INTERNATIONAL STANDARD

ISO 22538-1

First edition
2007-09-01

Space systems — Oxygen safety —

Part 1:
Design of oxygen systems and components

Systèmes spatiaux — Sécurité des systèmes d'oxygène —

Partie 1: Conception des systèmes d'oxygène et leurs composants

Reference number
ISO 22538-1:2007(E)

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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ISO 22538-1 was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

ISO 22538 consists of the following parts, under the general title *Space systems — Oxygen safety*:

— *Part 1: Design of oxygen systems and components*

— *Part 2: Selection of metallic materials for oxygen systems and components*

— *Part 3: Selection of non-metallic materials for oxygen systems and components*

— *Part 4: Hazards analyses for oxygen systems and components*

The following parts are under preparation:

— *Part 5: Operational and emergency procedures*

— *Part 6: Facility planning and implementation*

INTERNATIONAL STANDARD **ISO 22538-1:2007(E)**

Space systems — Oxygen safety —

Part 1:
Design of oxygen systems and components

1 Scope

This part of ISO 22538 describes a process for the design of oxygen systems and their components. This part of ISO 22538 applies equally to ground support equipment, launch vehicles and spacecraft.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 22538-2, *Space systems — Oxygen safety — Part 2: Selection of metallic materials for oxygen systems and components*

ISO 22538-3, *Space systems — Oxygen safety — Part 3: Selection of non-metallic materials for oxygen systems and components*

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1.1
direct oxygen service
service in which materials and components are in direct contact with oxygen during normal operations

3.1.2
indirect oxygen service
service in which materials and components are not normally in direct contact with oxygen but might be as a result of a malfunction, operator error or process disturbance

3.1.3
oxygen-enriched atmosphere
mixture (gas or liquid) that contains more than 25 volume percent oxygen

3.1.4
qualified technical personnel
persons such as engineers and chemists who, by virtue of education, training or experience, know how to apply physical and chemical principles involved in the reactions between oxygen and other materials

3.2 Abbreviated terms

CDR	critical design review
EPR	emergency procedures review
FMECA	failure modes and effects criticality analysis
GOX	gaseous oxygen
LOX	liquid oxygen
ORI	operational readiness inspection
PCTFE	polychlorotrifluoroethylene
PDR	preliminary design review
PTFE	polytetrafluoroethylene
SSA/SR	system safety analysis/safety review
TRR	test readiness review

4 Design approach

4.1 General

Oxygen is chemically stable and a strong oxidizer that supports combustion. It is not shock sensitive and is not flammable. Oxygen is reactive at ambient conditions and its reactivity increases with increasing pressure, temperature and concentration. Before embarking on a new task, it is important that designers, customers and operators understand the risks associated with oxygen systems.

4.2 Design specifications

Each new design project begins with specifications for the requested item. It is important that these specifications do not create an unnecessary risk for personnel or equipment. Most materials are flammable in high-pressure oxygen. An oxygen system designer shall understand that oxygen, fuel and a source of ignition are all that is necessary to start and propagate a fire. Many materials are combustible in oxygen-enriched environments and reactivity is generally increased with increasing temperature and pressure; therefore, materials selection criteria are critical in achieving a successful final product. The designer shall attempt to avoid using flammable materials; however, many materials that are flammable at operating conditions can be safely used in some applications by carefully avoiding ignition sources. The design shall never compromise safety to reduce costs.

4.3 Design reviews

4.3.1 General

In addition to the standard practice of reviewing functional operation, component ignition and combustion in oxygen-enriched environments shall also be assessed. The overall design process shall reduce hazards associated with component ignition and combustion. Before constructing oxygen facilities, equipment and systems, the design safety shall be approved by the designated installation safety authority or other approval points. The safety assessment process shall be integrated into the overall facility design review process. Each design review phase shall evaluate the safety aspects of the project according to its level of completion.

Reviews of the final drawings, designs, structures, and flow and containment systems shall include a safety assessment to identify potential system hazards and compliance with the proper regulatory organizations. The safety assessment shall also include the safety history of the system hardware. Such histories can identify equipment failures that may create hazardous conditions when the equipment is integrated.

All the procedures described in the following section refer to the design of both components and systems for oxygen use. The design reviews ultimately need to address all design aspects down to the individual part level because all parts pose potential hazards in oxygen service.

4.3.2 Preliminary design review (PDR)

A preliminary review shall be conducted on all materials and specifications.

4.3.3 Integrated failure modes and effects criticality analysis (FMECA) and hazard analysis

FMECA reviews each hardware item and analyses it for each possible single-point failure mode and single-barrier failure and their worst-case effects on the entire system. A FMECA will also include the results of the oxygen hazards analysis.

The interdependencies of all components shall be addressed and any single-point failures and the result of single-barrier failures shall be noted in a summary list of action items for correction. Single-barrier failures are often overlooked, but the potential for component-part failures, such as diaphragm failures, can cause hazardous oxygen-enriched environments and may cause a substantially increased risk of ignition near electrical components.

Attempting to correct single-point failures simply through procedural actions is not a reliable method. In addition, the FMECA shall consider the effects of failures in both static and dynamic operating conditions. When performed early in the design phase, this analysis greatly assists the designer in ensuring reliable systems. The FMECA shall be performed before fabrication of the component or system.

4.3.4 Systems and subsystems hazards analysis

The hazards analysis shall identify any conditions that could possibly cause death, injury or damage to the facility and surrounding property. It shall also

a) include the effects of component and assembly single-point failures,

b) review all ignition modes for all components and assemblies,

c) include hazards associated with contamination,

d) review secondary hazards, such as leakage to electrical equipment,

e) consider the effects of maintenance procedures on safety and performance, and

f) review toxicity concerns, especially for breathing oxygen.

4.3.5 Critical design review (CDR)

The final design review shall be held after all preliminary analyses have been completed and the action items from these analyses have been resolved. In this review, the final fabrication drawings and the supporting calculations are reviewed and all final action items resolved before authorizing fabrication and use.

4.3.6 System safety analysis/safety review (SSA/SR)

All safety aspects, including oxygen hazards, shall be reviewed to ensure the integrated design solution does not present unacceptable risks to personnel and property.

4.3.7 Other reviews

In addition to the PDR, FMECA, CDR and SSA/SR, the reviews below may be conducted as needed.

a) Test readiness review (TRR): Operational procedures, along with instrumentation and control systems, shall be evaluated for their capacity to provide the required safety. Equipment performance shall be verified by analysis or by certification testing. It may be necessary to develop special procedures to counter hazardous conditions.

b) Emergency procedures review (EPR): The safety of personnel at or near oxygen systems shall be carefully reviewed together with emergency procedures in the earliest planning and design stages. Advanced planning for a variety of emergencies, such as fires and explosions, shall be undertaken so that the first priority is to reduce any risk to life.

c) Operational readiness inspection (ORI): An ORI may be required for any major facility change. Oxygen hazards shall be specifically reviewed for compliance with basic safety requirements.

4.4 Component and system testing

4.4.1 Intent/compliance

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 and whether or not it is flight-rated hardware. Compliance with safety programmes for pressure vessels and pressurized systems is required.

4.4.2 Prototype development testing

Initial testing is often best performed with inert fluids or gases; however, acceptance tests of the final hardware configuration shall be conducted with clean oxygen and parts cleaned for oxygen service. Testing with oxygen shall begin only after an oxygen hazards analysis has been performed on the specific test hardware.

Engineering development testing is intended to verify safe and reliable operation over a realistic range of operating conditions. It includes pressure integrity tests, assembly leak tests and configurational tests.

Consider worst-case operating tests to re-evaluate limited design margins, single-point failures and any uncertainties in the design criteria.

Life-cycle and flow tests are important in this phase of testing. Life-cycle tests shall be performed to determine the safety and longevity of systems components. The components shall be tested in each operational mode with the number of cycles based on the anticipated end-use. These do not constitute qualification, life-cycle or pressure qualification (proof) tests.

4.4.3 Qualification and acceptance testing

Test requirements will vary for each component or assembly to be tested. The equipment supplier, test facility personnel and end-user shall develop a joint test programme to verify function and oxygen compatibility.

5 Design for high-pressure and high-temperature gaseous oxygen systems

5.1 Design features

Design features, such as physical design of components and the component location in the system, shall be effectively coupled with proper materials selection to achieve safe operations. Evaluation of such design features shall begin with the preliminary design reviews.

5.2 Materials guidelines

5.2.1 General

Guidelines on materials compatibility with oxygen can be found in documents such as ASTM Manual Series MNL36[1].

5.2.2 Materials

Designers of equipment for oxygen service shall thoroughly understand the reactivity of selected materials in oxygen-enriched environments. The designer shall usually avoid flammable materials; however, many materials that are flammable at operating conditions can safely be used by carefully avoiding ignition sources. Ensure, through testing if necessary, that the materials selected have the proper properties (e.g. strength, ductility and hardness) to operate safely under all conditions. Combinations of these properties shall be considered. For example, strength tends to decrease with increasing temperature, while ductility tends to decrease with decreasing temperature.

Evaluate materials for ignitability and flammability over their intended operating range. Use materials below ignition thresholds for the applicable ignition mechanisms. Most materials in contact with oxygen are combustible under certain conditions, e.g. flammability tends to increase with increasing pressure and temperature.

5.2.3 Ignition mechanisms

When selecting materials, consider ignition mechanisms that could be present in the system. Test data relating to material behaviour with respect to these ignition mechanisms shall be obtained or generated as a standard practice at the onset of the design process. Consideration of ignition mechanisms shall include (but not be limited to) mechanical impact, pneumatic impact, particle impact, promoted combustion, frictional heating, electrical arcing and single-barrier failures.

A large number of tests have been developed and evaluated by various groups, both private and public. Non-metallic materials are typically evaluated using the liquid and gaseous oxygen mechanical impact, pneumatic impact, resonance, heat of combustion, static discharge, auto-ignition temperature, oxygen index and promoted combustion tests. Metallic materials are typically evaluated using the promoted combustion, electrical arcing, rubbing friction, vibration and particle impact tests.

5.2.4 Additional materials guidelines

5.2.4.1 Effects of specific material processing, coatings and other surface preparations

The designer shall first attempt to meet all functional requirements without coatings, platings or hard-facings. In most applications, surface preparations can be avoided. Special cases may arise, however, in which a surface preparation cannot be avoided. One example is a valve that shall be fabricated entirely of a single metal alloy because of metal-to-fluid compatibility considerations; to avoid galling in this case, an oxygen-compatible solid film lubricant may be necessary. When a surface preparation cannot be avoided, the effect of cleaning procedures on the coating shall be considered. The designer shall consider the mechanical and physical properties at all use conditions. Generally, materials will become stronger and more brittle at reduced temperatures.

5.2.4.2 Material specific strength

The designer shall take advantage of specific strength, which often allows the use of the most oxygen-compatible materials to improve performance and decrease materials ignition hazards. Specific strength is the ratio of the material strength to density, and this is the critical parameter for determining the weight of flight-weight hardware. Using this ratio, it may be that metals with high strength can be used as a replacement for lightweight metals such as aluminium.

5.2.4.3 Lubrication

Fluorinated, chlorofluorinated and solid film lubricants that are approved for oxygen service shall be used. Hydrocarbon-based lubricants shall not be used for oxygen service.

5.2.4.4 Thermal expansion and contraction

Leaks are commonly caused by the disparity of thermal expansion coefficients between polymers and metals. Upon cooling, the shrinkage of polymers will exceed that of metals, and seals may lose the compression required for sealing.

5.3 General design guidelines

5.3.1 Materials

Alone, the use of ignition- and burn-resistant materials for components in oxygen systems will not eliminate oxygen fires. Designs shall consider system dynamics, component interactions and operational constraints, in addition to component design requirements, to prevent conditions leading to oxygen fires. See ISO 22538-2 and ISO 22538-3 for guidelines on materials selection and use.

Although it is not always possible to use materials that do not ignite under any operating condition, it is normally understood that the most ignition-resistant materials shall be used in any design. The designer shall also avoid ignition modes wherever possible, but what may not be clear is that the designer shall also consider the relative importance of the various ignition modes when designing new or modified hardware. This means that certain ignition modes are more likely than others to result in failures, either because of the amount of soft goods present or the likelihood of a particular event leading to component heating and subsequent ignition. To reduce the risk of ignitions, any ignition failure mode that involves soft goods, contamination or rapid pressurization shall be carefully scrutinized. The following design guides are presented roughly in order of priority.

5.3.2 Codes, regulations, laws and certifications

Codes, regulations and laws shall be designed, fabricated and installed as applicable. Ensure that the materials selected for use have the proper certifications.

5.3.3 Filters

Filters shall be used to isolate system particulate. They shall be placed in locations where they can be removed and inspected and where no possibility of back flow exists. A helpful practice is to check the pressure differentials across the filter to aid in tracking the filter status. Filters shall be used in the following locations:

a) module inlets and outlets;

b) disconnect points;

c) points required to isolate difficult-to-clean passageways;

d) upstream of valve seats.

5.3.4 Flow design

Design the component and system combination to avoid chatter. Design to minimize choked flow. Consider shut-off valves, metering valves, relief valves and regulators to reduce particle impact ignition risks.

Design to allow a blow-down of the system with filtered, dry, inert gas at the maximum flow rates and pressures after system fabrication. This serves to purge or isolate assembly-generated particulate.

Avoid captured vent systems. A relief valve or burst disc that is not open directly to the atmosphere, but rather has a tube or pipe connected to the outlet, is said to have a captured vent. If a captured vent is necessary, use highly ignition-resistant materials, such as copper or nickel/copper alloys.

5.3.5 Electrical concerns

Bulk oxygen systems are not considered to be hazardous locations. Therefore, general purpose or weatherproof types of electrical wiring and equipment are acceptable depending upon whether the installation is indoors or outdoors. Electrical terminals shall not turn or loosen when subject to service conditions; terminal points shall be protected from shorting out by eliminating foreign objects and contaminates.

Electrical wiring in high concentrations of gaseous oxygen (GOX) shall be encased in hermetically sealed conduits or conduits rendered inert with helium or nitrogen gas. The instruments, switches, flow sensors and electrical devices shall be designed in modular structure and hermetically sealed. Rendering inert with nitrogen or helium is recommended.

5.4 Specific system design guidelines

5.4.1 Minimize soft goods

Minimize the amount of soft goods and their exposure to flow. Soft goods exposed to flow can be readily heated through rapid compression or readily ignited through kindling chain reactions. Minimizing soft goods exposure by shielding with surrounding metals can significantly reduce ignition hazards.

5.4.2 Limit GOX pressurization rates

Soft goods (e.g. seals, coatings and lubricants) are susceptible to ignition from heating caused by rapid pressurization. For example, PTFE-lined hoses are sensitive to this ignition mode and their use with rapid pressurization applications is discouraged. Pressurization rates of valve and regulator actuators shall be minimized. In some applications, flow-metering devices are prudent for manually actuated valves, especially for quarter-turn ball valves.

5.4.3 Limit GOX flow velocities

Limiting flow velocities minimizes erosion problems and reduces the risk of particle impact ignitions. Although each material and configuration combination shall be reviewed individually, higher fluid velocities shall receive special attention, especially at flow restrictions.

5.4.4 Minimize mechanical impact

Mechanical impact ignitions can ignite large parts and the impacts can also ignite contamination and soft goods entrapped by the impact. Relief valves, shut-off valves, regulators and subminiature parts especially shall be reviewed for this hazard.

5.4.5 Minimize frictional heating

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

5.4.6 Minimize blunt flow impingement

The risk of particle impact ignitions can be reduced if potential impact surfaces are designed with shallow impact angles to reduce the kinetic energy absorbed by the surface upon impact.

5.4.7 Eliminate burrs and avoid sharp edges

Burrs and sharp edges on equipment provide ignition sources for particle impact and also provide the ingredients for kindling chain combustion propagation. Removal of this material is standard shop procedure and is essential for avoiding oxygen-enriched ignitions.

5.4.8 Design to minimize particulates

Particulate generated during manufacture, assembly and operation can be a source of particle impact ignition. Designs shall have provisions to minimize particulate generation through the normal operation of valve stems, pistons and other moving parts. This can be accomplished by using bearings, bushings and configurations to keep particulate away from oxygen-wetted regions. Additionally, the assembly, cleaning and maintenance practices shall minimize contamination. Oxidation and corrosion could also be a source of particles and shall be avoided.

5.4.9 Design to minimize rotating valve stems

Avoid rotating valve stems and sealing configurations that require rotation on assembly. Rotating valve stems and seals can gall and generate particulate matter.

5.4.10 Design to minimize electric arcing

Electrical arcs in oxygen-enriched environments can lead to heating and subsequent ignition.

5.4.11 Eliminate blind passages

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

5.4.12 Avoid crevices

Crevices are difficult to clean and inspect for particulate entrapment and resonant cavities. Cavities, especially those formed at the intersection of mating parts in assemblies, create a location where contamination can accumulate and increase ignition risks, as in blind passages.

5.4.13 Dynamic seal design

Design dynamic seals to minimize particulate generation. Minimize coefficients of friction and surface finishes and choose seal configurations to minimize particle generation that can cause particle impact ignitions.

5.4.14 Limit fluid-induced vibrations

Vibrations can cause fretting, galling, impacting and particle generation in components and systems. Check valve chatter and valve poppet oscillations are examples of this phenomenon. Particulate accumulations will increase the risk of particle impact ignition.

5.4.15 Single-point seal failures

Seals will degrade with time and use. Eventually, it can be expected that they may fail to seal the contained fluid. When this happens, the effects of an oxygen-enriched external environment, high velocity leakage and loss of mechanical integrity shall be addressed.

5.4.16 Eliminate seal and seat rotation

Sealed parts that require rotation at assembly (such as O-rings on threaded shafts) can generate particles that may migrate into the flow stream. Particulate generation also occurs in ball valves where the operation of the valve rotates a ball on a non-metallic seat.

A related phenomenon that may be described as “feathering” occurs when valve stems are rotated against some non-metallic seats, such as polychlorotrifluoroethylene (PCTFE). Because of the mechanical properties of some non-metallic materials, a thin, feather-like projection of material is extruded from the seat. The feathered material is more prone to ignite than the seat itself. PCTFE and other non-metallic materials subject to feathering shall only be used with caution for seals and seats in rotating configurations.

Ball valves are not recommended for oxygen systems because of their tendency to generate particulate and their fast opening times, which cause rapid pressurization of systems.

5.4.17 Avoid thin walls

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

5.4.18 Single-barrier failures

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

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

5.4.19 Seat shape, seals and squeeze

Designs in which an O-ring seals on an unusual seat shape may cause increased wear or accelerated extrusion of the O-ring material and the generation of particulate contamination.

Although the design of sealing interfaces is a necessary compromise, the design shall use standard shapes as much as possible. Past experience has shown that the elastomeric O-rings are successful in static environments but are usually poor choices in dynamic environments and shall only be considered in designs where the exposure to oxygen is minimized, such as line exposure. In some instances, polytetrafluoroethylene (PTFE) with a fluoroelastomer as a backup (which exposes the most compatible materials preferentially to oxygen) has been used for seals where elastomers shall be used and cannot be limited to line exposure. Rigid plastics such as polypyromellitimide have been used as seats in valves and regulators; however, the non-compliance 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 the precautions to eliminate galling have been taken.

Sufficient seal squeeze shall be allowed to avoid O-ring extrusion. Standard manufacturers’ dimensions and tolerances shall be incorporated into designs unless an overriding design constraint demands the change. Additionally, the dimensions of all parts in the valve assembly shall be carefully inspected. Ideally, adequate gland size shall be provided in the initial design.

5.4.20 Metal-to-metal seals

Metal-to-metal seals may be required in some cases. Polymeric materials cannot be used as seals in valves that control the flow of hot oxygen at high pressures and temperatures because they lose sealing properties, are easily ignited and wear too rapidly.

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

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

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

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

5.4.21 Effects of long-term operation

Cold flow of seals is a concern, especially for soft goods with little resiliency. With applied loads, these materials permanently deform, usually resulting in sealing loss.

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

Copper is often used for oxygen seals. It can provide a very reliable seal; however, at extremely high temperatures, the copper oxide that forms on exposed surfaces is then likely to become a source of particulate.

5.4.22 Power losses

Design equipment so that power losses, control pressure leakage or other loss of actuation sources return equipment to a fail-safe position to protect personnel and property in an accident.

5.4.23 Thermal expansion

The effects of thermal expansion shall be considered. Buckling can create component or piping failures.

5.4.24 Other considerations

For microgravity applications, the behaviour of materials in this environment shall be taken into account.

6 Design for cryogenic oxygen systems

6.1 General

In addition to the design requirements for high-pressure and high-temperature oxygen systems specified in Clause 5, specific considerations for cryogenic applications shall be applied. Liquid air or oxygen can easily vaporize and produce high-pressure regions in systems assumed to be at low pressure (liquid lock-up). If these potential high-pressure considerations are not considered when designing the system, serious hazards can exist.

6.2 Materials guidelines

Material requirements are similar to the requirements for GOX. One additional consideration is that vaporization of LOX occurs around heat sources such as ball bearings; this increases ignition risks and necessitates compensation for possible elevated pressure.

6.3 General system installation guidelines

6.3.1 Design features

Design features, such as the physical design of components and the component location in the system, shall be effectively coupled with proper materials selection to achieve safe operations. The designer shall avoid flammable materials in oxygen systems.

6.3.2 Thermal conditioning

Thermal conditioning of cryogenic systems is mandatory. A bypass flow path with pressure relief shall be provided. Thermal conditioning can be performed with liquid nitrogen or LOX. Carefully analyse system start-up for LOX pumps, as cavitation from improper chill-down can increase fluid pressures and damage parts (leading to premature failure of components) and may create start-up instabilities that can lead to ignition from frictional heating.

6.3.3 External condensation

Avoid condensation on external surfaces because the cryogen can liquefy air or freeze water and other vapours to create falling ice or other hazards.

6.3.4 Internal condensation

Avoid condensation on internal surfaces because the cryogen can freeze water and other vapours.

6.3.5 LOX long-term storage

Long-term storage of LOX and extended cyclic fill operations may concentrate low-volatility impurities in the storage container as a result of the loss of oxygen by boil-off. Therefore, the oxygen used on the basis of the original specifications may not be satisfactory. Pressure relief valves or other means shall be designed to prevent the back aspiration of volatile impurities into storage systems.

6.3.6 LOX analysis

The contents of vessels shall be analysed periodically for conformance to the specifications to limit the accumulation of contaminants from cyclic fill-and-drain operations. An inspection and system warm-up refurbishment shut-down cycle shall be established, based on the maximum calculated impurity content of the materials going through the tank or system. This shall allow frozen water and gas contaminants to vaporize and leave the vessels. Where practical, a mass balance of measurable contaminants shall be made for all fluids entering the system or the component.

6.4 Design specifications

The concerns are similar to those for high-pressure, high-temperature oxygen, with the addition of material embrittlement because of the low temperatures. Cracking, fractures, stress corrosion, soft goods and metals can cause premature failures.

6.5 Hazard considerations

Cryogenic hazards, such as cold injuries from exposure when handling equipment with LOX, shall be considered. Additionally, oxygen-containing equipment shall not be operated over asphalt pavement because of spill hazards and the potential for ignitions from oxygen-enriched asphalt, which can be readily ignited because of its shock sensitivity. When the use of LOX systems over asphalt cannot be avoided, all asphalt areas under uninsulated piping shall be protected to prevent contact with oxygen. Designers shall avoid ignition modes where possible.

6.6 Component hardware and systems design considerations

6.6.1 Liquid lock-up

Liquid lock-up can occur, requiring special pressure relief protection.

6.6.2 Liquid vaporization

Avoid fluid expansion regions in which the fluid can vaporize. If expansion is allowed to occur, the resulting fluid downstream will have two phases, gas and liquid, and the following could occur:

a) increased pressure 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 is not eliminated);

c) decreased performance of metering valves and other components sensitive to fluid properties.

6.6.3 Cavitation

Avoid cavitation of rotating equipment because the high pressures generated by the rapid vaporization during cavitation can exceed the rated capability of hardware. Additionally, dynamic instabilities can be created that allow rotating shafts and impellers to wear against housings, leading to failures from frictional heating.

6.6.4 Geysering

Avoid geysering of LOX and GOX caused by gas bubble formation in flowing liquid systems. This can create rapid pressurization of soft goods and can create a fluid hammer condition with rapid overpressurization on components, leading to bursting of pressure-containing components.

6.6.5 Hydrostatic overpressurization

Prevent hydrostatic overpressurization of tanks and dewars during filling operations by using a full tricock valve system or similar overfill protection to maintain an adequate ullage area.

6.6.6 Other considerations

The absorption of helium in liquid oxygen shall be taken into account in the design. An amount of evaporation of gaseous helium shall be considered for the characterization of input data for turbo pump design. For microgravity applications, the behaviour of liquid oxygen in this environment shall be taken into account.

6.7 Electrical design guidelines

In addition to the GOX guidelines in 5.3.5, electrical wiring inside LOX tanks shall be encased in hermetically sealed conduits or conduits rendered inert with nitrogen or helium gas. The instruments, switches, flow sensors and electrical devices shall be designed in a modular structure and hermetically sealed. Rendering inert with nitrogen or helium is recommended.

7 Standard practices

7.1 Liquid-oxygen vessels

7.1.1 General

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

7.1.2 LOX storage vessels

LOX storage vessels include an inner tank to contain the liquid and an outer jacket containing either powder or vacuum insulation or a combined powder-inert gas insulation to reduce heat transfer to the LOX. The construction, installation and testing of LOX storage vessels shall conform to the local applicable codes and standards which typically involve pressure, performance, leakage and welding test procedures.

7.1.3 Tank outlets

The tank outlet shall be clearly marked and shall 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 restrict liquid flow from the tank in case of a line failure downstream shall be provided as close to the tank annulus as possible. The emergency valve shall be quick-acting and shall be operable under conditions of heavy liquid spillage. A label shall be provided, listing the contents, capacity, operating pressures, direction of flow, dates of proof tests and dates of in-service inspection and recertification.

7.1.4 Tank trucks

The vibration and sloshing of LOX shall be minimized by careful selection of truck running gear and the placement of tank baffles and supporting systems. Vibration can be reduced by controlling unwanted expansion and contraction.

7.1.5 Tank pressure control

Neither tank pressure nor liquid shall open the isolation valves. The valves shall fail safely in a closed position on failure of the operating fluid supply. The emergency isolation valve shall be in addition to any normal isolation valve required for operation. Top-entry connections that extend into the liquid shall be protected by emergency valves.

7.2 Piping systems

7.2.1 General

All LOX piping systems shall be designed in accordance with local regulations and specifications. The design shall be based on the pressure and temperature limitations of the materials selected.

7.2.2 Underground piping

High-pressure oxygen shall not be transmitted in buried piping. Underground piping cannot be inspected as readily as visible piping for leaks, corrosion or other defects. Oxygen piping and equipment shall be installed at a distance from electric power lines or electrical equipment, far enough that any failure of the power lines or electrical equipment will not permit contact with the oxygen piping and equipment. All oxygen piping shall be adequately supported to avoid excessive vibration and to prevent deterioration by friction.

7.2.3 Piping requirements

Materials used in pressure-containing piping systems and piping elements shall conform to listed or published specifications covering chemical, physical and mechanical properties, methods and processes of manufacture, heat treatment and quality control, and shall otherwise meet the requirements of the design organization.

Piping and pressure-containing components shall be consistent with the accepted design philosophy, substantiated by a stress analysis to predict safe and reliable operation, pressure testing to verify predicted performance and successful experience under comparable design conditions with components that are similarly shaped and proportioned.

7.2.4 Velocity limits

All factors shall be considered when establishing safe velocity limits. A safe piping system, in addition to being designed and installed in accordance with all applicable regulations, shall further meet the special requirements for oxygen service. These special requirements include certain velocity restrictions and material specifications, as follows:

a) special criteria for design and location;

b) correct location and specification of joints, fittings, safety devices and filters;

c) thorough and adequate cleaning of the components of the system for oxygen service.

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

7.2.5 Piping, tubing and fittings

Piping, tubing and fittings shall be suitable for oxygen service and for pressures and temperatures at use conditions. Even when the system is built entirely of suitable materials, problems can develop if the pressurized gas flow is either started or stopped abruptly. Two main events cause problems:

a) flowing gas undergoing compression heating at elbows, dead ends and valves (any place it is suddenly stopped); the resulting temperature rise can be sufficient to ignite all polymeric materials commonly used in oxygen systems, including PCTFE;

b) mechanical shock to the system which may dislodge solid particles; if these particles are caught up in the flow and impinge on a surface, hot spots may result that cause ignition.

7.3 Liquid-oxygen piping systems

7.3.1 General

Many liquid-oxygen lines are vacuum-jacketed or insulated to reduce the heat input. The jacket design shall allow the jacket to follow natural thermal displacement of the inner line. Piping systems shall be sufficiently flexible to prevent thermal expansion or contraction from causing piping failures or leaks. Piping systems that are infrequently used or that are short may be uninsulated. Long pipe runs shall be vacuum-insulated. Bellows sections in vacuum jackets shall be used to compensate for contraction and expansion. Where practical, avoid cavitation in LOX systems.

7.3.2 Horizontal pipelines

Horizontal pipelines may experience cryogenic bowing because of stratified flow or because a single liquid layer exists on only the bottom of the pipe. The large forces normally generated by bowing shall be considered when designing pipe-guide supports for bellows expansion joints. The design of pipe-supporting systems shall be based on all concurrently acting loads transmitted into such supports. These loads shall include weight, service pressure and temperature, vibration, wind, earthquake, shock and thermal expansion and contraction. All supports and restraints shall be fabricated from materials suitable for oxygen service.

7.3.3 Piping overpressure

Each section of liquid-oxygen piping capable of being isolated shall 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 shall be equipped with protective devices for overpressure control, particularly from overpressures caused by insulation failures. The overpressure protection devices shall be located in such a manner that all parts of the system are protected from overpressure.

7.3.4 Low points

Low points (traps) on liquid discharge piping are to be avoided to prevent accumulating contaminants and trapping fluid. If traps are unavoidable, low-point drains shall be provided and designed so that all fluids drain onto oxygen-compatible surfaces. All tubing ends, fittings and other components used in oxygen systems shall be protected against damage and contamination.

7.4 Gaseous oxygen piping systems

7.4.1 General

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 both.

7.4.2 Quantitative limit

Until a more quantitative limit can be established, the following practices are recommended:

a) where practical, avoid sonic velocity in gases; where impractical, use the least reactive materials available;

b) if possible, avoid the use of non-metals at locations within the system where sonic velocity can occur;

c) maintain fluid system cleanliness to limit entrained particulates and perform blow-down with filtered, dry gaseous nitrogen at maximum anticipated pressure and flow before wetting the system with oxygen.

7.4.3 Gas velocity

Piping systems shall be designed to ensure the GOX in the system does not exceed specified velocities. Places where fluid velocities are higher shall be reviewed for particle impact ignition sensitivity.

7.4.4 Piping and fitting materials

For use at pressures above 5 MPa, oxygen piping and fittings shall be stainless steel, nickel, nickel/copper alloys, nickel/iron alloys or copper alloys because of ignition susceptibility.

7.5 Systems connections and joints

7.5.1 General

Materials shall be documented for compatibility with the total environment of pressure, temperature, flow rates and exposure time profiles. Materials for joints and fittings shall be similar to the piping metal to avoid developing electrical couples. When the use of different metals cannot be avoided, considerable care shall be taken when removing the fitting or connection so that any grit or contaminant resulting from the electrical couple is not left in the pipe.

7.5.2 Joints

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 contacting surfaces are joined to limit particulate entrapment. Exposed weld surfaces shall be ground to a smooth finish for ease of cleaning. With brazed and soldered joints, special care shall be taken to ensure surface cleanliness, close and uniform clearance and full penetration of the joint.

7.5.3 Vessel connections

Vessel connections to rigidly mounted test facility piping shall use supported and anchored flexible metal hose insulated for low-temperature service at the desired pressure. Recommendations for flexible hoses include a maximum allowable slack of about 5 % of the total length. For greater safety, the hose restraints shall be at least 50 % stronger than the calculated impact force on an open line moving through the flexure distance of the restraint.

7.5.4 Piping assemblies

Piping shall be assembled by welding, except at connections to valves, etc., where flanged joints are required. Welding procedures, welder qualification tests, welding operations and weld testing shall be in accordance with the required specifications. Backup rings shall not be used because of the difficulty of recleaning the system.

7.5.5 Transition joints

Transition joints such as aluminium to stainless steel shall not be used in LOX transportation systems. The large temperature cycles and severe mechanical jolts have frequently caused failures of such joints.

7.5.6 Transfer connections

Fill connections for loading and transfer from transportation systems shall terminate in the fixed ends of hose unions that use a unique design configuration (e.g. keyed) to prevent filling oxygen tanks with other fluids. Check valves shall be placed in the fill lines to prevent the tank from draining onto the ground should the fill lines fail.

The oxygen gas trailers and transfer connections shall 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 shall be provided with tethered end plates, caps, plugs or covers to protect the system from contamination or damage when not in use.

The absorption of helium in liquid oxygen shall be taken into account in the design. An amount of evaporation of gaseous helium shall be considered for the characterization of input data for a turbo pump. Moreover, the behaviour of liquid oxygen in microgravity shall been taken into account.

7.6 Components

7.6.1 Design

Components shall be designed specifically for use in oxygen or oxygen-enriched environments. This requires a thorough understanding of the reactivity of materials used in components designed for oxygen use. The major problems in component design are the ignition of metallic and non-metallic materials, adiabatic compression, mechanical overstress, seal erosion and contamination generation and control. The rate of flame propagation and ignition susceptibility of materials shall also be a prime consideration in the safe design of oxygen and oxygen-enriched systems. The oxygen compatibility of all materials in oxygen and oxygen-enriched environments shall be carefully evaluated under end-use conditions.

Designers shall:

a) minimize mechanical impact, frictional heating, particle impact, electrical arcing and use-generated particles during manufacture, assembly and operation, as well as the amount of organic and non-metallic materials exposed to oxygen flow;

b) limit flow velocities, pressurization rates and fluid-induced vibrations;

c) avoid blind passages, rotating valve stems and sealing configurations that require rotation on assembly, crevices that could lead to particle entrapment, and thin walls;

d) design dynamic seals to minimize particle generation and coefficients of friction and choose seal configurations to minimize particle generation;

e) consider the effects of thermal expansion, long-term operation and single-point failures;

f) design the system such that loss of power and pressure will return the system to a fail-safe position to protect personnel and property.

7.6.2 Valves

7.6.2.1 Accessibility and protection

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

7.6.2.2 Distribution systems

Valves in GOX distribution systems shall be kept to a minimum and shall be of good quality because they have mechanical joints that are susceptible to leaks. All valve materials shall be suitable for oxygen service and material selection shall meet velocity criteria. Stems, packing glands and other parts vital to proper valve operation shall be made of materials that will not readily corrode. The stem packing shall be oxygen-compatible.

Vessels used as test facility components shall have remotely operated fail-safe shut-off valves located close to the loading vessel. All large-capacity storage vessels shall have remotely controlled fail-safe shut-off valves. A manual override shall be considered in case of a power failure.

7.6.2.3 High-pressure systems

Valves that, from a safety viewpoint, are suitable for high-pressure GOX service may also be suitable for high-pressure LOX service. Adaptation for liquid service shall consider possible mechanical problems such as contraction strains, icing and glass transition temperatures of polymers. Extended-stem gate, globe or ball valves are satisfactory. Valves shall be provided with venting features to prevent trapping cryogenic liquid.

7.6.2.4 Check valves

Check valves shall not be used when bubble-free tightness is required. Check valves may only be used if a safety margin is maintained well above the maximum allowable working pressure. If the maximum allowable working pressure needs to be higher than the supply pressure, two shut-off valves with bleed valves between them shall be used.

Check valves might be completely tight at the start of service but develop leaks later. In fact, a single check valve is often more leak-proof than multiple check valves because the larger pressure drop closes it more tightly.

The safety of laboratory operations requires that bottled gases not be contaminated. Suppliers of bottled gases specifically prohibit contaminating gases in their bottles. Bottled gases have been contaminated because check valves in interconnected systems leaked, so the valves shall be checked regularly and the contents of the pressure vessels shall be analysed for contamination.

7.6.2.5 Isolation valves

Isolation valves shall operate either fully open or fully closed and never in a throttling or regulating mode.

7.6.2.6 Bypass valves

Where required, a bypass valve shall be provided around isolation valves; the bypass valve shall be of suitable materials because of the high velocity involved. If remotely operated bypass valves are used, the valves shall be fail-safe in case of power loss and shall close on a system emergency shut-down signal.

7.6.3 Pressure relief devices

7.6.3.1 General

Relief valves or rupture disks shall be installed on tanks, lines and component systems to prevent overpressurization. The capacity of a pressure relief device shall be equal to that of all the vessel and piping systems it is to protect. These devices shall be reliable and the settings shall be secured against accidental alteration.

7.6.3.2 Relief valves

Relief valves shall be functionally tested to verify that design requirements are satisfied, including testing both in the static and dynamic states. Relief valve riser pipes on high-pressure oxygen systems shall be analysed for resonant tuning.

Relief valves and similar devices shall not be considered to be secondary and passive components in the test hardware design; it shall be assumed that they will function at some time. Personnel safety and hardware damage shall be primary considerations.

7.6.3.3 Pipeline relief valves

All sections of the pipeline shall be adequately protected by pressure relief devices and shall have an adequate manual vent valve to allow for blow-down and purging. All equipment in any oxygen system that may be removed for inspection, maintenance, replacement, etc. shall be provided with a vent valve for blow-down and purging. Safety valves, vent valves and associated piping shall be constructed entirely of approved materials.

Inherent ignition hazards are associated with self-activating relief devices in oxygen systems. Therefore, relief devices and any vent lines connected just downstream shall be built from the most ignition-resistant materials available and positioned in remote locations or isolated from personnel by barriers or shields.

For protection against rupture hazards, all enclosures that contain liquid or that can trap liquids or cold vapours shall have rupture disks or relief valves installed.

7.6.3.4 Tube trailer valves

Gaseous oxygen tube trailers shall be equipped with normally closed shut-off valves that require power to remain open and that will automatically return to fully closed when the power is removed. These safety shut-off valves shall never be used for flow control. Manually operated main shut-off valves shall also be used to isolate trailers and to control flow, if required.

7.6.3.5 Bypass, vent and safety valves

Manual bypasses to act as pressure-equalizing valves shall be provided around all manual pipeline valves.

Vent and safety valves shall be located outdoors to discharge in a safe area. If they cannot be located outdoors, the discharge shall be piped outdoors. Lines leading to and from relief devices shall be of sufficient size to ensure the system will not be overpressurized. Piping and component orientation is critical and consideration shall be given to water aspiration and/or preventing rain from entering a system and thereafter freezing out against relief devices. Bug screens, thrust balancing and the potential to backstream contaminated water into a system shall also be addressed. Discharge lines shall be fabricated from ignition-resistant materials. Outlet ports shall be checked to ensure they cannot inadvertently become plugged. Resonant frequency or coupling in captured vent systems, which can aggravate a failure, shall be considered.

7.6.3.6 Pressure relief systems

The calculations that form the basis for pressure relief system design shall be provided. Such data shall include:

a) the maximum operating pressure under both normal and abnormal operating conditions,

b) the location and condition of relief devices,

c) the suggested means of installation,

d) the testing frequency,

e) the possible hazards caused by system operation, and

f) the materials of construction.

7.6.3.7 Safety devices

Safety devices shall be checked before use to prevent possible installation of incorrectly pressure-rated devices. The minimum relief capacities of the safety devices shall be as determined by the flow formulae in application codes and specifications.

7.6.4 Cylinders

Acceptable flexible links for connecting cylinders include stainless-steel tubing, which may be formed into loops to provide enough flexibility for easy hook-up, and is the preferred method. Flexible metal tube or pipe (such as bellows sections) are also recommended.

PTFE-lined flexible hoses may be used if particular care is exercised to ensure that pneumatic impact cannot occur. The risks may be minimized if procedures avoid operator error and the design incorporates a long, non-ignitable metallic housing at the downstream end of the flexible hose. Proper restraining cables and anchoring cables are required for flexible hoses. Shapes (such as those of bellows), tubes used in pressure gauges, small-diameter piping, dead-legs in piping and crevices (such as those in pipe threads) shall be avoided where possible.

7.6.5 Electrical wiring and equipment

Electrical equipment and fittings used in oxygen-enriched atmospheres shall be designed and approved for use at the maximum proposed pressure and oxygen concentration. Electrical equipment shall be provided with non-combustible insulation. The boxes and fittings shall be approved for use at the applicable oxygen pressure and concentration. Rain-tight fittings, boxes and equipment shall be used if an automated water spray system is located in the area.

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ICS 49.140

Price based on 20 pages