulate and film contamination. They are especially good for removing inorganic or polar materials. Aqueous cleaning functions by several mechanisms other than solvency, including saponification, displacement, emulsification, and dispersion. Ultrasonics are especially suited for aqueous cleaning. Typically, aqueous cleaning methods require hot water dilution and rinsing to achieve the best results. The use of hot water keeps aqueous detergents in solution and prevents them from depositing on surfaces.

Water used for dilution and rinsing of chemical cleaning agents must be as clean as or cleaner than the level of cleanliness desired and free of contaminants to prevent reactions with the cleaning agents. Water should be of a grade equal or better than that specified in ASTM Specification D 1 193, Type II, without the silica analysis. Water with a higher specific resistance may be required for particular applications or cleaning systems.

When aqueous cleaning is used on oxygen system components, rinsing and drying are of critical concern. Both acid and caustic cleaners can damage metal parts if not neutralized upon completion of cleaning. Furthermore, the heat of vaporization for water is an order of magnitude higher than of common chlorofluorocarbon solvents. Therefore, drying after aqueous cleaning requires a higher level of care to ensure that parts are properly free of moisture and vapor.

Aqueous cleaning methods include, but are not limited to, the following.

Hot-Water Cleaning

Hot-water cleaning removes gross organic and particulate contamination from parts by using low-to-moderate heat, detergent, and some mechanical agitation. Because they are milder than some other cleaners, detergent solutions can be used to clean both metallic and nonmetallic parts (but always check with the manufacturer for specific guidance before using any cleaning agent as some may not be appropriate for certain materials). Equipment used during hot-water cleaning may consist of a spray system or a cleaning vat with or without agitation of the solution. Cleaning generally consists of spraying and immersing the items in the solution for a specified period of time. Cleaning may be assisted by brushing parts with suitable brushes and using ultrasonic cleaners to aid in contaminant removal. Hot-water cleaning with detergent can be used where steam is not required to free and fluidize contaminants. Generally, only a small concentration of detergent is required (on the order of 5 to 10 % according to most manufacturers) with a minimum water temperature of 333 K (140°F). Keeping the water temperature hot during cleaning is essential for keeping the detergent in solution. Consideration should be given to the size, shape, and number of parts to ensure adequate contact between part surfaces and the solution. The solution temperature should be as recommended by the cleaning agent manufacturer. Water-soluble contaminants are best removed by prompt flushing with sufficient quantities of hot or cold clean water before the cleaning agents have time to precipitate.

Steam Cleaning

Steam cleaning removes organic and particulate contaminants from parts by using pressure, heat, and sometimes detergents. Some organics are removed by decreasing their viscosity, or "thinning" them, with steam heat. Detergent may be added to disperse and emulsify organics, which allows rinsing of the contaminant by condensed steam. The cleaning system should provide control over steam, water, and detergent flows to maximize efficiency of the detergent's chemical action, the steam heat effect, and the steam jet's scrubbing action.

> *Note: Always use proper protective equipment (eye protection, gloves, splash gear, safety shoes, and face shield) when using cleaning solutions that are acidic or caustic.*

Caustic Cleaning

Caustic cleaning uses highly alkaline solutions to remove organic contamination such as hydrocarbon oils, grease, and waxes. Caustic cleaning is commonly used for corrosion-resistant metals and Teflon. Some common alkaline salts available include lye, soda ash, trisodium phosphate, and sodium polyphosphate. Prepared solutions can be used in static tanks or vessels for component immersion. Alternatively, solutions can be pumped or jetted onto or through components. Depending on the cleaner used, solutions may be alkaline, nontoxic, biodegradable, or noncorrosive. Some detergents may be toxic or corrosive, and detergent properties should be verified by the manufacturer or supplier. The cleaning solution can be applied by spraying, immersing, or hand swabbing. Normally, caustic cleaning solutions are applied at temperatures up to 355 K (180°F). It is important that the cleaning solution reach all areas of the part to be cleaned. The cleaning solution can be reused until it becomes ineffective as determined by pH or contaminant concentration analysis. Experience may establish a contaminant level of the cleaning solution above which a surface cannot be acceptably cleaned.

> *Caution: Alkali and acid cleaners are detrimental to aluminum and most aluminum alloys. The use of such cleaners on aluminum and its alloys may compromise the mechanical properties of the materials.*

Acid Cleaning

Acid cleaning is a process in which a solution of mineral acid, organic acid, or acid salt (often in combination with a wetting agent and detergent) is used to remove oxides, oils, and other contaminants from parts, with or without the application of heat. Acid cleaning must be carefully controlled to avoid damage to the part surfaces, such as undesired etching or pickling. The type of cleaning agent selected will depend on the material or part to be cleaned. Common techniques for acid cleaning are immersion, swabbing, and spraying. Cleaning may be assisted by brushing parts with suitable brushes or using ultrasonic cleaners. After acid cleaning, surfaces must be thoroughly rinsed to remove all traces of acid.

> *Caution: Nitric acid pickling of copper or brass can result in nitrogen dioxide emissions. Local exhaust ventilation must be used as necessary to prevent exposure of personnel to this highly toxic gas.*

Solvents

The effectiveness of solvent cleaning is limited by the ability of the solvent to reach and dissolve any contaminants present. Solvents were once considered to be the principal procedure for removal of soluble organic contaminants from components to be used in oxygen service and were suitable for use with most metals. However, the use and attractiveness of chlorinated solvents as cleaning solutions have been limited by environmental concerns and legislative restrictions. In the past, the organic solvent of choice was chlorofluorocarbon (CFC) 113 (trichlorotrifluoroethane) [11], because it was an ideal solvent for performing particle count and nonvolatile residue analysis. It was also nonflammable and relatively nontoxic. However, production of CFC has been phased out, because the inadvertent release into the atmosphere damages the ozonosphere. Alternative cleaning solvents include hydrochlorofluorocarbons, hydrofluorocarbons, deionized water, isopropyl alcohol, and hydrofluoroethers.

> *Note: Under The Clean Air Act Amendments of 1990 and the U.N. Montreal Protocol, the use of CFC, 1,1,1-trichloroethane, and other ozone-depleting substances has been phased out. Applicable specifications and procedures should reflect these changes. Alternative cleaners for oxygen components and systems will be required.*

In many cases, chlorinated solvents are being replaced by aqueous or semiaqueous detergents or emulsion solutions, often in conjunction with deionized water as part of the process. Some cleaning agents, such as IPA and citrus-based cleaners, are not oxygen-compatible, and their presence in oxygen systems may lead to fires if not properly used or removed [12]. When these types of cleaning agents are used, it is essential that all traces of the cleaner are removed upon the completion of cleaning. Therefore, the procedure used for rinsing, purging, and drying must be carefully qualified. It may be required that detection equipment, such as a halogen leak detector or detector tube for chlorinated solvents, is used to ensure that no trace of the cleaning agents remains. When incompatible cleaners such as IPA are used to flow through fully assembled components or systems, a requirement commonly used for aerospace systems is to perform a hydrocarbon lockup on the parts to ensure that there is no greater than 5 ppm hydrocarbon present. To sample correctly, a lock-up and pressurization procedure, with a time allowance interval, is necessary.

> *Note: If solvents that are not oxygen-compatible, such as IPA, are used, the solvents must be removed and the removal must be verified prior to wetting the system with oxygen. Additionally, flammable cleaning solvents may be absorbed by soft goods and the effects of this absorption must be assessed.*

Before starting any cleaning operation, a reference sample of fresh clean solvent should be set aside to use as a base reference. At intervals throughout the procedure, samples of used solvent can be compared with the reference sample to determine the level of contamination. Methods of determining contamination can be by comparison to the color of the reference sample, by fluorescence under ultraviolet light, by analysis, or by evaporation. Clean glass bottles must be used to hold samples. After completion of any solvent cleaning method, all gross residual cleaning fluid must be drained from the component to prevent drying in pools. The component must then be purged and dried with heated dry, oil-free air or nitrogen. Small components may be air dried if appropriate, so long as they do not become recontaminated.

> *Note: Solvent cleaning solutions often damage plastics and elastomers. The manufacturer should be consulted or sample parts should be tested to ensure that the solvent is not harmful to the item being cleaned.*

Cleaning Aids

Cleaning aids and materials, such as gloves, brushes, wipes, protective garments, packaging materials, and chemicals, must be tested and approved before use in any cleaning operation. All materials used should be clean, lint-free, and free from traces of oil or grease. In general, clean wire brushes manufactured from stainless steel, copper, brass, or bronze wire are recommended. Cloths used for are typically composed of cotton, linen, or paper. The *ASTM Standard Practice for Determination of Soluble Residual Contamination in Materials and Components by Soxhlet Extraction* (ASTM G 120) gives a test method for determining the compatibility of cleaning aids and materials with the solvents used for cleaning.

Cleaning Procedures

No single cleaning procedure is sufficient to meet all cleanliness requirements. Different materials require different cleaning agents, and different procedures must be used for different component geometries. Cleaning may be a single-step or multistep process, depending upon the material involved. It should be taken into account that most cleaning and inspection methods are limited by their ability to reach and dissolve any contaminants present. This section will provide some basic information about cleaning procedures. Further information can be found in ASTM G 93, CGA G-4.1/ EIGA IGC 33/06/E, SAE ARP 1176, and Refs [1–8].

Operations that have the potential to contaminate the hardware, such as hydrostatic testing† and dye penetrant inspection, should be performed before cleaning. Special cleaning procedures may be required to remove heavy oils and greases, rust, welding discoloration, and slag. Components or parts that could be damaged during cleaning should be cleaned separately. Calibration-sensitive items should be processed by qualified personnel. Depending on the design of the component or system, special procedures may also be required. Typical cleaning operations may include the following:

- disassembly and examination,
- precleaning,
- intermediate cleaning,
- final cleaning,
- rinsing,
- inspection and cleanliness verification,
- drying,
- reassembly and functional testing, and
- packaging.

Disassembly and Examination

Whenever possible, oxygen-system cleaning should begin by disassembling all components to their individual parts. If cleaning is attempted by flowing solutions through assembled components, contaminants trapped in component recesses may not be removed effectively, the cleaning solutions may become entrapped in the components, and vulnerable internal parts may be damaged by the cleaning solutions. Therefore, in-situ cleaning of fully assembled systems and flow cleaning of components is not always effective and is not recommended.

> *Note: Whenever possible, all oxygen components and systems should be cleaned at the fully disassembled piece-part level. Cleaning performed by flowing solutions through assembled components and systems is not recommended.*

Components should either be cleaned before assembly or disassembled and their parts grouped according to the method of cleaning. During disassembly, individual parts should be examined to assess their serviceability. If sealing surfaces are damaged or cracked, the component must be repaired or replaced. Special attention should be directed to nonmetals[†] because many solvents will reduce the desired physical properties or destroy the nonmetals. On used and long-stored components, remove and discard all nonmetallic parts if possible, and replace them with new, like parts. Materials used to fabricate replacement parts must have oxygen compatibility equivalent to or better than the original materials.

Precleaning

The purpose of precleaning is to prepare items for cleaning, and the cleaning environment and handling procedure used for precleaning operations are not critical. Precleaning should be used to remove gross contaminants, such as excessive oxide or scale buildup, large quantities of oils and greases, and inorganic particulates. Precleaning reduces the quantity of contaminants, thereby increasing the useful life and effectiveness of the cleaning solutions used in subsequent cleaning operations.

> *Note: Degreasing is required only for heavily oil- or grease-contaminated items. Alkaline cleaners used to clean metallic parts and detergents used to clean both metallic and nonmetallic parts may effectively remove small amounts of grease and oil.*

Metal parts may be degreased by immersing, spraying, or vapor-rinsing the part with a degreasing agent until all surfaces have been thoroughly flushed or wetted. Mechanical aids, such as brushes, may be used to assist in precleaning if necessary.

> *Note: Oxygen-wetted surfaces should be handled only with approved, clean gloves in the following steps.*

Intermediate Cleaning

The intermediate cleaning stage generally consists of subjecting the part to chemical cleaning solutions designed to remove solvent residues and residual contaminants. The cleaning environment and handling procedures used for intermediate cleaning operations are more restrictive than those used for precleaning. The cleaning environment and solutions must be appropriately controlled to maximize solution efficiency, minimize introducing contaminants, and minimize compromising subsequent final cleaning operations.

Various commercially available chemical cleaning solutions can be used in conjunction with mechanical cleaning to remove firmly attached contaminants. Commonly used cleaning solutions include alkaline solutions, acid solutions, mild alkaline liquid detergents, and rust and scale removers. Rinsing and drying are critical steps to perform once intermediate cleaning has been completed. To ensure the proper cleaning has been completed, visual inspection should be conducted by a highly trained inspector. Visual inspection techniques generally consist of white and black light inspections or variations thereof, which are further described below under "Visual Inspection." Cleaning should be continued until the inspector passes the component.

> *Note: Special attention should be directed to nonmetals because many solvents will reduce the desired physical properties or destroy the nonmetals.*

Final Cleaning

When components are required to meet very high degrees of cleanliness, such as in nuclear, space, and electronic applications, they are subjected to a final cleaning stage. This final stage involves the removal of minute contaminants and is generally performed with chemical cleaning methods, rather than mechanical cleaning methods. At this stage of cleaning, protection from recontamination of the component by the cleaning solutions or the environment becomes critical. To obtain very high degrees of cleanliness, the cleaning environments may require strict controls, such as those found in classified cleanrooms. The final cleaning stage incorporates expanded drying and purging operations with a packaging program to protect the component from recontamination.

Rinsing

Rinsing is very important to ensure that chemical or aqueous cleaning agents are removed from the parts. The parts should be thoroughly sprayed, rinsed, or immersed in deionized, distilled, filtered water to remove all the cleaning agent.

> *Note: If solvents that are not oxygen-compatible, such as IPA, are used, the solvents must be removed and the removal must be verified before wetting the system with oxygen.*

Inspection and Cleanliness Verification

Inspection and cleanliness verification is a crucial part of the cleaning process. There are various methods for determining the cleanliness of the cleaned parts, and the selection of an appropriate method should ensure that the method is adequate to detect the required level of cleanliness. Personnel performing inspection and cleanliness verification should be qualified through training and relevant experience.

Common inspection and cleanliness verification methods include qualitative methods and quantitative methods. When qualitative methods, such as visual inspection, the wipe test, and the water break test, are used, they should be used in conjunction with a quantifiable cleaning process or other methods that are able to quantify the amount of contaminants present.

Visual Inspection

Visual inspection should be conducted by a highly trained inspector. In some cases, magnified assistance of otoscope, glass, or boroscope may be required. The parts should be visually inspected under both a strong white and black light for contaminants. If inspection reveals the presence of nonacceptable contamination, such as with oils or greases, residues of cleaning agents, or particles, the item must be partially or even completely recleaned.

Note: Visual inspection with the naked eye will only detect particulate matter larger than 50 µm as well as moisture, oils, and greases. Visual inspection must be used in conjunction with a quantifiable cleaning process or other methods that are able to quantify the amount of contaminants present.

White Light Inspection

White light inspection is the most common test used to detect the presence of contaminants such as oil, greases, preservatives, moisture, corrosion products, weld slag, filings, chips, and other foreign matter. Items should be inspected for the presence of contaminants and for the absence of accumulations of lint fibers. White light inspection will detect particulate matter larger than 50 µm and moisture, oils, greases, etc., in relatively large amounts. Any visual contaminant is cause for recleaning [13].

Black Light Inspection

Many, but not all, common organic oils or greases will fluoresce in the presence of black (ultraviolet) light. Black light inspection allows the detection of such materials when they may not be detectable in white light. To perform black light inspection, surfaces are observed in darkness or subdued light, using an ultraviolet light radiating at wave lengths between 250 and 370 nm and an intensity of 800 µW/cm^2. Some materials that do fluoresce, such as cotton lint, may be acceptable unless present in excessive amounts. It should be noted that fluorocarbon oils, such as PTFE greases, do not fluoresce and therefore can not be detected with black light inspection. Accumulations of lint or dust noted under black light should be removed by blowing with dry oil-free air or nitrogen, wiping with a clean lint-free cloth, or vacuuming. If fluorescence shows up as a blotch, smear, smudge, or film, the entire component should be recleaned [13].

Wipe Test

The wipe test is useful when visual inspection with white and black light is inconclusive or not possible. To perform the wipe test, a white filter paper or clean lint-free cotton or linen cloth is rubbed across the surface of the part. This paper or cloth is then examined under white and/or black light for the presence of contaminants. Several areas of the part surfaces should be tested. Because it is not acceptable to leave cloth or paper particles on the equipment, this method is not suitable for rough surfaces.

Water Break Test

The water break test is a useful method for determining whether or not there are oils or greases on the parts. To perform the test, drinking or distilled water is sprayed on a surface that should be as horizontal as possible. If the amounts of oil or grease are very small, an unbroken layer of water will stay on the part for several seconds. If higher amounts of oil or grease are on the surface, the water will quickly contract and form small beads or droplets between water-free areas.

Solvent Extraction

Solvent extraction is a quantitative verification method that allows the determination of the amount of contaminants present on parts. Considerable experience is necessary to assess the results of this method. The method is based on the comparison of used and unused solvent.

To perform solvent extraction, the parts should be rinsed with enough distilled solvent to obtain a reasonably sized sample. Some considerations involved in the verification of cleanliness include the following:

1. Typically, 0.1 m^2 (1 ft^2) of surface area is rinsed with 100 mL (0.026 gal) of solvent. Collect this solvent in a clean sample beaker.
2. Filter the sample in the beaker through a 0.45-µm (1.77×10^{-5} in.) filter. Size and count the particulate.
3. For organic solvents the filtrate is evaporated in a clean, preweighed tare dish to determine the amount of nonvolatile residue left in the tare dish. For verification of removal of hydrocarbon contaminants using aqueous processes, alternative verification methods are available in ASTM G 136 and G 144.
4. Typical NASA, ASTM, and CGA cleanliness specifications are given in Tables 6-1 and 6-2. The maximum allowable nonvolatile residue on parts used for oxygen service is normally 1 mg/ft^2 (~10 mg/m^2) for aerospace applications and 50 mg/ft^2 (~538 mg/m^2) for industrial applications. Particulate requirements for specific components and systems depend on the application, with levels of 50, 100, and 300 being the most common.
5. If parts fail to meet the required specifications, the precision cleaning must be repeated. Precleaning should be repeated only when necessary.

Drying

Drying is the removal of water or other solvents from critical surfaces. The actual process of drying involves a change of state and requires energy. The amount of energy depends on many factors such as the solvent to be evaporated, the configuration of the hardware, the temperature of the operation, and the thermal conductivity of the liquid and the hardware. The removal of vapor is also critical in drying, and a means for removal of vapor must be provided. This is usually accomplished with a moving dry gas purge. In selection of a drying process, consideration must be given to the level of dryness required. The user should evaluate each method for the specific application intended. There are three basic water removal methods commonly used:

- Physical–actual removal of liquid by, for example, scrapping, wiping, centrifuging, or blowing.
- Solvent–wetting the part with a higher-vapor pressure liquid (alcohol or hydrofluorocarbons, for example) to displace the water.
- Evaporation–adding energy and physically removing the vapor, such as drying by oven, air, vacuum drying oven, or purge.

Note: Care should be taken when drying after HCFC-based solvent cleaning because acid formation has been *shown to promote stress corrosion cracking in pressure vessels.*

Note: Care should be taken to thoroughly dry system or components after IPA is used because IPA is flammable and will ignite and burn in oxygen systems [12].

Note: Care should be taken to remove all excess moisture prior to vacuum drying or to develop a process that will prevent moisture and particularly liquid water from freezing to the surface of the component.

Drying of small- and medium-size hardware often is accomplished in filtered gas-purged ovens. System and tank drying may be achieved by purging with a clean, flowing, dry gas, usually nitrogen or air. Care must be taken in measuring the dew point of a flowing gas. It is possible to inadvertently measure the dryness of the purge gas only. Items dried with a flowing, heated, dry gas purge are usually considered dry when the dew point of the exit gas is within 5°F (3 K) of the purge gas.

Component Reassembly and Functional Testing

During reassembly and functional testing of components and systems, extra care must be taken to ensure that cleanliness is not compromised. When reassembling the system or components, only visually clean tools should be used. Using tools that are dedicated only for assembling oxygen components and systems is common. The operator should wear clean, lint-free gloves if there is a need to touch oxygen-wetted surfaces, and outer garments consistent with the class of the reassembly area. Small components should be assembled in a clean, dust-free environment. All openings and clean surfaces should be covered with oxygen clean caps, plugs or bags. For critical components, FEP (i.e., Teflon) or CTFE (Aclar) film is often used until the system is ready for assembly.

Leak-testing of the assembled component can be accomplished with oxygen-compatible leak-check solution or other methods (such as pressure-decay) while the component is pressurized with clean, dry air or nitrogen. Final operational tests should be performed as required at the rated pressure and flow rate. Such tests should be performed with clean, dry nitrogen or air for greater safety. It is noteworthy that any system used for leak checking or testing clean oxygen hardware must be as clean as or cleaner than the oxygen equipment to minimize contamination after assembly.

Packaging

Items cleaned for oxygen service should be packaged as soon as possible after cleanliness verification is obtained. Labeling is always required. Double-bagging may be required. Guidelines for double-bagging and labeling are as follows:

Inner Bag

The inner bag protects the cleanliness of the part. After a part has been precision cleaned, it should be bagged in an oxygen-compatible film. The film used for bagging oxygen system parts must be as clean as the item being packaged. FEP (Teflon) or CTFE (Aclar) film are commonly used for the inner bag.

Outer Bag

The outer bag is used primarily as a vapor barrier and to protect the inner bag. It protects the inner bag and the part from abrasion, particles, and moisture. The outer bag should be impermeable to moisture, and is commonly made of polyethylene.

Label

A label should be affixed to the outer bag of each bagged part to document, at a minimum, the cleanliness level and what cleaning specification was used. It is also useful to include the date the part was cleaned and the intended media of the part or component. Phrases such as the following may also be included for extra guidance, "Cleaned for oxygen service. Do not open until ready for assembly."

For large equipment that cannot be properly bagged, openings should be sealed with oxygen-compatible caps or plugs. The outside surfaces of such equipment should be maintained as clean as possible until final assembly into the system for use.

Typical Cleaning of Specific Materials

The cleaning solution used will depend on the material to be cleaned. Materials such as 300 series stainless steels, Monel alloys, Inconel alloys, and Teflon usually are cleaned in an alkaline solution and then in an acid solution. Carbon steel usually is cleaned by a rust and scale remover, if required, and then in an alkaline solution followed by a rust inhibitor. In severe cases of rust or corrosion, carbon steel may be bead-blasted. Copper and brass are usually cleaned in an alkaline solution, and then acid-pickled. Aluminum and nonmetals (other than Teflon) should be cleaned in less caustic solutions. Other specialized materials may require different cleaning techniques; materials should not be cleaned in solutions with which they react significantly.

Clean Assembly of Oxygen Systems

Even the best-designed oxygen systems can contain hazardous ignition sources if fabricated or assembled incorrectly. Careful assembly is extremely important for high-pressure oxygen systems because contaminants generated during assembly are a potential source of readily ignitable material. Elimination of all contaminants is highly desirable; however, complete elimination is rarely feasible in complex assemblies involving, for example, nonmetallic seals, threads, screw lock plugs, press fits, welds, soldered and brazed joints, and lubricants. Careful assembly procedures can minimize the quantity of contaminants remaining in a system and thus the potential for contaminant ignition. After initial mockup assembly, oxygen systems must be disassembled and thoroughly cleaned, reassembled, leak tested, and purged with clean, oil-free, filtered, dry, gaseous nitrogen or helium before they are wetted with oxygen.

Maintaining Cleanliness During Assembly

Procedures for system and component assembly or reassembly after cleaning must be stringently controlled to ensure that the required cleanliness levels are not compromised. All components requiring reassembly, such as valves, regulators, and filters, should be reassembled in a clean room or flow bench. Personnel should be properly attired in clean room garments and gloves as appropriate to maintain the cleanliness of the parts. All tools used in clean, filtered environments (i.e., clean rooms) must be precision cleaned to the required levels.

Personnel assembling an oxygen system should visually inspect all components prior to installation to ensure cleanliness, and any components found to be contaminated should: (1) be reported to the authority having jurisdiction, and (2) not be used unless approved by the authority having jurisdiction.

The assembly or reassembly of systems should be accomplished in a manner that minimizes system contamination. Components should be kept in clean bags until immediately before assembly. One technique commonly used is to build up the system as subassemblies, using the same techniques as for components, such as in a filtered-air environment. When the size or location of a system precludes this practice, a low-pressure purge of the system by a clean, inert gas during reassembly or a portable clean tent can be used to reduce contamination. Before exposing a system to oxygen, an inert-gas purge should be performed to remove assembly generated contaminants. Generally, this postassembly inert gas purge is performed at pressures and flow rates the same as or greater than the maximum oxygen pressures and flow rates in order to mobilize particulate.

For large systems such as pipelines, systems should be inspected at both the inlet and discharge ends, and at all accessible points to assess the condition of the internal surface after completion of construction. If considered necessary according to the quality control procedure, samples can be taken at all accessible openings by wiping the internal surface of the pipeline with white, lint-free cloths or filter papers of a type that have not been treated with optical brighteners. The inspection should include one of the following procedures:

- Visual inspection of the internal surfaces using white light to ensure that the cleaning has been effective and that a metal finish which is free of grease, loose rust, slag, scale and other debris has been achieved. A light film of surface rust is acceptable.
- Inspection of the end sections of the internal bore by black light to verify the absence of oil or grease.
- Inspection of wipes (if taken) by bright white light and black light to verify the absence of oil or grease.

Assembling Seals

Seals should not be forced into bores or over shafts that are without adequate chamfers. These parts should be inspected for burrs and sharp edges before they are assembled. A chamfer will always have a sharp edge unless it is specifically removed. Hardened steel may have a very pronounced sharp edge at the intersection of the chamfer cut and the outer diameter of the shaft.

Installation of an O-ring over threads with an outer diameter exceeding the inside diameter of the O-ring should be avoided or a shield should be used to prevent the sharp thread edge from contacting the inner surface of the O-ring. If no alternative exists at the assembly stage, the assembly specifications should require additional cleaning after the O-ring and threaded part have been assembled and before the components are installed in the next level of assembly. A light coating of oxygen-compatible seal lubricant should be used to ease assembly.

Hardware that is designed in such as way that cuts or abrasions could occur to soft goods during assembly can cause feathering of the soft goods. This feathering will create contaminants and provide a future contaminant generation source, as the soft good will continue to shed particles during its functional life.

Threaded Assembly

Care should be taken when assembling threaded connections because particulates can be generated as the threads are engaged and tightened. To minimize the amount of particulate generated, oxygen-compatible lubricants and thread tapes should be used. The amount of lubricant and thread tape should be minimized. Assembly procedure documents should ensure that the installation of threaded valve parts into housing bores is performed with the housing inverted (bore opening pointing down), so contaminants generated during assembly fall away from the component rather than into flow paths.

Deformable Parts

Parts such as screw-locking devices, which are deformed by other parts during assembly, may generate particulate. These parts usually are nonmetallic inserts. Their use should be limited as much as possible, and their installation should be sequenced so that they are driven in only once. Further assembly and disassembly increases the amount of particulate created.

Press Fits

Press fits generate particulate during their assembly from the relative motion of the two highly loaded surfaces. The particulate can be partially removed by cleaning the joined parts immediately after pressing them together; this step should be specified on the subassembly drawing. Assembly procedure documents should ensure that the installation of press-fit and push-fit parts into housing bores is performed with the housing inverted (bore opening pointing down), so contaminants generated during assembly fall away from the component rather than into flow paths.

Components with press-fit parts are extremely difficult to clean. These parts should never be submerged into a cleaning solution or bath, as the cleaning solution can become entrapped between the two press-fit parts, leach out later, and become a contaminant.

Welded Soldered and Brazed Joints

If left in the as-formed condition, welded, soldered, and brazed joints may leave slag, rough surface pores, porosity, or cracks that can generate or trap contaminants. Such joints should be minimized in oxygen components. When welds cannot be avoided, they should be specified as full-penetration so that all contacting surface areas are joined. The use of full-penetration welds prevents entrapment of particulate and eliminates uncleanable, blind surfaces. Exposed weld surfaces should be ground to a smooth finish to facilitate precision cleaning.

Burrs

Removal of burrs and sharp edges is of critical importance in oxygen systems. Burr removal in small-diameter internal passageways at the intersection of cross drills is a common problem. The best results have been obtained with small, motorized grinding tools and with electrical discharge machining. A borescope, otoscope, or other inspection tool can be used to verify burr removal when required.

Lubricants and Thread Tapes

Lubricants and thread tapes should be used whenever they are required to reduce abrasion and damage to seals and threaded assemblies during assembly and to enhance the operational sealing or sliding of parts. Lubricants should be applied lightly, and excess lubricant should be removed to prevent future migration and attaching with other contaminants. If a lubricant migrates into an area that should not be lubricated, it can cause functional anomalies, as when regulator control mechanisms fail to respond properly because of contamination by excess lubricant. Additionally, avoid using excessive lengths of thread tapes.

Hydrocarbon-based lubricants must not be used in oxygen systems because they can easily ignite; the incorrect use of hydrocarbon-based lubricants is a common cause of oxygen system fires. The most oxygen-compatible lubricants are highly fluorinated materials. However, some highly fluorinated lubricants are shock-sensitive in oxygen, so compatibility testing is always required if test data are not available. The most oxygen-compatible thread tapes are PTFE tapes. Even the most compatible lubricants and tapes can react with oxygen when system design limits on temperature, pressure, or pressure rise rates are exceeded.

Dry fit up of components is desired when possible so that subsequent final assembly will not push thread tape and lubricants into the oxygen-wetted passages. Lubricants and thread tape should be installed allowing a two-thread gap from the exposed end of the fitting to prevent introduction into the oxygen system. Also, the threaded tape should be cut rather than torn to prevent vulnerable jagged edges from being introduced inadvertently into the oxygen-wetted regions.

Maintaining the Cleanliness of Oxygen Systems

Special care must be taken to ensure that oxygen systems are maintained clean through deliberate procedures during use and maintenance. Clean, powder-free gloves should be worn whenever breaking into a system or handling oxygen-wetted surfaces of components. Personnel should take care to clean off the area near where the system will be broken into to prevent exterior contamination from entering the system. If possible, the use of an inert gas purge during removal and installation of components is a good way to prevent contamination of the system during maintenance. When components are removed from a system, open ports should be protected with oxygen-compatible plugs, caps, and bags. In addition, vent-line terminations should be protected from contamination by using tees, screens, or both. After breaking into an oxygen system, whenever possible an inert-gas purge should be performed to remove assembly-generated contaminants prior to exposing the system to oxygen.

When a component is removed from an oxygen system, it should be inspected to determine its degree of cleanliness. This provides an opportunity to determine the cleanliness of the system and to establish cleaning intervals and levels. For example, when a filter is removed it should be back-flushed, and the trapped debris should be analyzed. The results of the analysis can help in determining the cleanliness and health of the oxygen system, as well as determining the maintenance cycle for the filter.

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7

Operating Procedures

Introduction

TO ENSURE THE SAFE OPERATION OF OXYGEN systems, standard operating procedures (SOPs) should be developed. These SOPs should be prepared and reviewed by persons familiar with the work being done, as well as with oxygen safety; oxygen risks and hazards; and safety guidelines, practices, codes, and standards. SOPs for all hazardous operations should be reviewed by the designated safety authority. Occupational health personnel should be involved in the review cycle when operational procedures involve potential health hazards. SOPs should provide for the control of hazards†[1] to an acceptable risk and should be reviewed periodically for observance and improvement. The design of safe facilities and equipment should consider human capabilities and the limitations of personnel responsible for operations.

The procedures should include:

- notification of the designated safety authority during hazardous operations,
- protection of personnel,
- prevention and detection of oxygen leaks, and
- elimination of ignition sources.

Personnel

Equipment failures caused by operator errors can result in fires, explosions, injury, and extensive damage. Consideration for the safety of personnel at and near oxygen storage and use facilities must start in the earliest planning and design stages. Safety documentation should describe the safety organization and comment specifically on inspections, training, safety communications and meetings, operations safety and instruction manuals, incident investigations, and safety instruction records. The authority having jurisdiction should assure that the safety equipment required at the operational site is present.

Warning systems should be used to monitor oxygen systems that have the potential of endangering personnel. The warning systems should be shielded and designed so the operation of a single detection device serves to alarm, but not necessarily to initiate basic fire and emergency protection. System and equipment safety components should be installed for control of automatic equipment to reduce the hazards indicated by the warning systems. Manual controls within the system should include automatic limiting devices to prevent over-ranging.

The authority having jurisdiction should establish policies and procedures by which appropriate personnel have proper awareness of oxygen transport, loading, and use operations. Operators should be trained for proper operations and kept informed of any changes in operating or safety procedures. The operators must be qualified and certified for working with gaseous oxygen (GOX) and liquid oxygen (LOX) and also should be trained in the corrective actions required in an incident. Personnel engaged in operations should be advised of the hazards that may be encountered. Procedures should include personal protective equipment, as described in Chapter 1, and the use of the buddy system† for all handling operations involving LOX.

Operator Certification†

Before being certified to work with GOX or LOX, all operators should demonstrate the following:

- knowledge of the properties of GOX or LOX, or both;
- general knowledge of approved materials that are compatible with GOX and LOX under operating conditions,
- familiarity with manufacturers' manuals detailing equipment operations;
- proficiency in the use and care of protective equipment and clothing and safety equipment;
- proficiency in maintaining a clean system and clean equipment in oxygen service;
- recognition of normal operations and symptoms that indicate deviations from such operations; and
- conscientious following of instructions and checklist requirements.

Confined Space

Personnel should not be permitted to enter a confined space that may be subject to oxygen enrichment or oxygen depletion or a confined space that contains a toxic material until an assessment of that space is made and specific authorization is obtained. Entry must be done in accordance with OSHA requirements, and only trained personnel should be allowed to use monitoring equipment, evaluate entry, and perform actual entry. Free entrance is permissible only if the oxygen concentration is between 19.5 and 23.5 vol%. Instruments used for determining oxygen enrichment or oxygen depletion must be calibrated in accordance with specific requirements for the instrument.

Cooldown and Loading Procedures

Approved cooldown and loading procedures must be followed to limit liquid geysering† and large circumferential and radial temperature gradients in the piping. Liquid flow cools a pipe faster than comparable gas flow, and nonuniform cooling may occur with two-phase flow. Flow rates that predict nonstratified LOX flows in pipes of various sizes are presented in Chapter 5. System failures have occurred from operational pressure surges. The procedures and checklists should ensure operation

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[1] The † indicates a term defined in the Glossary (Appendix G).

sequencing to prevent pressure spikes. In addition, special care should be taken to ensure that the flow velocities present during cooldown and loading procedures do not pose a particle impact ignition hazard (as described in Chapters 2 and 5).

Cryogenic Cold-Shock

Cold-shocking a newly assembled LOX system by loading it with clean liquid nitrogen after final assembly is highly recommended. After the cryogenic cold-shock, the system should be emptied of liquid nitrogen and warmed to ambient temperature. Bolts and threaded connections must then be retorqued to prescribed values, and gas leak-checking procedures should follow. After cold-shock, the entire system should be inspected for evidence of cracking, distortion, or any other anomaly, with special attention directed to welds. Then system cleanliness must be checked and verified.

Hydrostatic Testing

Whenever possible, hydrostatic testing should be performed prior to oxygen cleaning to prevent contamination of the hardware. If hydrostatic testing cannot be performed prior to cleaning, steps must be taken to ensure that the cleanliness of the hardware is not compromised. Where cleaning requirements preclude post-hydrostatic testing of a cold-shocked system, a thorough review of system integrity should be conducted. This includes cases where a previously tested system is to be modified [1].

Examinations

A visual safety examination of the oxygen systems should include verification of dimensions, joint preparations, alignment, welding or joining, supports, assembly, and erection. Examples of conditions to be observed are as follows:

- mechanical damage;
- cracking (especially at welds and areas of known stress concentration);
- bulges or blisters;
- leakage;
- loose nuts, bolts, or other parts;
- excessive vibration;
- abnormal noise;
- overtemperature;
- discrepancies in gage readings;
- pipe hanger condition;
- flexible hose antiwhip devices;
- frost on vacuum-jacketed lines and on container;
- obstruction in relief-valve vents; and
- evidence of contamination in system.

Good Practices

Whenever possible, operating procedures and instructions should include the use of good practices such as the following.

System Assembly

1. All systems and components should be cleaned before assembly (Chapter 6). Personnel assembling an oxygen system should visually inspect all components before installation to ensure cleanliness, and any components found to be contaminated should be reported.
2. Oxygen systems should be assembled in a clean area. Whenever possible, there should be a specific area set aside for oxygen system work. Ideally, a flow bench would be used for assembly of components and portions of the system. Avoid assembling outdoors, especially in bad weather.
3. Minimize the time of exposure of components cleaned for oxygen service to potential sources of contamination. Before assembly, gather all necessary fittings, hardlines, components, and lubricants. Keep components bagged until use, and unbag components only when it is time to install them. Assemble systems in a linear fashion to minimize the time of exposure to potential sources of contamination.
4. Wear clean, powder-free gloves, and change gloves often.
5. Minimize the quantity of lubricants used. Ensure that all lubricants used are oxygen compatible.
6. Ensure that proper lubricants, softgoods, and metals are used to avoid material substitution errors. Require vendor certification of materials. If pedigree or material certification has been lost, the component or part must not be used.
7. Keep inventories separate and do not keep incompatible lubricants or softgoods in work areas related to oxygen systems.
8. Ensure that vent line terminations are protected from contamination by using tees, screens, or both.
9. Perform the first leak check using dry, oil-free, filtered, inert gas.
10. Before exposing a system to oxygen, perform an inert-gas purge to remove assembly-generated contaminants.

System Operation and Maintenance

1. Use remote operation for the first oxygen exposure to a system.
2. When opening manual valves, do not torque the handle hard against the stop. Otherwise, the next operator may mistakenly assume the valve is closed.
3. Reduce personnel exposure by minimizing hands-on operation, using remotely operated components, and barriers for protection of personnel.
4. When breaking into a system, verify that the system is depressurized and use double isolation from the oxygen supply.
5. Take care to clean off the area near where the system will be broken into to prevent exterior contamination from entering the system.
6. Consider the use of an inert-gas purge during removal and installation of components.
7. Wear clean, powder-free gloves when breaking into a system or handling oxygen components.
8. Protect open ports with oxygen-compatible plugs, caps, and bags.
9. Be aware of oxygen enrichment in clothing and consider the need to ventilate exposed materials in an area free of ignition sources for 30 min after exposure to oxygen.
10. After breaking into an oxygen system, perform an inert-gas purge to remove assembly-generated contaminants.
11. Ensure adequate ventilation to avoid oxygen enrichment of the atmosphere in the vicinity of potential leak sites.
12. Minimize flammables near oxygen systems.

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8

Facility Planning and Implementation

Introduction

PLANNING FOR THE PROTECTION AND SAFETY OF personnel and equipment must start at the initial facility design stages because of the hazards†[1] associated with oxygen and oxygen-enriched air. This planning should include a review of the hazards associated with each system as well as proper design to safely store oxygen, dispose of oxygen, and manage fires. Once an oxygen system is installed, there must be inspections and certifications† to ensure that it is safe to use. In addition, steps must be taken to ensure that a system is maintained and that any necessary modifications are safely implemented. This chapter describes the life cycle of an oxygen system, beginning with topics related to facility planning and design, followed by a brief discussion of the steps that should be taken once an oxygen system is built to ensure that it is safe to use. This chapter is concluded with discussions of the steps that are taken once an oxygen system is in use and continuing through its decommissioning.

Hazards Assessment

In addition to the component- and system-level oxygen compatibility assessment discussed in Chapter 4, a facility-level hazards assessment should be performed for each facility system or subsystem. The purpose of this assessment is to identify areas or operations with high probabilities of failure that could result in leakage, fires, and explosions. The results of the hazards assessment allow a better understanding of the basis for the safety requirements and emphasize the need for compliance with established regulations.

Methods of performing hazards assessment include techniques such as fault hazard analysis and fault-tree analysis, failure mode and effects analysis and single-barrier failure analysis, safety reviews, and environmental reviews. In fault hazard analysis and fault-tree analysis, undesirable events are evaluated and displayed. In failure mode and effects analysis and single-barrier failure analysis, potential failures and the resulting effects on the safety of the system (to include ignition and combustion in oxygen-enriched† atmospheres) are evaluated [1,2]. Safety reviews are reviews of all aspects of safety, including oxygen hazards, to ensure that the integrated design solution does not present unacceptable risks to personnel and property. Environmental reviews serve to provide an understanding of potential environmental effects and how they can be effectively controlled.

Situations during transportation, storage, transfer, testing, and vaporization where life, health, environment, and property may be exposed to substantial hazards should be considered in the hazards assessment. The probability of events occurring and causing spills, the nature of the spill, and the risks of fires and explosions should be also included in the evaluation. Hazards resulting from leaks and spills, overpressurization, and transportation can be found in Chapter 1. Some other specific hazards are listed below.

Liquid Oxygen (LOX) and Gaseous Oxygen (GOX) System Failures

Ignition mechanisms (Chapter 2) in LOX and GOX systems can lead to fires and explosions. Piping and valving in vaporization systems may fail, causing injury and low-temperature exposures. Combustion of the materials in oxygen may occur, resulting in extensive damage from fires and explosions. The use of proper materials (Chapter 3), suitable design practices (Chapter 5), and proper operating procedures (Chapter 7) will limit system failures.

Overpressurization

Overpressurization, which is discussed further in Chapter 1, can result in rupture of pressure vessels, lines, and components.

Access Control

Test cells and buildings in which combustible or explosive mixtures are present should not be entered under any condition. Entering an operating test cell must be considered dangerous. Authorized personnel should enter only after conditions within the area have been determined to be safe.

Oxygen Enrichment

Oxygen enrichment can be a hazardous condition leading to ignition and fire. Devices that warn of the presence of oxygen enrichment should be used to minimize this hazard, and personnel should be properly trained to handle oxygen enrichment.

Liquid Air

Impact-sensitive gels can form if liquid air is allowed to drip onto porous hydrocarbon materials, such as asphalt, or onto surfaces contaminated with materials such as oils or greases. Liquid air can form on surfaces of uninsulated lines and components at temperature less than about 82 K (−312°F), which is colder than the normal boiling point NBP of LOX, 90.18 K (−297.3°F). The condensate will be approximately 50 % oxygen [3].

General Facility Guidelines

Some general facility design guidelines for oxygen facilities are as follows:

1. Provide two exit routes from all buildings, test cells, and areas with oxygen systems.
2. Use the fewest possible piping joints.

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[1] The † indicates a term defined in the Glossary (Appendix G).

3. When oxygen systems are inside of buildings, provide isolation valves outside of the buildings to allow shutoff of the oxygen supply.
4. Anticipate indirect oxygen exposure that may result from system failures.
5. Detectors, sensors, and continuous sampling devices that operate both an audible and visible alarm should be used to warn personnel of areas with combustible or explosive† mixtures and high or low oxygen concentrations. More information is given in the section "Oxygen Detection."
6. Avoid venting into confined spaces†.
7. Consider the effect of an oxygen system's particular location, use, size, and criticality on the cost of cleaning and inspection procedures.
8. Access should be provided for the operation and maintenance of safety and control equipment. Locate instrumentation and controls so that the system can be inspected, serviced, and operated without presenting a hazard to personnel. Lighting should be provided for equipment inspection and safe personnel movement.
9. Locate oxygen systems a safe distance from heat or thermal radiation sources.
10. Limit ignition sources and provide lightning protection in the form of lightning rods, aerial cables, and suitably connected ground rods in all preparation, storage, and use areas. All equipment in buildings should be interconnected and grounded to prevent inducing sparks between equipment during lightning strikes (NFPA 70).
11. Design the facility to manage fires. Provide an automatic remote shutoff to isolate critical components from all bulk oxygen supplies. Consideration should be given for the installation of water spray systems.
12. Provide sufficient clearance for vehicles in structures over roads, driveways, and accesses. Roads, curves, and driveways should have sufficient width and radius to accommodate required vehicles.

Quantity-Distance Guidelines

Planning for oxygen facilities must include consideration for the quantity of oxygen and the proximity of the operations relative to other exposures (including personnel, roadways, fuels storage, etc.). Generally, bulk storage applications follow quantity-distance guidelines used by industry, as described in the section "Bulk GOX and LOX Storage for Nonpropellant Use." Applications in which quantities of oxygen are used in conjunction with fuels (as propellants) or other energetic materials follow quantity-distance guidelines used by the military, as described in the section "Bulk LOX Storage for Propellant Use." Deviation from military and industrial practice must be supported by design features or operational safeguards, or both, that have been subjected to a hazard assessment that is documented and approved by the authority having jurisdiction. Operations with quantities that are less than the quantities specified within the quantity-distance guidelines, such as laboratories, are subject to the controls of the authority having jurisdiction.

Quantity-distance relationships are intended as a basic guide in choosing sites and determining separation distances. Quantity-distance criteria for bulk oxygen storage facilities are intended to provide protection from external fire exposure. Quantity-distance criteria for oxygen-fuel systems, however, are intended to reduce the effects of fire, explosion, fragmentation†, and detonation by keeping the hazard source at a safe distance from people and facilities. Blast effects and fragmentation are discussed further in Appendix E.

Bulk GOX and LOX Storage for Nonpropellant Use

The quantity-distance criteria for the nonpropellant use of LOX shall be as established by NFPA 50[2] and 29 CFR 1910.104 [4], which both apply to oxygen containers that are stationary or movable, with oxygen stored as a gas or liquid. NFPA 50 applies to bulk oxygen storage systems that have a storage capacity of more than 566 m^3 (20 000 ft^3) of oxygen at normal temperature and pressure (NTP)†, including unconnected reserves on hand at the site. Oxygen storage systems with a capacity of 566 m^3 (20 000 ft^3) or less are covered by *Standard for the Design and Installation of Oxygen-Fuel Gas Systems for Welding, Cutting, and Allied Processes* (NFPA 51). 29 CFR 1910.104 applies to bulk oxygen storage systems that have a storage capacity of more than 386 m^3 (13 000 ft^3) at NTP connected in service or ready for service or more than 708 m^3 (25 000 ft^3) at NTP connected in service or ready for service, or more than 708 m^3 (25 000 ft^3) at NTP, including unconnected reserves on hand at the site.

The minimum distances from any bulk GOX storage container (nonpropellant use) to exposures, measured in the most direct line (except as noted), shall be as given in 29 CFR 1910.104 [4]. A summary of the minimum distances as specified in 29 CFR 1910.104 is given in Table 8-1. NFPA 50 specifies that Exposure Type 3 in Table 8-1 shall apply to all elements of a bulk oxygen system in which the oxygen storage is high-pressure gas; when the storage is liquid, this provision shall apply only to pressure regulators, safety devices, vaporizers, manifolds, and interconnecting piping.

Some additional recommendations from NFPA 50 for separation of bulk oxygen systems (nonpropellant use) are as follows:

1. A minimum of 15 m (50 ft) in a direct line to areas occupied by nonambulatory patients from the inner container pressure relief discharge piping outlets and filling and vent connections.
2. At least 1.5 m (5 ft) to any line of adjoining property that may be built upon.
3. Not less than 3 m (10 ft) to any public sidewalk or parked vehicles.
4. A minimum of 22.5 m (75 ft) to liquified hydrogen storage of any quantity.
5. At least 15 m (50 ft) from places of public assembly.
6. Weeds and long dry grass within 4.6 m (15 ft) of any bulk oxygen storage container shall be cut back.

Bulk LOX Storage for Propellant Use

The quantity-distance criteria for LOX storage siting in relation to other facilities and other propellants for the use of LOX as a propellant are given by *Ammunition and Explosives Safety Standards* (DoD 6055.9-STD) [5]. DoD 6055.9-STD. governs the employment of energetic liquids (which includes LOX) in the following, and no other, uses: space launch

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[2] NFPA has created a new standard, NFPA 55 Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks (2005 Ed.), which incorporates NFPA 50 into its Chapter 9.

TABLE 8-1—Quantity-distance requirements for nonpropellant bulk oxygen storage systems[a] located outdoors [4].

	Distance[b] from Exposure to Bulk Oxygen Storage System[a]	
Type of Exposure	m	ft
1. Combustible structures	15.2[c]	50[c]
2. Fire-resistive structures[d]	7.6[c,e,f]	25[c,e,f]
3. Openings in wall of fire-resistive structures	3.0[f]	10[f]
4. Flammable[†] liquid storage, above-ground:		
a. 0 to 3 785 L (0 to 1 000 gal) capacity	15.2[c]	50[c]
b. over 3 785 L (1 000 gal) capacity	27.4[c]	90[c]
5. Flammable liquid storage tank, below-ground:		
a. 0 to 3 785 L (0 to 1 000 gal) capacity	4.6[c,g]	15[c,g]
b. over 3 785 L (1 000 gal) capacity	9.1[c,g]	30[c,g]
6. Fill, vent, or other opening in flammable liquid storage tank below ground:		
a. 0 to 3 785 L (0 to 1 000 gal) capacity	15.2[c,g]	50[c,g]
b. over 3 785 L (1 000 gal) capacity	15.2[c,g]	50[c,g]
7. Combustible liquid storage, above-ground:		
a. 0 to 3 785 L (0 to 1 000 gal) capacity	7.6[c]	25[c]
b. over 3 785 L (1 000 gal) capacity	15.2[c]	50[c]
8. Combustible liquid storage tank, below-ground	4.6[c,g]	15[c,g]
9. Fill, vent, or other opening in combustible liquid storage tank below-ground	12.2[c,g]	40[c,g]
10. Flammable gas storage:[h]		
a. less than 141.6 m^3 (5 000 ft^3) capacity at NTP[i]	15.2[c]	50[c]
b. over 141.6 m^3 (5 000 ft^3) capacity at NTP[i]	27.4[c]	90[c]
11. Highly combustible materials[j]	15.2[c]	50[c]
12. Slow-burning materials[k]	7.6[c]	25[c]
13. Confining walls:[l]		
a. in one direction	22.9	75
b. in approximately 90° direction	10.7	35
14. Congested areas[m]	7.6	25

[a] Applies to storage capacity of more than 386 m^3 (13 000 ft^3) of oxygen at NTP connected in service or ready for service, or more than 708 m^3 (25 000 ft^3) of oxygen at NTP including unconnected reserves on hand at the site. The oxygen containers may be stationary or movable, and the oxygen may be stored as gas or liquid.

[b] Minimum distance measured in the most direct line except as indicated for exposure Types 5 and 8.

[c] Given distance does not apply where protective structures such as firewalls of adequate height to safeguard the oxygen storage systems are located between the bulk oxygen storage installation and the exposure. In such cases, the bulk oxygen storage installation may be a minimum distance of 0.3 m (1 ft) from the firewall.

[d] Structures with fire-resistive exterior walls or sprinklered buildings of other construction.

[e] Distance shall not be less than one-half the height of adjacent side wall of the structure.

[f] Distance shall be adequate to permit maintenance, but shall not be less than 0.3 m (1 ft).

[g] Distance measured horizontally from an oxygen storage container to a flammable or combustible liquid tank.

[h] Includes compressed flammable gases, liquefied flammable gases, and flammable gases in low pressure gas holders.

[i] NTP = normal temperature (293.15 K [68°F]) and absolute pressure [101.3 kPa (14.7 psi)].

[j] Includes solid materials that burn rapidly, such as excelsior or paper.

[k] Includes solid materials that burn slowly, such as coal and heavy timber.

[l] Includes courtyards and similar confining areas, but does not include firewalls less than 6.1 m (20 ft) high, to provide adequate ventilation in such areas.

[m] Includes areas such as offices, lunchrooms, locker rooms, time clock areas, and similar locations where people may congregate.

vehicles, rockets, missiles, associated static test apparatus, and ammunition and explosives. Some of the pertinent limitations, applications, and requirements of DoD 6055.9-STD are summarized in this section.

DoD 6055.9-STD applies to the storage of energetic liquids (defined as a liquid, slurry, or gel that consists of, or contains, an explosive, oxidizer, fuel, or combination of the above that may undergo, contribute to, or cause rapid exothermic decomposition, deflagration, or detonation) in all types of containers, including rocket and missile tankage. The quantity of explosive material and distance separation relationships provide the levels of protection that are described in the standard. The relationships are based on levels of risk considered acceptable for specific exposures as shown in the tables in the standard. These separation distances do not provide absolute safety or protection; thus, greater distances than those given in the tables should be used if practical. Laboratory quantities should be stored and handled as prescribed by the authority having jurisdiction. The quantity-distance requirements are based only on the energetic liquid's reaction (blast overpressure[†] and container fragmentation[†]). The quantity-distance requirements were developed on the premise that the authority having jurisdiction will ensure the materials of construction are compatible with the energetic liquids, facilities are of appropriate design, fire protection and drainage control techniques are employed, and other specialized controls are used when required.

The standards are based upon the estimated credible damage resulting from an incident, without considering the probabilities or frequency of occurrence. The storage of more than one energetic liquid is governed by the assignment of a compatibility group designation for the energetic liquids. The potential damage or injury of an explosion can be reduced by the separation distance between a potential explosion site (defined as the location of a quantity of ammunition and explosives that will create a blast, fragment, thermal, or debris hazard in the event of an accidental explosion of its contents) and an exposed site (defined as a location exposed to the potential hazardous effects, e.g. blast, fragments, debris, or heat flux, from an explosion at a potential explosion site); the ability of the potential explosion site to suppress blast overpressure, primary, and secondary fragments; and the ability of the exposed site to resist the effects of an explosion at the potential explosion site.

The standard establishes explosives safety criteria (quantity-distance relationships) for a potential explosion site and an exposed site based on blast, fragment, firebrand, thermal, and ground-shock effects. Explosive is defined in DoD 6055.9-STD as:

> a substance or a mixture of substances that is capable by chemical reaction of producing gas at such temperature, pressure, and speed as to cause damage to the surroundings. The term "explosive" includes all substances variously known as high explosives and propellants, together with igniter, primer, initiation, and pyrotechnic (e.g., illuminant, smoke, delay, decoy, flare, and incendiary compositions).

The predominant hazard of an individual energetic liquid can vary depending on the location of the energetic liquid storage and the operations involved. The locations governed by DoD 6055.9-STD are (in order of decreasing hazards): launch pad, static test stand, ready storage, cold-flow operation, bulk storage, rest storage, run tankage, and pipeline.

For conditions that involve only LOX, and the primary hazards that govern are fire and fragments, DoD 6055.9-STD specifies the separation distance from LOX storage in a detached building or tank to various exposures shall be as given in Table 8-2. These conditions are those that typically exist in locations such as bulk storage, rest storage, and pipeline. Table 8-2 provides minimum distance requirements for storage of bulk quantities and, in some cases, pressure vessels and other commercial packaging of energetic liquids. Positive measures must be provided to control the flow of LOX in the event of a leak or spill, to prevent possible fire propagation or accumulation near storage, prevent mixing of incompatible energetic liquids and all of the above.

For conditions that involve the potential intermixing of incompatible energetic liquids (such as a fuel and an oxidizer) and a resulting explosion with blast overpressure and fragments, DoD 6055.9-STD specifies that the QD shall be determined on the basis of the explosive equivalent of the mixture of the energetic liquids involved. These conditions are those that typically exist in locations such as launch pads and static test stands. For these conditions, where incompatible energetic liquids are in close proximity to each other and their intermixing (unplanned) is a possibility, DoD 6055.9-STD specifies that an energetic liquid explosive equivalent be used to determine minimum separation distances. This explosive equivalent is a function of factors such as:

- the energetic liquids involved (such as liquid hydrogen and LOX),
- the total mass of the energetic liquids subject to intermixing,
- the location involved (such as, launch pad and static test stand), and
- the extent of the protection that is provided at the LOX storage location, at the potential explosion site, or both.

The energetic liquid explosive equivalents involving LOX are presented in Table 8-3. The energetic liquid explosive equivalents obtained from Table 8-3 are to be used in Table 8-4 to obtain the minimum separation distance from LOX storage at locations such as launch pads and static test stands to inhabited buildings, public traffic routes, and other potential explosion sites. The net explosive weight for quantity distance (NEWQD) of Table 8-4 is the sum of the energetic liquid explosive equivalent and the weight of any other non-nuclear explosive involved.

When more than one potential explosion site is involved, or the exposed site also contains ammunition and explosives, the minimum separation distance is determined for both sites and the greater of the separation distances governs.

Storage Systems

As defined in NFPA 50, Standard for Bulk Oxygen Systems at Consumer Sites, a bulk oxygen system is an assembly of equipment, such as oxygen storage containers, pressure regulators, safety devices, vaporizers, manifolds, and interconnecting piping that has a storage capacity of more than 566 m^3 (20 000 ft^3) of oxygen at NTP including unconnected reserves on hand

TABLE 8-2—Minimum separation distance from LOX storage in a detached building or tank to various exposures.[a-c]

Type of Exposure	Minimum Separation Distance, m (ft)
Inhabited building[d] and populous location	30.5 (100)
Public traffic route[e]	30.5 (100)
Adjacent compatible energetic liquid storage	15.2 (50)
Ammunition and explosives-related building	30.5 (100)
Ammunition and explosives aboveground storage location	30.5 (100)

[a] Source: DoD 6055.9-STD (5). Additional guidelines relating to equipment assembly and installation, facility design, and other fire protection issues also apply (see DoD 6055.9-STD [5]).

[b] The separation distance is independent of oxygen quantity.

[c] These distances do not apply where a protective structure having an NFPA fire resistance rating of at least 2 h interrupts the line of sight between the oxygen system and the exposure.

[d] Inhabited building is defined as structures, other than ammunition and explosives-related buildings, occupied by personnel or the general public, both within and outside DoD establishments (e.g., schools, churches, residences, quarters, service clubs, aircraft passenger terminals, stores, shops, factories, hospitals, theaters, mess halls, post offices, or post exchanges).

[e] Public traffic route is defined as any public street, road, highway, navigable stream, or passenger railroad, including roads on a military reservation that are used routinely by the general public for through traffic.

TABLE 8-3—Energetic liquid explosive equivalent for LOX with a fuel used on static test stands and launch pads[a-g]

	TNT Equivalence, kg (lb)	
Energetic Liquids	**Static Test Stand**	**Range Launch**
LOX/LH_2[h]	See Note *i*	See Note *i*
LOX/RP-1[j]	10 %	20 % up to 226 795 kg (500 000 lb) + 10 % over 226 795 kg (500 000 lb)
LOX/LH_2 + LOX/RP-1[j]	Sum of LOX/LH_2 (see Note *i*) + 10 % of LOX/RP-1[j]	Sum of LOX/LH_2 (see Note *i*) + 20 % of LOX/RP-1[j]

[a] Source: DoD 6055.9-STD [5]

[b] The percentage factors given here are to be used to determine equivalencies of energetic liquid mixtures at static test stands and range launch pads when such energetic liquids are located aboveground and are unconfined except for their tankage. Other configurations will be considered on an individual basis to determine equivalencies.

[c] The explosives equivalent weight calculated by the use of this table will be added to any non-nuclear explosive weight aboard before distances can be determined from Table 8-4.

[d] These equivalencies apply also for the following substitutions:
- Alcohols or other hydrocarbons for RP-1
- H_2O_2 for LOX (only when LOX is in combination with RP-1 or equivalent hydrocarbon fuel).

[e] For quantities of energetic liquids up to but not over the equivalent of 45.5 kg (100 lb) of ammunition and explosives, the distance will be determined on an individual basis by the authority having jurisdiction. All personnel and facilities, whether involved in the operation or not, will be protected by operating procedures, equipment design, shielding, barricading, or other suitable means.

[f] Distances less than intraline are not specified. Where a number of prepackaged energetic liquid units are stored together, separation distance to other storage facilities will be determined on an individual basis by the authority having jurisdiction, taking into consideration normal hazard classification procedures.

[g] Energetic liquid explosive equivalents for hypergols (hydrazine and nitrogen tetroxide, for example) and other energetic liquids are given in DoD 6055.9-STD [5].

[h] LH_2 is liquid hydrogen.

[i] For siting launch vehicles and static test stands, explosive equivalent weight is the larger of:
  i. The weight equal to $4.13Q^{2/3}$ or $8W^{2/3}$ where Q is the mass of LH_2/LOX in kilograms and W is the mass of LH_2/LOX in pounds; or,
  ii. 14 % of the LOX/LH_2 mass.

Note: For these calculations, use the total mass of LOX/LH_2 present in the launch vehicle, or the total mass in test stand run tankage and piping for which there is no positive means to prevent mixing in credible mishaps. When it can be reliably demonstrated that the maximum credible event involves a lesser quantity of energetic liquids subject to involvement in a single reaction, the lesser quantity may be used in determining the explosive equivalent yield. When siting is based on a quantity less than the total energetic liquids present, the maximum credible event and associated explosive yield analysis must be documented in an approved site plan.

[j] RP-1 is a high-boiling kerosene fraction used as a rocket propellant.

at the site. The bulk oxygen system terminates at the point where oxygen at service pressure first enters the supply line. The oxygen containers may be stationary or movable, and the oxygen may be stored as gas or liquid.

Occupational Safety and Health Administration (OSHA) (29 CFR 1910.104) [4] defines a bulk oxygen system similar to the NFPA except for the storage capacity, which OSHA defines as a bulk oxygen system with more than 368 m^3 (13 000 ft^3) of oxygen at NTP, connected in service or ready for service, or more than 708 m^3 (25 000 ft^3) of oxygen (NTP), including unconnected reserves at the site [4].

The installation and location of nonpropellant bulk oxygen (both GOX and LOX) systems should conform to the requirements in 29 CFR 1910.104 [4] and NFPA 50. The quantity-distance guidelines for the location of oxygen storage systems were given in the previous sections for both nonpropellant and propellant use of oxygen.

Bulk oxygen storage systems should be located aboveground and outdoors or should be installed in a building of fire-resistive, noncombustible, or limited-combustible construction as defined in *Standard on Types of Building Construction* (NFPA 220) that is adequately vented and used for that purpose exclusively. Containers and associated equipment should not be located beneath, or exposed by the failure of, electric power lines, piping containing any class flammable[†] or combustible liquids[†], or piping containing flammable gases (NFPA 50).

Where it is necessary to locate a bulk oxygen system on ground lower than all classes of adjacent flammable or combustible liquid storage, suitable means should be taken (such as diking, diversion curbs, or grading) to prevent accumulation of liquids under the bulk oxygen system (NFPA 50).

Noncombustible barriers should be provided to deflect any incidental flow of LOX away from the site boundaries and control areas. LOX spills into public drainage systems should be prevented. Manholes and cable ducts should not be located in LOX storage and test areas.

LOX installations should be located at recommended distances from buildings, fuel storage facilities, and piping to provide minimum risks to personnel and equipment. An impermeable, noncombustible barrier must be provided to deflect any incidental flow of oxygen liquid or vapor from hazardous equipment, such as pumps, hot electrical equipment, or fuel lines, that are immediately adjacent to the LOX or GOX lines and that could be exposed to the effluent of a gaseous or liquid leak.

LOX tanks should be located away from oil lines and areas where hydrocarbons and fuels can accumulate. The tanks must not be located on asphalt, and oily or contaminated soil must be removed and replaced with concrete or

TABLE 8-4—Separation distances from LOX and fuel storage at a static test stand or a range launch pad to inhabited buildings, public traffic routes, and potential explosion sites.[a]

NEWQD,[b] kg (lb)	Inhabited Building Distance,[c] m (ft)		Public Traffic Route Distance, m (ft)	Intraline Distance[g] Between LOX Storage and a Potential Explosion Site,[h] m (ft)	
	Open[d]	Structure[e]		Barricaded[i] Distance	Unbarricaded Distance
<0.23 (0.5)	71.9 (236)	61.0 (200)	(Note *f*)	(Note *j*)	(Note *j*)
0.3 (0.7)	80.2 (263)	61.0 (200)	(Note *f*)	(Note *j*)	(Note *j*)
0.45 (1)	88.8 (291)	61.0 (200)	(Note *f*)	(Note *j*)	(Note *j*)
0.91 (2)	105.5 (346)	61.0 (200)	(Note *f*)	(Note *j*)	(Note *j*)
1.4 (3)	115.3 (378)	61.0 (200)	(Note *f*)	(Note *j*)	(Note *j*)
2.3 (5)	127.7 (419)	61.0 (200)	(Note *f*)	(Note *j*)	(Note *j*)
3.2 (7)	135.6 (445)	61.0 (200)	(Note *f*)	(Note *j*)	(Note *j*)
4.5 (10)	144.4 (474)	61.0 (200)	(Note *f*)	(Note *j*)	(Note *j*)
6.8 (15)	154.2 (506)	61.0 (200)	(Note *f*)	(Note *j*)	(Note *j*)
9.1 (20)	161.1 (529)	61.0 (200)	(Note *f*)	(Note *j*)	(Note *j*)
13.6 (30)	170.9 (561)	61.0 (200)	(Note *f*)	(Note *j*)	(Note *j*)
14.1 (31)	171.7 (563)	61.0 (200)	(Note *f*)	(Note *j*)	(Note *j*)
22.7 (50)	183.2 (601)	118.2 (388)	(Note *f*)	10.1 (33)	20.2 (66)
31.8 (70)	191.3 (628)	158.1 (519)	(Note *f*)	11.3 (37)	22.6 (74)
45.4 (100)	200.4 (658)	200.4 (658)	(Note *f*)	12.7 (42)	25.5 (84)
68.0 (150)	248.5 (815)	248.5 (815)	(Note *f*)	14.6 (48)	29.1 (96)
90.7 (200)	282.6 (927)	282.6 (927)	(Note *f*)	16.0 (53)	32.1 (105)
136.1 (300)	330.6 (1 085)	330.6 (1 085)	(Note *f*)	18.4 (60)	36.7 (120)
204.1 (450)	378.7 (1 243)	378.7 (1 243)	(Note *f*)	(Note *k*)	(Note *k*)
226.8 (500)	381.0 (1 250)		228.6 (750)	21.8 (71)	43.5 (143)
317.5 (700)	381.0 (1 250)		228.6 (750)	24.4 (80)	48.7 (160)
453.6 (1 000)	381.0 (1 250)		228.6 (750)	27.4 (90)	54.9 (180)
680.4 (1 500)	381.0 (1 250)		228.6 (750)	31.4 (103)	62.8 (206)
907.2 (2 000)	381.0 (1 250)		228.6 (750)	34.6 (113)	69.1 (227)
1 360.8 (3 000)	381.0 (1 250)		228.6 (750)	39.6 (130)	79.1 (260)
2 268.0 (5 000)	381.0 (1 250)		228.6 (750)	46.9 (154)	93.8 (308)
3 175.1 (7 000)	381.0 (1 250)		228.6 (750)	52.5 (172)	104.9 (344)
4 535.9 (10 000)	381.0 (1 250)		228.6 (750)	59.1 (194)	118.2 (388)
6 803.9 (15 000)	381.0 (1 250)		228.6 (750)	67.6 (222)	135.3 (444)
9 071.8 (20 000)	381.0 (1 250)		228.6 (750)	74.5 (244)	148.9 (489)
13 607.7 (30 000)	381.0 (1 250)		228.6 (750)	85.2 (280)	170.5 (559)
20 411.6 (45 000)	433.7 (1 423)		260.3 (854)	(Note *k*)	(Note *k*)
22 679.5 (50 000)	448.9 (1 474)		269.4 (884)	101.1 (332)	202.1 (663)
31 751.3 (70 000)	502.2 (1 649)		301.3 (989)	113.0 (371)	226.1 (742)
45 359.0 (100 000)	565.6 (1 857)		339.4 (1 114)	127.3 (418)	254.6 (835)
68 038.5 (150 000)	715.2 (2 346)		429.1 (1 408)	145.7(478)	291.5 (956)
90 718.0 (200 000)	844.4 (2 770)		506.6 (1 662)	160.4 (526)	320.8 (1 053)
113 397.5 (250 000)	960.4 (3 151)		576.2 (1 891)	(Note *k*)	(Note *k*)
136 077.0 (300 000)	1 020.5 (3 347)		612.3 (2 008)	183.6 (602)	367.2 (1 205)
226 795.0 (500 000)	1 209.9 (3 969)		725.9 (2 381)	217.7 (714)	435.4 (1 429)
317 513 (700 000)	(Note *k*)		(Note *k*)	243.6 (799)	487.1 (1 598)
453 590 (1 000 000)	(Note *k*)		(Note *k*)	274.3 (900)	548.6 (1 800)
680 385 (1 500 000)	(Note *k*)		(Note *k*)	314.0 (1 030)	628.0 (2 060)
907 180 (2 000 000)	(Note *k*)		(Note *k*)	345.6 (1 134)	691.2 (2 268)
1 360 770 (3 000 000)	(Note *k*)		(Note *k*)	395.6 (1 298)	791.2 (2 596)
2 267 950 (5 000 000)	(Note *k*)		(Note *k*)	469.0 (1 539)	938.1 (3 078)

[a] Source: DoD 6055.9-STD [5]. In addition to the values provided here, DoD 6055.9-STD also provides, in most cases, equations that permit the calculation of distances for quantities of NEWQD that are not listed in the table, and equations for calculating NEWQD for a specified distance.

[b] NEWQD = net explosive weight for quantity distance as obtained from Table 8-3, and consideration of other hazardous materials involved (see Note c of Table 8-3).

[c] For NEWQD <13,607.7 kg (30 000 lb), the distance is controlled by fragments and debris. Lesser distances may be permitted for certain situations. The minimum fragment distance is defined as the distance at which the density of hazardous fragments becomes 1 per 55.7 m^2 (600 ft^2). (*Note:* This distance is not the maximum fragment range.)

[d] Open indicates LOX storage in the open, or in an enclosure that is incapable of stopping primary fragments, which is defined as fragments from materials in intimate contact with reacting ammunition and explosives.

[e] Structure indicates LOX storage in an enclosure that is capable of stopping primary fragments.

[f] Computed as 60 % of applicable inhabited building distance.

[g] Intraline distance is the distance to be maintained between two ammunition and explosives-related buildings or sites within an ammunition and explosives-related operating line. The term "ammunition and explosives" includes liquid propellants (such as LOX).

[h] A potential explosion site is the location of a quantity of ammunition and explosives that will create a blast, fragment, thermal, or debris hazard in the event of an accidental explosion of its contents.

[i] Barricade is an intervening natural or artificial barrier of such type, size, and construction that limits the effect of an explosion on nearby buildings or exposures in a prescribed manner.

[j] For less than 22.7 kg (50 lb), less distance may be used when structures, blast mats, and the like can completely contain fragments and debris. This table is not applicable when blast, fragments, and debris are completely confined, as in certain test firing barricades.

[k] This distance was not given in DoD 6055.9-STD.

crushed stone. The location and amount of nearby flammable liquid† and fuel storage must be reviewed frequently.

Storage tanks and impounding areas for propellant use of oxygen must be located far enough from property lines to prevent damage by radiant heat† exposure and fragmentation to buildings and personnel located outside the plant property limits. Radiant heat flux must be limited at the property lines to avoid damage to off-property structures.

Ground slope modification, appropriately sized gullies and dikes, and barricades must be used for protection of facilities adjacent to oxygen storage and use facilities.

Oxygen storage and use facilities must be protected from failures of adjacent equipment (for example, pumps), which could produce shrapnel.

The system and component designs and installations should restrict the presence of combustible materials. Items to be considered include mechanical devices, instruments, and operating procedures. Mechanical devices include suitable fittings and connections, valves and valve outlet designs, transfer hoses, filters, and check valves. Instruments include analyzers to monitor oxygen purity and to detect leaks and spills. Operating procedures include purging with Gaseous Nitrogen (GN_2) before wetting with oxygen, attention to cleanliness requirements, and quality control programs.

Storage Vessels

At present, the minimum conventional vessel design criteria including engineering design calculations and procedures, fabrication, testing, and inspection for oxygen vessels are those presented in the ASME Boiler Pressure Vessel Code. This code also includes recommended formulas for calculating shell and head thicknesses to withstand the designed internal pressures and for determining thickness requirements for vessel openings and reinforcements. It must be recognized that the code suggests minimum safe standards that can be exceeded if they are found to be insufficient on the basis of specialized experiences. For example, Section VIII, Division 2 (Alternative Rules) of the *ASME Boiler and Pressure Vessel Code* allows the use of higher design stresses than are permitted under Section VIII, Division 1 (Pressure Vessels) but also requires greater attention to design analysis, loadings, fatigue evaluation, fabrication, and inspection. Section VIII, Division 2 (Alternate Rules) requires more precise design procedures and prohibits a number of common design details. This reference specifically delineates fabrication procedures and requires more complete examination and testing. The guidelines presented in Section VIII, Division 2 should be reviewed, and many of the requirements should be accepted as the minimum for LOX vessels.

In many instances where oxygen is used as a propellant, LOX storage vessels for ground support equipment are designed to serve as both storage and run tanks; as run tanks they provide the oxygen directly into the test or flight equipment without an intermediate vessel or liquid transfer operation. The design and construction requirements for such a combined storage-run tank are more demanding because the pressure and flow requirements are usually considerably greater than those for a storage vessel alone.

Large industrial oxygen users commonly purchase LOX storage vessels from vendors who are familiar with low-temperature equipment design, fabrication, and operation. The specifications should be sufficiently detailed for a LOX storage system that is safe for long-term use. The design calculations must take into consideration the intended use of the vessel and its storage and heat leak requirements.

Rollover

Rollover is a mechanism by which an abnormal pressure rise in a cryogenic storage vessel can occur. This phenomenon is associated with the storage of fluids in which a surface layer of the fluid becomes denser than the fluid beneath it and subsequently the denser layer sinks to the bottom and warmer fluid rises to the surface. This commonly occurs in lakes in cold climates where the water on the surface cools (becoming denser) and sinks to the bottom, which permits warmer water to come to the surface where it is cooled and then sinks to the bottom. Thus, no freezing occurs until the entire body of water is cooled to approximately 277 K (39°F). The same phenomenon has occurred in the Dead Sea, where surface evaporation of the water has resulted in a denser layer on the surface, which eventually sank allowing the subsurface water to rise.

Rollover can occur in cryogenic fluid storage vessels, especially in a closed vessel where the fluid can stratify. A cryogenic fluid in a storage vessel is subject to heat input from the ambient environment on the outside of the vessel. Heat enters the fluid from the bottom and the sides. The top layer of fluid in a vessel can lose heat through evaporation (and is thus cooled and gets denser), but the bottom layer tends to lose heat only by conduction to the top layer (and thus gets warmer and less dense). As the lower fluid, which gets warmer and has a higher vapor pressure, approaches the surface, it also is suddenly relieved of hydrostatic pressure and can boil vigorously. This phenomenon is characterized by a sudden rapid generation of vapor. This large increase in boiloff can be a hazard if the storage vessel's pressure relief system is unable to handle it. Multicomponent fluids, such as liquefied natural gas (LNG), with a number of constituents each with a different vapor pressure and a different density at any given temperature, are especially susceptible to rollover.

Rollover has occurred in LNG storage vessels; i.e. demonstrated using fluids, such as LNG, Freon, salt water, and a liquid nitrogen and LOX mixture.

Methods for addressing the overpressure hazard presented by rollover include the following:

- providing a properly designed pressure relief system,
- mixing, or stirring, of the fluid to prevent stratification, and
- using a proper refill procedure (transfer a fluid that is denser than the fluid in the vessel to the top of the vessel, or a fluid that is less dense to the bottom of the vessel; i.e., transfer in such a way that good mixing of the transfer fluid and the fluid in the vessel is achieved).

Storage and Handling of Compressed Gas Cylinders

Compressed gas cylinders containing oxygen must be stored and handled in accordance with established procedures as given in standards and codes such as CGA G-4, CGA P-1, NFPA 55, NFPA 50, NFPA 51, and 29CFR1910.104. The following are some of the requirements from those standards:

1. Compressed gas containers, cylinders, or tanks, in storage or in use, should be restrained to prevent their being knocked over or falling. Compressed gas cylinders may be secured to a cart or a fixed object (CGA G-4, CGA P-1, NFPA 55).

2. A valve-protection cap should be kept on a compressed gas cylinder unless the cylinder is in use (CGA G-4, CGA P-1, NFPA 55).
3. Compressed gas cylinders of oxygen should be kept at the location and minimum separation distance from flammable and other hazardous fluids, as specified by standards and codes such as CGA G-4, CGA P-1, NFPA 51, NFPA 50, and 29CFR1910.104.

Storage and Handling of LOX Cylinders

LOX cylinders are double-walled pressure vessels, usually of 170.3-L (45-gal) capacity or greater. LOX cylinders normally operate at an absolute pressure greater than 172 kPa (40 psia); consequently, they are classified as compressed gas cylinders and must be designed, constructed, tested, packaged, and shipped as required by federal regulations (CGA G-4). LOX cylinders should not be confused with atmospheric pressure LOX containers, which are commonly referred to as "dewars" (CGA G-4). The following are some LOX cylinder storage and handling guidelines. A LOX cylinder:

- should not be subjected to shocks, falls, or impacts because it has an inner container suspension system that is designed to minimize heat leak. Damage to the inner container could allow LOX to enter the annular space where it would rapidly vaporize, rapidly build up pressure, and cause an explosive rupture of the outer shell (CGA G-4).
- should always be kept upright (CGA G-4).
- should be moved only on a four-wheeled cart designed for transporting a full cylinder, which is very heavy (CGA G-4).
- should be kept at the location and minimum separation distance from flammable and other hazardous fluids as specified by standards and codes, such as CGA G-4, CGA P-1, NFPA 51, NFPA 50, NFPA 55, and 29CFR1910.104.

Venting and Disposal Systems

LOX Disposal

Uncontaminated LOX should be disposed of using contained vaporization systems. It should not be dumped on the ground because organic materials such as macadam or asphalt, which are impact sensitive in LOX, may be present (see "Leaks and Spills" in Chapter 1). Recommended vaporization systems include:

- Direct-contact steam vaporizers in which LOX is mixed with steam in open-ended vessels. The vaporized liquid is ejected from the top of the vessel along with entrained air and condensed steam.
- Heat sink vaporizers, which are large containers filled with clean gravel and covered to exclude atmospheric contamination. The capacity of this type of vaporizer is limited to the sensible heat of the gravel.

Vapor cloud dispersion studies should be performed, taking into account evaporation rates, cold vapor stability, spill sizes, and ground conditions. The studies should include the effects of ignition under various stages of developing oxygen-enriched† air-fuel mixtures.

A problem with LOX disposal is the concentration of relatively small quantities of dissolved hydrocarbons caused by preferential vaporization of oxygen. When LOX has been contaminated by fuel, isolate the area from ignition sources and evacuate personnel. Allow the oxygen to evaporate and the residual fuel gel to achieve ambient temperature. The hazard associated with this impact-sensitive gel is long-lived and difficult to assess. Inert the oxygen system thoroughly with GN_2 before any other cleanup step.

GOX and LOX Venting

All dewar, storage, and flow systems should be equipped with unobstructed venting systems. Materials used in disposal and vent systems should be corrosion-resistant and maintained at the required cleanliness level. Oxygen venting and dumping should be restricted to concentrations that are safe for personnel at all directions and distances. A complete operations and failure mode analysis should provide the basis for determining such conditions.

Generally, venting GOX from a pressurized system to the surrounding atmposphere creates a region of high gas velocity proximate to the relief component (i.e., vent valves, pressure-relief valves, pressure safety valves, and rupture disks). As such, particle impact is an active ignition mechanism in these components and has been known to cause fires in relief devices and associated piping. Even systems venting to atmospheric pressure can retain high gas velocities and elevated pressures for extended distances downstream of relief components. Thus, local gas velocities and associated pressures immediately upstream, internal to, and downstream of relief devices should be calculated to ensure that proper materials for the application are used. For more information on particle impact, see Chapters 2, 3, and 5.

Interconnecting vent discharges to the same vent stack may overpressurize parts of the vent system. The vent system must be designed to handle the flows from all discharges, or it may produce backpressure in other parts of the system. Inadequate designs may effectively change the release pressure on all pressure-relief valves and rupture disks connected to the vent system because these devices detect a differential pressure.

High-pressure, high-capacity vent discharges and low-pressure vent discharges should not be connected to the same vent stack unless the vent capacity is sufficient to avoid overpressurization of the weakest part of the system.

Venting should be far enough from personnel areas to permit natural dilution to safe limits. Consideration should be given for both oxygen enrichment and oxygen depletion, when venting inert gases from an oxygen system or when cleaning or purging the system. Before venting or relieving pressure, operating personnel should be cleared from the area.

Vent-stack outlets should be downwind from the prevailing wind direction, well removed from air intakes of test cells and control buildings, and away from walkways, platforms, and traffic lanes. Large, scheduled discharges should be when the wind is favorable.

Discharges from all storage and transportation systems (from rupture disks and pressure relief valves) should be to the outdoors through a vent line sized to carry the boiloff that would result from a total loss of insulation. The oxygen vents should be located at the highest possible point and should exhaust the gas vertically. Venting into valve and pump operating enclosures will saturate the area and, in an emergency, the operators could be exposed to excessive hazards while attempting to control the equipment.

The vent design should provide protection from rain, snow, and ice buildup. To restrict the entry and freezing of atmospheric water, outlets of small vent pipes should be turned downward, and outlets of large vent stacks should have caps. The use of tees is recommended for vent-stack outlets. A low-point drip leg should be incorporated into vent-stack designs with vent-line plumbing and valving oriented to drop towards a collection area. All probable sources of water entry should be controlled in this manner to prevent freezing components, which will make this safety system inoperable.

Screens should be mounted over vent openings to prevent insects or birds from building nests that will block the opening. Rapid pressurization of such contaminants has led to fires. For more information on rapid pressurization, see Chapters 2, 3, and 5.

Oxygen Detection

Whether oxygen detectors are installed is a decision that should be made by the authority having jurisdiction. Considerations involved in making this decision should include system construction and complexity, as well as the effects of system leaks on the facility or adjacent equipment. The installation of a detector system does not eliminate or reduce the requirement that systems be constructed leak-free and that the system be inspected and validated at regular intervals.

Reliable oxygen detection and monitoring systems should:

- Identify possible oxygen-enriched areas. Although detection systems will not pinpoint a leak, they may or may not indicate the existence of one depending on wind, or detection method. Leak detection by observation alone is not adequate. Although the cloud and moisture that accompany LOX leaks is visible, leak detection by observing such clouds is not reliable.
- Warn whenever the worst allowable condition is exceeded. Visual alarms should be considered for the system to indicate that a problem exists.
- Be designed and installed to allow for proper operation of the test equipment, while at the same time providing adequate warning time to reduce the potential for exposure to possible hazards or hazardous conditions.

Only detection units validated and approved by the authority having jurisdiction with a review for oxygen and oxygen-enriched atmospheres should be used. The detection units and their response times should be evaluated for suitable performance. Typical oxygen detection equipment used at NASA test facilities, for example, includes the following (ranging from 0 to 25 and 0 to 100 vol %):

- galvanic,
- paramagnetic,
- electrochemical (ZrO_2 sensor, fuel cell, open-cathode oxygen cell, polarographic),
- gas chromatograph, and
- mass spectrometer.

When planning an oxygen detection system, several steps should be taken:

1. Evaluate and list all possible sources to be monitored. Valid justification should be presented for any sources that are not considered for monitoring.
2. Evaluate the expected response time of the oxygen detection system to ensure the compatibility of the fire detection or safety system considered for use.
3. Include carefully maintained and periodically recalibrated detectors as well as means to ensure that any leaking oxygen passing the detectors will be sensed.
4. To initiate corrective actions in as short a time as possible, consider the oxygen detection system with the fire detection and other safety systems used.

Locations requiring consideration for detectors include the following:

- leak sources in which the possibility of fire must be eliminated, such as valve complexes, buildings, containers, and test equipment;
- at LOX valves, outside LOX containers, and at exposed LOX lines, although leaks from these sources may be allowed to diffuse into the atmosphere; and
- vacuum-jacketed LOX equipment. Leaks through vacuum-jacketed equipment can best be detected by temperature-monitoring systems. When it has been established that a leak exists in a vacuum-insulated vessel, the first step is to analyze the discharge of the vacuum pump with an oxygen analyzer to determine whether the leak is in the outer casing or in the liquid container. If the analysis shows a normal purity of approximately 21 vol % oxygen, the leak into the vacuum space is probably from the atmosphere. An analysis that shows nitrogen would be a more positive indication that the leak was from the atmosphere.

Fire Protection Systems for Oxygen-Enriched Environments

NFPA 53 contains relevant data pertaining to fire extinguishing in oxygen-enriched atmospheres. Much of the information in this section summarizes portions of Chapter 7 of NFPA 53.

Various techniques and methods have been developed that provide protection against fires and explosions:

- containers sufficiently strong to withstand explosions (*ASME Boiler and Pressure Vessel Code*, Section VIII, and *Guide for Explosion Venting* [NFPA 68]);
- venting methods to prevent vessel failures (NFPA 68 and Ref [6]).
- sufficient clearances and separations between oxygen containers and incompatible materials, storage tanks, plant equipment, buildings, and property lines that any incident or malfunction has a minimum effect on facility personnel and public safety. These may include protective enclosures such as barricades or cell enclosures [7].
- Ignition- and flame-prevention techniques (*NFPA Fire Protection Handbook*).

General

Because the combustion rate of materials in oxygen-enriched atmospheres is so greatly increased, response by professional fire fighters may not be quick enough to preclude major damage to a facility. For this reason, operational personnel must be fully trained and instructed in the operation of the firefighting equipment provided. However, operational personnel should not attempt to fight any major fires. Their mission should be to secure the system as best possible, notify the fire department, and advise and direct qualified fire-fighting personnel as needed. The heightened level of oxygen fire volatility should further emphasize the use of highly trained firefighting professionals.

Extinguishing systems designed for the normal atmosphere may not be effective in an oxygen-enriched atmosphere. Rigid specifications for the design of fire-extinguishing systems for any planned or potential oxygen-enriched atmosphere have not been established. Each location will have its own particular set of requirements. General guidelines have been delineated that will help set up a fire-extinguishing system for a particular use.

An evacuation plan for personnel in oxygen-enriched atmospheres should be developed and the personnel should be instructed. Quick evacuation is necessary to protect personnel from fire exposure, toxic gas exposure, and extinguishing agent exposure. Fire protection provisions for hyperbaric and hypobaric facilities are in *Standard for Health Care Facilities* (NFPA 99) and *Standard for Hypobaric Facilities* (NFPA 99B).

Fire-Extinguishing Systems

Fire-extinguishing systems may be either automatic or manual.

Automatic

It is recommended that fixed fire-extinguishing systems capable of automatic actuation by fire detection systems be established for locations containing oxygen-enriched environments. In such systems, the emphasis of the design should be on early detection, rapid activation of the suppression system, and evacuation of personnel. Where possible, detection systems should concentrate on sensing fires as soon as possible, especially in the earliest stages of smoldering, before visible smoke or flames. Air-sampling particle detection systems have been used in this application to continuously monitor equipment and enclosed spaces. The extinguishing system also should provide rapid discharge such as that used in deluge-type water sprays. Where protection of personnel is an issue, preprimed deluge systems should be considered. It is up to the responsible authority to decide if the automatic system should be kept in operation continuously during unoccupied periods. Spaces left unattended for short time periods should have the automatic system still in operation.

Manual

Manual fire-extinguishing systems can be used as a supplement to an automatic system. In some cases, small fires may be extinguished manually before actuation of an automatic system.

Fire-Extinguishing Agents

Depending on the location and application, personnel may work in oxygen-enriched atmospheres. Therefore, the use of specific fire-extinguishing agents must be evaluated with respect to their inherent toxicity and the toxicity of breakdown products when used. Because materials burn more rapidly, burn with greater intensity, and spread fires more easily in oxygen-enriched atmospheres, significant increases in water densities or gaseous concentrations of extinguishing mediums are necessary to extinguish fires. In addition, the rate at which extinguishing agents are applied should be increased. Although there are no standards for a minimum system design, the most effective general rule is to provide complete coverage with as much water or another acceptable extinguishing medium as practically possible. In enclosed oxygen-enriched systems occupied by personnel, the toxicity of the extinguishing medium and the ability of personnel to evacuate with the suppression system operating must be considered in the design. Standards for extinguishing in hypobaric and hyperbaric facilities are contained in NFPA 99B and NFPA 99, respectively.

Materials for fire fighting involving an oxygen-enriched environment should be restricted to water (preferred), sand, or chemical fire extinguishers using dry chemicals based on sodium bicarbonate, potassium bicarbonate, carbon dioxide, phosphates, or an appropriate grade of halogenated hydrocarbon (except chlorinated hydrocarbons). Methyl bromide fire extinguishers should not be used [8]. Water is the most effective extinguishing agent when sufficiently applied. A design using fixed water spray nozzles can be effective. NFPA 15, Water Spray Fixed Systems for Fire Protection, covers installations of systems for areas with ordinary atmospheric air, but many of the design criteria are pertinent to areas with oxygen-enriched atmospheres. Only limited data exist regarding the effectiveness of carbon dioxide in extinguishing fires in oxygen-enriched atmospheres [9,10]. The flooding of an entire space is generally impractical because of the hazards to personnel from asphyxiation and toxicity.

Barricades

Barricades[3] needed in oxygen propellant test areas to shield personnel, dewars, and adjoining areas from blast waves[†] or fragments resulting from a pressure vessel failure may also be needed to isolate LOX storage areas from public or private property that may otherwise be too close [5]. To control liquid and vapor travel caused by spills, facilities should include barricades, shields for diverting spills, or impoundment areas. Any loading areas and terrain below transfer piping should be graded toward a sump or impoundment area. The surfaces within these areas should be cleaned of oils, greases, hydrocarbons, and other materials, such as vegetation, that can be easily ignited. Inspections should be made to ensure good housekeeping. Liquid-containment dikes surrounding storage vessels should be designed to contain 110 % of the LOX in the fully loaded vessel.

The most common types of barricades are mounds and revetments. A mound is an elevation of naturally sloped soil with a crest at least 0.914 m (3 ft) wide, with the soil at an elevation such that any line-of-sight, from the structure containing the oxygen hazard to the structure(s) to be protected, passes through the mound. A revetment is a mound modified by a retaining wall on the side facing the potential hazard source.

Results of analytical studies and tests show that:

1. Barricades reduce peak pressures and shock waves immediately behind the barricades. However, the blast wave can reform at some distance past the barricade.
2. Revetments are more efficient than mounds in reducing peak pressures and impulses near the barricades.
3. Peak pressure and impulse are greatly influenced by the height above the ground, the location of the barricade, and the barricade dimensions and configuration.

Pumps are usually required at oxygen storage and use facilities, and protection should be provided against overpressures from liquid flash off and from pump failures yielding shrapnel [11–16]. Housings for high-rotational-speed test rigs may be designed as the shrapnel shield between the rig and the vessel. When determining the location for pressure vessels, consider the possibility of tank rupture caused by impact from adjacent hardware. Shrapnel-proof barriers may be used to prevent the propagation of an explosion from one tank to another and to protect personnel and critical equipment.

Personnel guards should be specified for exposed moving parts and for hot and cold surfaces.

For more information about barricades, see Ref [16], which is a report on the design of barricades for hazardous

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[3] The requirements for barricaded open storage modules are explained in Chapter 5, "Facilities Construction and Siting," of Ref [5].

pressure systems, and Ref [17], which is a paper on options to consider when designing to limit explosion damage.

Facility Inspection

An oxygen facility, including storage, piping, and other components, should be inspected prior to initial operations of the facility to ensure compliance with material, fabrication, workmanship, assembly, and test requirements. The completion of all required inspections and testing should be verified. Verification should include, but not be limited to, certifications and records pertaining to materials, components, heat treatment, inspection and testing, and qualification of welding operators and procedures. The authority having jurisdiction should assure that the safety equipment required at the operational site is present and that all necessary support organizations, such as security, have been notified.

Material identification should be required for all storage vessels, piping, and components used in fabrication and assembly of an oxygen system. No substitutions for the materials and components specified in the engineering design should be permitted except when the substitution has written approval of the authority having jurisdiction.

Storage vessels should be inspected in accordance with the ASME Boiler and Pressure Vessel Code. Visual inspections should verify dimensions, joint preparation (alignment, welding, or joining), and the assembly and erection of supports.

Piping, and piping components, should be inspected in accordance with the ASME Power Piping Code (ASME B31.3). Visual inspections should verify dimensions, joint preparation (alignment, welding, or joining), and the assembly and installation of supports. Piping, and its components, should be inspected before and during installation for the integrity of seals and other means of protection provided to maintain the special cleanliness or dryness requirements specified for oxygen systems.

A bulk oxygen storage system installed on consumer premises shall be inspected annually by a qualified representative of the equipment owner (NFPA 50).

Facility Testing, Certification,† and Recertification

All pressure vessels, piping, and their components should be designed, tested, operated, and maintained in accordance with the requirements and standards specified by the authority having jurisdiction. A schedule for the inspection, certification, and recertification should be established by the authority having jurisdiction for each oxygen storage vessel or pressurized system component.

Records should be made and retained for each inspection and recertification inspection of an oxygen system (especially pressure vessels and pressurized system components). These records should be retained for the life of the vessel or component. These records should include such information as: vessel or component identification, test performed, conditions of the test, test results, test method, test fluid, test pressure, hold time, test temperature, description of any leaks or failures, and approval of the authority having jurisdiction.

Leak and pressure testing methods and operations should be specified and approved by the authority having jurisdiction. Personnel and equipment should be adequately protected during the leak and pressure testing. Any system to be used in oxygen service should be leak tested before operation. Leak testing is commonly performed in conjunction with pressure testing of the system. The system should be leak tested to the extent possible with inert gases before oxygen is introduced into the system. After installation, all field-erected piping should be tested and proved gas tight at the maximum operating pressure. Any medium used for testing should be oil free and nonflammable (29CFR1910.104).

A cryogenic system should be cold tested after it has been pressure tested and proved gas tight. The cold test may be made with liquid nitrogen, if necessary, with appropriate adjustment made for weight. The appropriate cryogenic temperature should be maintained in the system for a minimum of 1 h.

All welds in storage vessels and piping should be tested as required by the *ASME Boiler and Pressure Code* and the *ASME Power Piping Code* (ASME B31.3), as appropriate.

Facility Maintenance

The equipment and functioning of each charged bulk oxygen system should be maintained in a safe operating condition. A bulk oxygen storage system installed on consumer premises should be maintained by a qualified representative of the equipment owner (NFPA 50). A facility that is temporarily out of service should continue to be maintained in an appropriate manner as specified in a plan approved by the authority having jurisdiction (NFPA 55).

Facility maintenance should include:

- maintenance of the fire-extinguishment systems,
- inspection of pressure vessels and pressurized systems, and
- the removal of wood and long dry grass within 4.6 m (15 ft) of any bulk oxygen storage container (29CFR1910.104).

Facility Repairs, Modifications, and Decommissioning

Before any repairs, modifications, or decommissioning are performed, cryogenic vessels or piping systems should be drained, warmed to ambient temperature, purged, and sampled. All connections to other systems should be disconnected and tagged. Disconnected lines should have blank flanges with gaskets to prevent leaking or spilling. Any electric power supply to equipment within the vessel or piping should be de-energized. Vessels or piping systems placed in standby condition should be maintained under a positive pressure of dry gaseous nitrogen.

For major repairs, modifications, or decommissioning, the vacuum annulus of a LOX storage vessel should be warmed and purged with dry gaseous nitrogen. The purge should be sufficient for warming the insulation to remove absorbed moisture or other gases. Warm nitrogen purge rates of 4 to 7 m^3/min per cubic meter (4 to 7 ft^3/min per cubic foot) of insulation should be sufficient. Approved procedures should ensure that the inert gas purging does not result in a potential asphyxiation hazard to personnel. Purging is more effective when a sparger arrangement of breathers is located at the bottom of the casing. Helium should not be used to purge a vacuum annulus because of the difficulty of removing it from the annulus when the vessel is reactivated. Nitrogen should not be used to purge a vacuum annulus if the temperature of the inner vessel is sufficiently low to condense the nitrogen.

A facility that is not kept current, or is not monitored and inspected on a regular basis, is deemed to be permanently out of service and should be closed in an appropriate manner as specified in a closure plan by the authority having jurisdiction (NFPA 55).

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[4] CFR Title 29, *Occupational Safety and Health Standards, Code of Federal Regulations*, Part 1910, Sections. 94(d), 104, 114, 115, 252(a), and 252(f), 1986.

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9

Transportation

Standards and Guidelines

STANDARDS AND GUIDELINES FOR THE transportation of oxygen are for the protection of people and infrastructure. Transportation of gaseous oxygen (GOX) or liquid oxygen (LOX) on public thoroughfares is covered by federal and state transportation standards and guidelines (Table D-1, Appendix D). All operations for the transport of GOX or LOX shall adhere to these standards.

Transportation of GOX or LOX on nonpublic thoroughfares is controlled by the authority having jurisdiction, is the responsibility of cognizant site authorities, and is covered by federal and state labor standards and guidelines. Where conditions and requirements of use on site are similar to those of public thoroughfares, federal and state transportation standards and guidelines should be used (Table D-1, Appendix D).

Definitions

GOX and LOX can be transported by means that vary from small cylinders to tanks on barges, railroad cars, and trucks. Transport containers are described according to definitions developed by the DOT (49 CFR 171.8) [1]. Basic definitions include the following:

1. GOX is specified as a compressed gas (UN1072) with a hazard class of 2.2 (nonflammable gas, oxidizer) by DOT (see 49 CFR 172.101 and 49 CFR 173.115) [1].
2. LOX is specified as a refrigerated liquid (cryogenic liquid) (UN1073) with a hazard class of 2.2 (nonflammable gas, oxidizer) by DOT (see 49 CFR 172.101 and 49 CFR 173.115) [1].
3. A cargo tank is described by 49 CFR 171.8 [1] as a bulk packaging that:
   a. Is a tank intended primarily for the carriage of liquids or gases and includes appurtenances, reinforcements, fittings, and closures (for "tank," see 49 CFR 178.345−1(c), 178.337−1, or 178.338−1 [1], as applicable);
   b. Is permanently attached to, or forms a part of, a motor vehicle, or is not permanently attached to a motor vehicle but that, by reason of its size, construction, or attachment to a motor vehicle is loaded or unloaded without being removed from the motor vehicle; and
   c. Is not fabricated under a specification for cylinders, portable tanks, tank cars, or multiunit tank car tanks.
4. A cylinder is defined by 49 CFR 171.8 [1] as "a pressure vessel with a circular cross section designed for absolute pressures greater than 275.7 kPa (40 psi). It does not include a portable tank, multi unit car tank, cargo tank, or tank car" [1].

Transport on Public Thoroughfares

General

Although most transport on public thoroughfares involves commercial carriers, the responsibility for complying with federal and state transportation laws rests not only with them, but also with the organizations that handle and receive oxygen. Transportation of oxygen-loaded systems should not be scheduled during peak traffic periods, if possible.

Training

Personnel involved in handling, receiving, shipping, and transport of a hazardous material must receive Hazardous Materials (HAZMAT) training (49 CFR 172.700) [1].

Emergency Response

During all phases of transport, emergency response information is required at facilities where hazardous materials are either loaded, stored, or handled (49 CFR 172.600) [1]. Advanced planning for a variety of potentially hazardous and disastrous fires and explosions shall be undertaken with full realization that the first priority is reduction of any risk to the lives of emergency personnel and bystanders. Shipments of oxygen may be monitored by CHEMTREC, whose toll-free emergency telephone number is 800-424-9300 (worldwide 202-483-7616). Dow Chemical's Emergency Response System provides another emergency resource with a Continental USA contact at 800-DOW-CHEM (369-2436) and a Europe, Middle East, and Africa contact in the Netherlands at 31-115-694982.

Transport Requirements for GOX

General requirements for the transport of GOX are given in *Table of Hazardous Materials and Special Provisions* 49 CFR 172.101 [1], and *Shippers-General Requirements for Shipments and Packaging* 49 CFR 173 [1].

> *The proper shipping name for GOX is* "Oxygen, compressed." *Packaging must be labeled* "NONFLAMMABLE GAS, OXIDIZER."

Special packaging requirements are given in *Charging of Cylinders with Nonliquified Compressed Gases* (49 CFR 173.302) [1]; *Limited Quantities of Compressed Gases* (49 CFR 173.306) [1]; and *Compressed Gases in Cargo Tanks and Portable Tanks* (49 CFR 173.315) [1]. Specifications for the qualification, maintenance, and use of cylinders are covered in 49 CFR 173.34 [1], for the design of cylinders in 49 CFR 178.36 [1], for the design of cargo tank motor vehicles in 49 CFR 178.337 [1], and for the loading and unloading of cylinders in 49 CFR 177.840 [1].

GOX in quantities up to 75 kg (165 lb) may be transported on board passenger aircraft or railcars. GOX in quantities up to 150 kg (330 lb) are permitted aboard cargo aircraft. It may be stowed on deck or under deck on a cargo vessel or a passenger vessel (49 CFR 172.101) [1].

Transport Requirements for LOX

General requirements for the transport of LOX are given in *Tables of Hazardous Materials and Special Provisions* 49 CFR 172.101 [1], and *Shippers-General Requirements for Shipments and Packaging* 49 CFR 173 [1].

> *The proper shipping name for LOX is* "Oxygen, refrigerated liquid (cryogenic liquid)."
> *Packaging must be labeled* "NONFLAMMABLE GAS, OXIDIZER."

Packaging requirements are given in *Cryogenic Liquids in Cylinders* (49 CFR 173.316) [1]; *Cryogenic Liquids in Cargo Tanks* (49 CFR 173.318) [1]; and *Cryogenic Liquids; Exceptions* (49 CFR 173.320) [1]. Specifications for the qualification, maintenance, and use of tank cars are covered in 49 CFR 173.31 [1], for the design of insulated cargo tanks in 49 CFR 178.338 [1], and for the loading and unloading of cylinders in *Class 2 (gases) Materials* (49 CFR 177.840) [1].

LOX is not permitted abroad passenger aircraft, passenger railcars, or cargo aircraft. It may be stowed on deck on a cargo vessel, but is prohibited on a passenger vessel (49 CFR 172.101) [1].

Transport on Site-Controlled Thoroughfares

Standard Commercial Operation on Site

Federal and state transportation guidelines can be applied in lieu of special requirements on privately and government-controlled sites where conditions and requirements of use are similar to those of public thoroughfares.

Noncommercial Transport Equipment

Noncommercial Equipment or Special Operations

Special equipment or operations used for the transport of oxygen must meet federal and state labor requirements (29 CFR) [2] as well as additional requirements of the cognizant authority having jurisdiction.

Guidelines for the Design of Noncommercial Transport Equipment

General Guidelines

- Where applicable, standard oxygen design practice should be used (Chapters 2 through 5).
- The tank design will be in accordance with accepted design practice (ASME Boiler and Pressure Vessel Code).
- Redundant pressure relief protection must be provided to the tank and piping systems.
- The design of the undercarriage should isolate the tank and piping systems from potential collision damage.
- Controls should prevent oxygen venting while the vehicle is in motion.
- The trailer should use a fail-safe emergency brake system.

Requirements for Highway Service

The design of noncommercial vehicles must comply with federal and state transportation guidelines for operation on public thoroughfares as discussed earlier in this chapter. In addition to the general guidelines above, the design must meet highway standards for cargo tank design (49 CFR 178.338 [1] for cryogenic transport and 49 CFR 178.337 [1] for gas carriers).

General Operating Procedures

The following guidelines apply to all oxygen transport operations.

General

Operational areas should remain clear of nonessential personnel. Appropriate personal protective equipment should be used. Facilities should maintain necessary deluge systems. Operational procedural checklists should be used.

Transport systems should be adequately grounded. Spark-producing and electrical equipment that is within the operational area and is not hazard-proof should be turned off and locked out. All tools used shall comply with established safety requirements. All tank inlets and outlets, except safety relief devices, should be marked to designate whether they are covered by vapor or liquid when the tank is filled.

The operational area should be kept free of combustible materials. Oxygen will vigorously support combustion of any materials such as paint, oils, or lubricants that make up the cargo tank or may be found on the ground.

> *Note: LOX forms shock-sensitive explosive compounds with carbonaceous materials. Transfer operations should not be conducted over asphalt surfaces or porous surfaces such as sand that may hide the presence of oils and greases.*

Trailers should be equipped with a dry-chemical fire extinguisher. The rating should not be less than 10 BC.

In the event of an oxygen leak the transfer must be stopped and the leak repaired. In the event of a fire the oxygen sources should be isolated as quickly as possible.

Repair Operations

Before any type of maintenance is attempted, the system should be depressurized; all oxygen lines disconnected, drained, or vented, and purged; the operations area inspected; and the security of all systems verified. Repairs, alterations, cleaning, or other operations performed in confined spaces where oxygen vapors or gases are likely to exist are not recommended until a detailed safety procedure is established. As a minimum, this procedure should include the evacuation and purging requirements necessary to ensure safe entry in the confined space. The personnel engaged in the operations should be advised of the hazards that may be encountered, and at least one person should be immediately available while the work is being performed to administer emergency rescue, should it be necessary.

Venting Operations

Where possible, facility venting should be used. In the field, a safe location, remote if possible, should be selected for venting. Consideration should be given to the wind direction so that vented gas will be carried away safely.

Inspection, Certification, and Recertification of Mobile Vessels

Mobile vessels shall be recertified periodically (see 49 CFR 180) [1], especially for public thoroughfares. Department of Transportation specifications require periodic pressure retests of LOX vessels and of pressure-relief valves (49 CFR 173.31 and 173.33) [1]. See 49 CFR 178.337 [1] for GOX and 49 CFR 178.338 [1] for LOX tankage testing.

Transportation Emergencies

Initial Actions

The first concern in a transportation emergency shall be to prevent death or injury. In an incident or emergency, try to get the vehicle off the road if possible, preferably to an open location that is off an asphalt road or parking lot. Shut off the tractor-trailer electrical system. Post warning lights and signs and keep people at least 152 m (500 ft) away for GOX or 800 m (1/2 mile) away for LOX. Contact authorities and obtain help:

> **CHEMTREC (800-424-9300)** (worldwide 202-483-7616)

Emergency Actions

Emergency actions to combat leaks and fires involving oxygen tractor-trailers include pulling the vehicle into the least hazardous area and turning the ignition off. For fires originating near the engine, use a fire extinguisher; for tire fires, use water or chemical fire extinguishers or both. Tires may reignite 20 to 30 min after the initial fire has been extinguished, so the driver should not leave the scene until the tire temperature is lowered sufficiently. Also, the driver should not leave the scene until the fire has been completely extinguished and the burning materials cooled.

Aid should be requested from the nearest fire or police department or both. On the highway, the environment in which a fire and subsequent damage may occur is difficult to control. An incident may occur at any time and at any place along the route. A controlled release of oxygen from the trailer through venting should take into account all possible ignition sources, vapor dispersion, population exposure, and general safe operations. Flares normally used for highway vehicular incident identification should not be used in close proximity to upset or damage LOX tanks.

References

[1] CFR Title 49, *Transportation, Code of Federal Regulations*, Parts 171–180, Sections 171.8, 172.101, 172.700, 173.31, 173.33, 173.34, 173.115, 173.302, 173.306, 173.315, 173.316, 173.318, 173.320, 173.600, 177.840, 178.36, 178.337, 178.338.

[2] CFR Title 29, *Occupational Safety and Health Standards, Code of Federal Regulations*, Part 1910, Sections 94(d), 104, 114, 115, 252(a), and 252(f).

APPENDIX A

Chemical and Physical Properties of Oxygen

Oxygen, in both the gaseous and liquid states, is a powerful oxidizer that vigorously supports combustion.

The molecular weight of oxygen, O_2, is 31.9988 on the C^{12} scale, and its atomic weight is 15.9994 [A1]. Oxygen was the base used for chemical atomic weights, being assigned the atomic weight 16.000, until 1961 when the International Union of Pure and Applied Chemistry adopted carbon 12 as the new basis [A2,A3].

Oxygen has eight isotopes. There are three naturally occurring stable isotopes of oxygen; these have atomic mass numbers of 16, 17, and 18 [A2 – A4]. The naturally occurring isotopes of oxygen are difficult to separate; therefore, property data are generally obtained from naturally occurring oxygen, which has a concentration in the ratio of 10000:4:20 for the three isotopes of atomic mass numbers 16, 17, and 18 [A2]. Also, the data are most generally given for diatomic, molecular oxygen, O_2 [A2]. The metastable molecule, O_3 (ozone), is not addressed in this manual.

Gaseous oxygen (GOX) is colorless, transparent, odorless, and tasteless. High-purity liquid oxygen (LOX) is light blue, odorless, and transparent.

GOX is about 1.1 times as heavy as air (specific gravity = 1.105). LOX is slightly more dense than water (specific gravity = 1.14).

LOX is a cryogenic liquid and boils vigorously at ambient pressure. It is chemically stable, is not shock sensitive, and will

TABLE A-1—Properties of oxygen at standard (STP) and normal (NTP) conditions [A1].

Properties	STP	NTP
Temperature, K (°F)	273.15 (32)	293.15 (68)
Pressure (absolute), kPa (psi)	101.325 (14.696)	101.325 (14.696)
Density, kg/m^3 (lb_m/ft^3)	1.429 (0.0892)	1.331 (0.0831)
Compressibility factor (PV/RT)	0.9990	0.9992
Specific heat		
At constant pressure (C_p), J/g·K (Btu/lb_m·°R)	0.9166 (0.2191)	0.9188 (0.2196)
At constant volume (C_v), J/g·K (Btu/lb_m·°R)	0.6550 (0.1566)	0.6575 (0.1572)
Specific heat ratio (C_p/C_v)	1.40	1.40
Enthalpy, J/g (Btu/lb_m)	248.06 (106.72)	266.41 (114.62)
Internal energy, J/g (Btu/lb_m)	177.16 (76.216)	190.30 (81.871)
Entropy, J/g·K (Btu/lb_m·°R)	6.325 (1.512)	6.391 (1.527)
Velocity of sound, m/s (ft/s)	315 (1034)	326 (1070)
Viscosity, mPa·s (lb/ft·s)	19.24 (0.01924)	20.36 (0.02036)
Thermal conductivity, mW/m·K (Btu/ft·h·°R)	24.28 (1.293×10^{-5})	25.75 (1.368×10^{-5})
Dielectric constant	1.00053	1.00049
Equivalent volume/volume liquid at NBP	798.4	857.1

of LOX vessels and of pressure-relief valves (49 CFR 173.31 and 173.33) [1]. See 49 CFR 178.337 [1] for GOX and 49 CFR 178.338 [1] for LOX tankage testing.

Transportation Emergencies

Initial Actions

The first concern in a transportation emergency shall be to prevent death or injury. In an incident or emergency, try to get the vehicle off the road if possible, preferably to an open location that is off an asphalt road or parking lot. Shut off the tractor-trailer electrical system. Post warning lights and signs and keep people at least 152 m (500 ft) away for GOX or 800 m (1/2 mile) away for LOX. Contact authorities and obtain help:

> **CHEMTREC (800-424-9300)** (worldwide 202-483-7616)

Emergency Actions

Emergency actions to combat leaks and fires involving oxygen tractor-trailers include pulling the vehicle into the least hazardous area and turning the ignition off. For fires originating near the engine, use a fire extinguisher; for tire fires, use water or chemical fire extinguishers or both. Tires may reignite 20 to 30 min after the initial fire has been extinguished, so the driver should not leave the scene until the tire temperature is lowered sufficiently. Also, the driver should not leave the scene until the fire has been completely extinguished and the burning materials cooled.

Aid should be requested from the nearest fire or police department or both. On the highway, the environment in which a fire and subsequent damage may occur is difficult to control. An incident may occur at any time and at any place along the route. A controlled release of oxygen from the trailer through venting should take into account all possible ignition sources, vapor dispersion, population exposure, and general safe operations. Flares normally used for highway vehicular incident identification should not be used in close proximity to upset or damage LOX tanks.

References

[1] CFR Title 49, *Transportation, Code of Federal Regulations*, Parts 171–180, Sections 171.8, 172.101, 172.700, 173.31, 173.33, 173.34, 173.115, 173.302, 173.306, 173.315, 173.316, 173.318, 173.320, 173.600, 177.840, 178.36, 178.337, 178.338.

[2] CFR Title 29, *Occupational Safety and Health Standards, Code of Federal Regulations*, Part 1910, Sections 94(d), 104, 114, 115, 252(a), and 252(f).

APPENDIX A

Chemical and Physical Properties of Oxygen

Oxygen, in both the gaseous and liquid states, is a powerful oxidizer that vigorously supports combustion.

The molecular weight of oxygen, O_2, is 31.9988 on the C^{12} scale, and its atomic weight is 15.9994 [A1]. Oxygen was the base used for chemical atomic weights, being assigned the atomic weight 16.000, until 1961 when the International Union of Pure and Applied Chemistry adopted carbon 12 as the new basis [A2,A3].

Oxygen has eight isotopes. There are three naturally occurring stable isotopes of oxygen; these have atomic mass numbers of 16, 17, and 18 [A2 − A4]. The naturally occurring isotopes of oxygen are difficult to separate; therefore, property data are generally obtained from naturally occurring oxygen, which has a concentration in the ratio of 10000:4:20 for the three isotopes of atomic mass numbers 16, 17, and 18 [A2]. Also, the data are most generally given for diatomic, molecular oxygen, O_2 [A2]. The metastable molecule, O_3 (ozone), is not addressed in this manual.

Gaseous oxygen (GOX) is colorless, transparent, odorless, and tasteless. High-purity liquid oxygen (LOX) is light blue, odorless, and transparent.

GOX is about 1.1 times as heavy as air (specific gravity = 1.105). LOX is slightly more dense than water (specific gravity = 1.14).

LOX is a cryogenic liquid and boils vigorously at ambient pressure. It is chemically stable, is not shock sensitive, and will

TABLE A-1—Properties of oxygen at standard (STP) and normal (NTP) conditions [A1].

Properties	STP	NTP
Temperature, K (°F)	273.15 (32)	293.15 (68)
Pressure (absolute), kPa (psi)	101.325 (14.696)	101.325 (14.696)
Density, kg/m^3 (lb$_m$/ft^3)	1.429 (0.0892)	1.331 (0.0831)
Compressibility factor (PV/RT)	0.9990	0.9992
Specific heat		
At constant pressure (C_p), J/g·K (Btu/lb$_m$·°R)	0.9166 (0.2191)	0.9188 (0.2196)
At constant volume (C_v), J/g·K (Btu/lb$_m$·°R)	0.6550 (0.1566)	0.6575 (0.1572)
Specific heat ratio (C_p/C_v)	1.40	1.40
Enthalpy, J/g (Btu/lb$_m$)	248.06 (106.72)	266.41 (114.62)
Internal energy, J/g (Btu/lb$_m$)	177.16 (76.216)	190.30 (81.871)
Entropy, J/g·K (Btu/lb$_m$·°R)	6.325 (1.512)	6.391 (1.527)
Velocity of sound, m/s (ft/s)	315 (1034)	326 (1070)
Viscosity, mPa·s (lb/ft·s)	19.24 (0.01924)	20.36 (0.02036)
Thermal conductivity, mW/m·K (Btu/ft·h·°R)	24.28 (1.293×10^{-5})	25.75 (1.368×10^{-5})
Dielectric constant	1.00053	1.00049
Equivalent volume/volume liquid at NBP	798.4	857.1

not decompose. Most common solvents are solid at LOX temperatures, 54.4 to 90.2 K (−361.8 to −297.4°F).

Oxygen is not ordinarily considered a toxic gas. However, lung damage may result if the oxygen concentration in the atmosphere exceeds 60 vol% [A4]. Roth [A5], in reviewing the literature on oxygen toxicity, notes that the respiratory tract is adversely affected by oxygen at pressures to 2 atm; the central nervous system is adversely affected at higher pressures [A4, A5]. The prolonged exposure to pure oxygen at 1 atm may result in bronchitis, pneumonia, and lung collapse [A4,A5]. More information is located in the "Health" section of Chapter 1.

A selection of thermophysical properties of oxygen is given in Tables A-1 through A-4. Properties at standard conditions (STP and NTP) are given in Table A-1, at the critical point (CP) in Table A-2, at the normal boiling point (NBP)†[1] in Table A-3, and at the triple point (TP) in Table A-4.

TABLE A-2—Fixed point properties of oxygen at its critical point [A1].

Property	Value
Temperature, K (°F)	154.576 (–181.4)
Pressure (absolute), kPa (psi)	5042.7 (731.4)
Density, kg/m^3 (lb_m/ft^3)	436.1 (27.288)
Compressibility factor (PV/RT)	0.2879
Heat of fusion and vaporization, J/g (Btu/lb_m)	0
Specific heat	
At saturation (C_s), J/g·K (Btu/lb_m·°R)	Very large
At constant pressure (C_p), J/g·K (Btu/lb_m·°R)	Very large
At constant volume (C_v), J/g·K (Btu/lb_m·°R)	1.209 (0.289)[a]
Specific heat ratio (C_p/C_v)	Large
Enthalpy, J/g (Btu/lb_m)	32.257 (13.88)[a]
Internal energy, J/g (Btu/lb_m)	20.70 (8.904)
Entropy, J/g·K (Btu/lb_m·°R)	4.2008 (1.004)
Velocity of sound, m/s (ft/s)	164 (538)
Viscosity, mPa·s (lb_m/ft·s)	31 (2.083 × 10^{-5})[a]
Thermal conductivity, mW/m·K (Btu/ft·h·°F)	Unavailable
Dielectric constant	1.17082
Surface tension, N/m (lb_f/ft)	0
Equivalent volume/volume liquid at NBP	2.2616

[a] Estimate.

PARAMAGNETISM

LOX is slightly magnetic in contrast with other cryogens, which are nonmagnetic [A3]. Its outstanding difference from most other cryogenic fluids is its strong paramagnetism [A2]. It is sufficiently paramagnetic to be attracted by a hand-held magnet [A6]. The paramagnetic susceptibility of LOX is 1.003 at its NBP [A3].

Solubility

LOX is completely miscible with liquid nitrogen and liquid fluorine. Methane is highly soluble in LOX, light hydrocarbons are usually soluble, and acetylene is soluble only to approximately 4 ppm. Contaminants in LOX may be in solution if they are present in quantities less than the solubility limit [A6]. Most solid hydrocarbons are less dense than LOX and will tend to float on the liquid surface [A6]. They may give evidence of their presence by forming a ring of solid material around the interior wall of the container near the liquid surface [A7]. The solubility of several hydrocarbons in LOX, as well as their lower flammability limits, is given in Table A-5.

Oxygen is soluble in water, and the quantity that may be dissolved decreases as the temperature of the water increases. The solubility of oxygen in water (vol/vol) is 4.89 % at 273 K (32°F), 3.16% at 298 K (77°F), 2.46% at 323 K (122°F), and 2.30 % at 373 K (212°F) [A8].

TABLE A-3—Fixed point properties of oxygen at its normal boiling point (NBP) [A1].

Properties	Liquid	Vapor
Temperature, K (°F)	90.180 (–297.3)	90.180 (–297.3)
Pressure (absolute), kPa (psi)	101.325 (14.696)	101.325 (14.696)
Density, kg/m^3 (lb_m/ft^3)	1140.7 (71.215)	4.477 (0.2795)
Compressibility factor (PV/RT)	0.00379	0.9662
Heat of vaporization, J/g (Btu/lb_m)	212.89 (91.589)	
Specific heat		
At saturation (C_s), J/g·K (Btu/lb_m·°R)	1.692 (0.4044)	–1.663 (–0.397)
At constant pressure (C_p), J/g·K (Btu/lb_m·°R)	1.696 (0.4054)	0.9616 (0.2298)
At constant volume (C_v), J/g·K (Btu/lb_m·°R)	0.9263 (0.2214)	0.6650 (0.159)
Specific heat ratio (C_p/C_v)	1.832	1.447
Enthalpy, J/g (Btu/lb_m)	–133.45 (–57.412)	79.439 (34.176)
Internal energy, J/g (Btu/lb_m)	–133.54 (–57.450)	56.798 (24.436)
Entropy, J/g·K (Btu/lb_m·°R)	2.943 (0.7034)	5.3027 (1.2674)
Velocity of sound, m/s (ft/s)	903 (2963)	178 (584)
Viscosity, mPa·s (lb_m/ft·s)	195.8 (1.316 × 10^{-4})	6.85 (4.603 × 10^{-6})
Thermal conductivity, mW/m·K (Btu/ft·h·°R)	151.5 (0.08759)	8.544 (0.00494)
Dielectric constant	1.4870	1.00166
Surface tension, N/m (lb_f/ft)	0.0132 (0.0009045)	
Equivalent volume/volume liquid at NBP	1	254.9

---

[1] The † indicates a term defined in the Glossary (Appendix G).

TABLE A-4—Fixed point properties of oxygen at its triple point [A1].

Properties	Solid	Liquid	Vapor
Temperature, K (°F)	54.351 (–361.8)	54.351 (–361.8)	54.351 (–361.8)
Pressure (absolute), kPa (psi)	0.1517 (0.0220)	0.1517 (0.0220)	0.1517 (0.0220)
Density, kg/m^3 (lbm/ft^3)	1.359 (84.82)	1.306 (81.56)	0.01075 (0.000671)
Compressibility factor (PV/RT)		0.0000082	0.9986
Heat of fusion and vaporization, J/g (Btu/lbm)	13.90 (5.980)	242.55 (104.35)	. . .
Specific heat			
At saturation (C_s), J/g·K Btu/lbm·°R)	1.440 (0.3441)	1.666 (0.3982)	–3.397 (–0.8119)
At constant pressure (C_p), J/g·K (Btu/lbm·°R)		1.665 (0.3979)	0.9103 (0.2176)
At constant volume (C_v), J/g·K (Btu/lbm·°R)		1.114 (0.2663)	0.6503 (0.1554)
Specific heat ratio (C_p/C_v)		1.494	1.400
Enthalpy, J/g (Btu/lb$_m$)	–207.33 (–89.197)	–193.43 (–83.217)	49.120 (21.132)
Internal energy, J/g (Btu/lb$_m$)	–207.33 (–89.197)	–193.43 (–83.127)	35.000 (15.058)
Entropy, J/g·K (Btu/lb$_m$·°R)	1.841 (0.4401)	2.097 (0.5013)	6.5484 (1.565)
Velocity of sound, m/s (ft/s)	. . .	1.159 (3.803)	141 (463)
Viscosity, mPa·s (lb$_m$/ft·s)	. . .	619.4 (4.162 x10^{-4})	3.914 (2.630 x 10^{-6})
Thermal conductivity, mW/m·K (Btu/ft·h·°R)	. . .	192.9 (0.1115)	4.826 (0.00279)
Dielectric constant	1.614 (estimated)	1.5687	1.000004
Surface tension, N/m (lb$_f$/ft)	. . .	0.02265 (0.00155)	. . .
Equivalent volume/volume liquid at NBP	0.8397	0.8732	106.068

TABLE A-5—Solubility limit and lower flammability limit of hydrocarbons soluble in LOX [A7].

Hydrocarbon	Solubility, mol·ppm	Lower Flammable Limit, mol·ppm
Methane	980 000	50 000
Ethane	215 000	30 000
Propane	50 000	21 200
Ethylene	27 500	27 500
Propylene	700	20 000
i-Butane	1 910	18 000
Butene-1	1 000	16 000
n-Butane	860	18 600
i-Butylene	135	18 000
n-Pentane	20	14 000
Acetylene	5	25 000
n-Hexane	2	11 800
n-Decane	0.6	7 700
Acetone	1.5	. . .
Methanol	12	. . .
Ethanol	15	. . .

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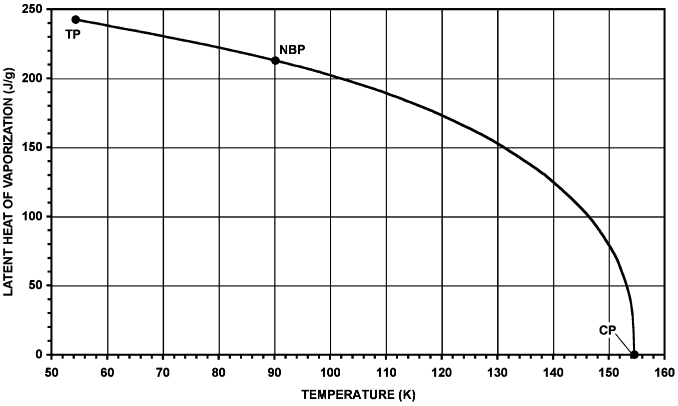

Fig. A-1—Latent heat of vaporization of liquid oxygen [A1].

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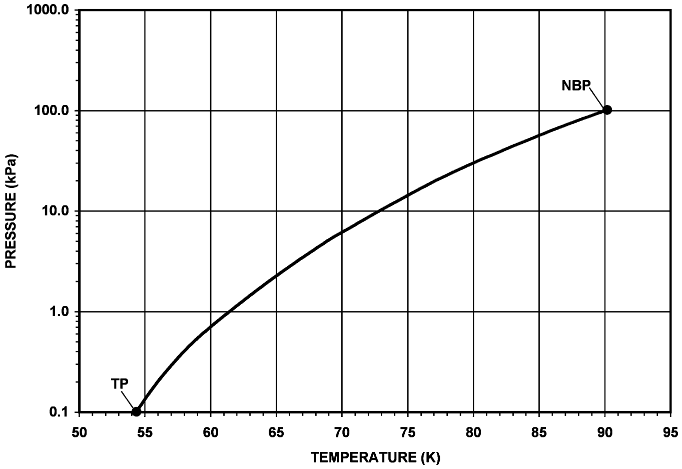

Fig. A-2—Vapor pressure of liquid oxygen from the TP to the NBP [A1].

HEAT OF VAPORIZATION

The latent heat of vaporization (the heat required to convert a unit mass of a fluid from the liquid state to the vapor state at constant pressure) of liquid oxygen is shown in Fig. A-1.

VAPOR PRESSURE

The vapor pressure (the P(T) of a liquid and its vapor in equilibrium) of liquid oxygen from the TP to the NBP is shown in Fig. A-2, and from the NBP to the CP in Fig. A-3.

SURFACE TENSION

The surface tension (the amount of work required to increase the surface area of a liquid by one unit of area) of liquid oxygen is shown in Fig. A-4. This property is defined only for the saturated liquid, not for the compressed fluid state.

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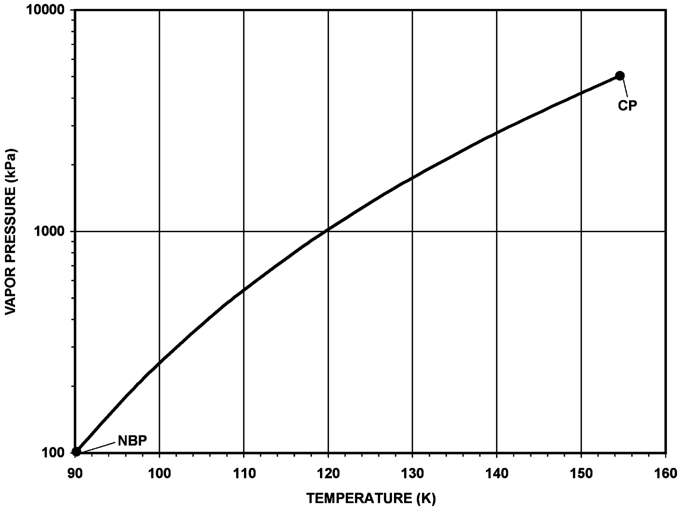

Fig. A-3—Vapor pressure of liquid oxygen from the NBP to the CP [A1].

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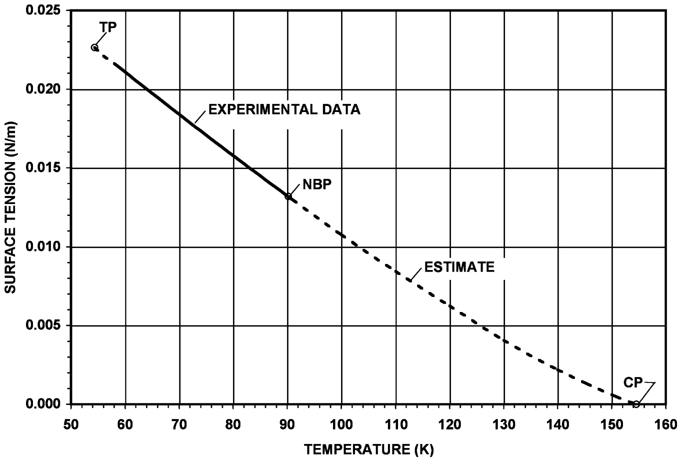

Fig. A-4—Surface tension of liquid oxygen [A1].

JOULE-THOMSON EFFECT

The Joule-Thomson effect is defined as the temperature change that occurs when a gas expands, through a restricted orifice, from a higher pressure to a lower pressure without exchanging heat, without gaining kinetic energy, and without performing work during the expansion process. This is a constant enthalpy (isenthalpic) process. In practice, this pressure change usually occurs at a valve. The change in temperature can be either positive or negative. A temperature increase will occur if the gas is expanded at a temperature and pressure condition that is outside the temperature and pressure conditions that define the Joule-Thomson inversion curve for the gas. A temperature decrease will occur if the gas is expanded at a temperature and pressure condition that is inside the Joule-Thomson inversion curve. The Joule-Thomson inversion curve for oxygen is shown in Fig. A-5. The oxygen Joule-Thomson inversion curve is a compilation of experimental and estimated data from Ref [A1]. Also shown in Fig. A-5 are four curves that show the isenthalpic expansion of oxygen from various initial conditions.

LIVE GRAPH
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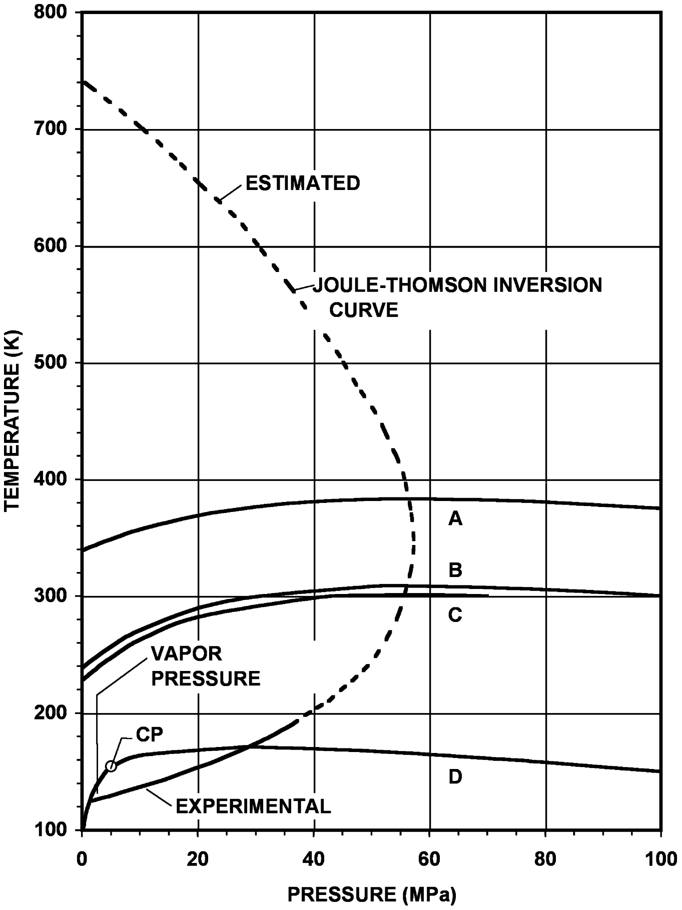

Fig. A-5—Joule-Thomson inversion curve for oxygen. Curves A-D show the isenthalpic expansion of oxygen from the following initial temperature and pressure conditions: Curve A—375 K, 100 MPa; Curve B—300 K, 100 MPa; Curve C—300 K, 70 MPa; Curve D—150 K, 100 MPa. CP = Critical Point.

TABLE A-6—Joule-Thomson coefficients for some selected temperature-pressure conditions.

Temperature (K)	Pressure (MPa)	J-T Coefficient (K/MPa)
100	20.3	–0.33555
150	15	0.085459
	20.3	–0.04935
	35	–0.22411
	70	–0.36151
	100	–0.40356
200	15	1.9609
	20.3	0.96718
	35	0.10706
	70	–0.28805
	100	–0.38088
300	15	1.6934
	20.3	1.3323
	35	0.54234
	70	–0.15410
	100	–0.33254
375	15	1.1218
	35	0.43555
	70	–0.13831
	100	–0.32447
400	15	0.96873
	35	0.38187
	70	–0.14423
	100	–0.32626

The Joule-Thomson coefficient is the derivative of the change in temperature as a result of a change in pressure at constant enthalpy. The Joule-Thomson coefficient is the slope of the isenthalpic lines, such as Curves A through D of Fig. A-5. The Joule-Thomson coefficient is zero at the Joule-Thomson inversion curve; that is, the Joule-Thomson inversion curve is the loci of the points where the Joule-Thomson coefficient is zero and the curve is at a maximum. The Joule-Thomson coefficients for some selected temperature and pressure conditions are given in Table A-6.

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APPENDIX B

Physical Properties of Engineering Materials

The mechanical and thermal properties–and, in some cases, other properties such as electrical, magnetic, and optical–of materials used in oxygen systems are important. The purpose of this section is to provide a brief introduction to the mechanical and thermal properties of some materials commonly used in oxygen systems, as well as to the properties and behavior of materials at cryogenic temperatures, such as the temperature of liquid oxygen (LOX). There are several significant phenomena that can appear at cryogenic temperatures, such as a ductile-brittle transition, that must be considered when selecting materials for LOX and cold gaseous oxygen (GOX) service.

Generally, the strength of a material at room temperature, or higher temperature if necessary for operational requirements, should be accounted for in the design of cryogenic equipment, although material strength generally tends to increase as its temperature is lowered. This recommendation is based on the recognition that the equipment must also operate at room temperature (or higher), and that temperature gradients are possible within the equipment, especially during cooldown or warmup.

There are many variables in a material and in its loading; consequently, material property values that are given in this guideline document should not be considered as approved design values. Approved design values may be obtained, for example, from the *ASME Boiler and Pressure Code* (for materials used in a pressure vessel) and from ANSI/ASME B31.3 for pressure piping. Representative allowable stress values for some materials from ANSI/ASME B31.3 are given in Table B-1.

TABLE B-1—Minimum temperatures and basic allowable stresses in tension for selected metals.[a]

Metal and/or Alloy[b]	Metal Form[c]	Minimum Temperature[d] K (°F)	Specified Minimum Tensile Strength MPa (ksi)	Specified Minimum Yield Strength MPa (ksi)	Basic Allowable Stress[e] MPa (ksi)
Aluminum alloy					
1100-0, B241	Pipe and tube	4.2 (–452)	75.8 (11)	20.7 (3)	13.8 (2.0)
3003-0, B241	Pipe and tube	4.2 (–452)	96.5 (14)	34.5 (5)	22.8 (3.3)
5083-0, B241	Pipe and tube	4.2 (–452)	268.9 (39)	110.3 (16)	73.8 (10.7)
6061-T6, B241	Pipe and tube	4.2 (–452)	262.0 (38)	241.3 (35)	87.6 (12.7)
Copper and copper alloy					
Cu pipe, B42, annealed	Pipe and tube	4.2 (–452)	206.8 (30)	62.1 (9)	41.4 (6.0)
Red brass pipe	Pipe and tube	4.2 (–452)	275.8 (40)	82.7 (12)	55.2 (8.0)
70Cu-30Ni, B466	Pipe and tube	4.2 (–452)	344.7 (50)	124.1 (18)	82.7 (12.0)
Nickel and nickel alloy					
Ni, B161	Pipe and tube	74.8 (–325)	379.2 (55)	103.4 (15)	68.9 (10.0)
Ni-Cu, B165	Pipe and tube	74.8 (–325)	482.6 (70)	193.1 (28)	128.9 (18.7)
Ni-Cr-Fe, B167	Pipe and tube	74.8 (–325)	551.6 (80)	206.8 (30)	137.9 (20.0)
Steel, carbon					
A285 Grade C, A524	Pipe and tube	244 (–20)	379.2 (55)	206.8 (30)	126.2 (18.3)
A442 Grade 50, A672	Pipe and tube	–[f]	413.7 (60)	220.6 (32)	137.9 (20.0)
Steel, low and intermediate alloy					
3.5 Ni, A333	Pipe and tube	172 (–150)	448.2 (65)	241.3 (35)	149.6 (21.7)
5 Ni, A645	plate	103 (–275)	655.0 (95)	448.2 (65)	218.6 (31.7)
9 Ni, A333	Pipe and tube	77 (–320)	689.5 (100)	517.1 (75)	218.6 (31.7)
Steel, stainless, ferritic					
405 (12Cr-Al), A240	Plate and sheet	244 (–20)	413.7 (60)	172.4 (25)	115.1 (16.7)
430 (17Cr), A240	Plate and sheet	244 (–20)	448.2 (65)	206.8 (30)	137.9 (18.4)

Continued

SUBJECT INDEX

NOTE: This index cites entries from pages where substantive information is given about topics. Peripheral mentions of topics are not indexed. Entries marked with *f* indicate figures; *t* indicates tables.

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