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Space systems — Oxygen safety —

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

Systèmes spatiaux — Sécurité des systèmes d'oxygène —

Partie 2: Sélection des matériaux métalliques pour les systèmes d'oxygène et leurs composants

Reference number
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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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

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.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 22538-2 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*

Introduction

Metallic materials, although used extensively, are flammable in oxygen. The ignitability of metallic materials varies considerably, but the risk associated with the flammability of metallic materials can be minimized through proper selection combined with proper design. When selecting metallic materials for high-pressure oxygen systems, the susceptibility to ignition of the metal and the possible ignition sources in the system are given equal consideration with the structural requirements.

Mechanical or particle impact is a credible ignition source in high-pressure oxygen systems. Other mechanisms for ignition of metallic materials are considered, although test data may not exist. Ignition of metallic materials by burning contaminants has not been studied experimentally, but the use of incompatible oils and greases (especially hydrocarbon greases) is one of the more common causes of oxygen-system fires. Improper component design or installation can result in a fire when metallic materials with insufficient mechanical strength are chosen for the given application.

INTERNATIONAL STANDARD **ISO 22538-2:2007(E)**

Space systems — Oxygen safety —

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

1 Scope

This part of ISO 22538 describes a process for the selection of metallic materials for 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 4589 (all parts), *Plastics — Determination of burning behaviour by oxygen index*

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

3.2 Abbreviated terms

AIT	auto-ignition temperature
GOX	gaseous oxygen
LOX	liquid oxygen

4 General

4.1 Overview

Metals are the most frequently used construction materials in oxygen systems. Metals are generally less susceptible to ignition than polymers. They are often ignited by a kindling chain reaction from a polymer or hydrocarbon contaminant. Selection of the proper metals in an oxygen system, coupled with good design practice, can minimize the hazards of ignition and combustion of the metal. While selecting metals for oxygen service, situational or configurational flammability shall be evaluated.

4.2 Background

Experience has shown that a safe oxygen system is not necessarily achieved merely by selecting the best materials available. Experienced designers have gained considerable understanding of the effects of geometry on the design of oxygen systems and components and have developed design features directed at overcoming the physical limitations of materials. Information required to select materials shall include material composition and configuration, environmental and operational conditions, as well as ignition and combustion behaviour of the materials in the operational conditions. Accelerated oxygen deterioration, degradation and durability tests shall be conducted for overall evaluation of the materials.

Material selection alone does not preclude ignition, but proper choices can markedly reduce the probability of ignition. For example, ignition induced by particle impact can be minimized by selecting metal alloys that do not ignite in a particle impact test performed at the use conditions. Galling can be largely eliminated if potential rubbing surfaces are made from materials with widely differing hardness. For all types of ignition mechanisms, selecting materials that have relatively small exothermic heats of combustion will reduce not only the probability of ignition, but also the probability of propagation. Materials with high heats of combustion shall be avoided.

Materials used in liquid-oxygen systems shall meet the requirements for gaseous oxygen and have satisfactory physical properties, such as strength and ductility, at low operating temperatures.

See Annex A for test data.

4.3 Design considerations

The operational pressure and the structural requirements are given equal attention in the design of the system. While materials selection does not preclude system failures, proper materials selection coupled with good design practice can reduce the probability of system failures. Materials evaluation and selection are based on both materials testing for ignition and combustion characteristics and studies of liquid-oxygen (LOX) and gaseous-oxygen (GOX) failures. No single test has been developed that can apply to all materials to determine either absolute ignition limits or consistent relative ratings. When selecting a material for oxygen systems, its ability to undergo specific cleaning procedures to remove contaminants, particulates and combustible materials without damage shall be considered.

Information required to select materials and evaluate system safety shall include material compositions and configurations, environmental and operational considerations (temperature, pressure, flow rate or ignition mechanisms) and ignition and combustion behaviour of the materials in the given environmental conditions. Materials used in LOX systems shall have satisfactory physical properties, such as strength and ductility, at operating temperature.

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

The exposure of a material to stress may result in aging. The stress may be a result of time, pressure, contact with materials or chemicals, temperature, abrasion, light, gaseous or particle impact, tensile or compressive force (either static or cyclic) or other stressors during the service life. Aging may alter the surface, the chemistry and the strength of a material and it may affect the ignition properties of a material.

4.4 Materials certification

Materials procured for use in oxygen systems require a material certification from the manufacturer. In addition, it is good practice to confirm the manufacturer-supplied information.

4.5 Materials control

Materials used in LOX, GOX and oxygen-enriched systems shall be carefully controlled. The materials shall be carefully evaluated, and their susceptibility to ignition and the possible ignition sources in the system shall be taken into account. The materials that pass the required tests shall be considered for design.

5 Ignition mechanisms

5.1 General

In oxygen and oxygen-enriched atmospheres, the ignition of fuel-oxygen mixtures occurs with lower energy inputs and at lower temperatures than in air. For example, the minimum spark energy required for the ignition of hydrogen in air is 0,019 mJ at 1 atmosphere, but the minimum spark energy for the ignition of hydrogen in 1 atmosphere of oxygen is only 0,001 2 mJ.

5.2 Ignition conditions

The usual conditions for ignition are a function of temperature, time and turbulence. The temperature shall be high enough to cause melting, vaporization and significant reactions. The time shall be long enough to allow the heat input to be absorbed by the reactants so that a runaway thermochemical process can occur. The turbulence shall be high enough to allow good mixing between the fuel and the oxidizer, so that heat can be transferred from the reacted media to the unreacted media.

5.3 Materials tests

To date, no single test has been developed that can produce either absolute ignition limits or consistent relative ratings for all materials. Materials are evaluated by testing for their ignition and burning characteristics and by studying oxygen-related failures. An assessment of the causes of accidents and fires suggests that materials and components used in oxygen systems could be vulnerable to ignition that may lead to catastrophic fires.

5.4 Ignition factors

Factors affecting the ignition of solid materials include

- material composition and purity,
- size, shape and condition of the sample,
- characteristics of oxide layers,
- testing apparatus,
- ignition source,
- gas pressure, and
- gas concentration and composition.

The ignition process depends upon the geometry and operating conditions; therefore, caution shall be taken in interpreting the results of any ignition experiment and in generalizing ignition data.

Care shall be taken in applying ignition temperature data, especially for metals, to actual components. Ignition temperatures are not inherent materials properties but are dependent upon the items listed previously. When applying ignition temperature data, it shall be ensured that the ignition temperature data were obtained in a manner similar to the end-use application. Failure to do this can result in erroneous materials selection decisions. For example, the ignition temperatures of aluminium in oxygen vary from 660 °C (which is the melting point of aluminium) to 1 747 °C (which is the melting point of aluminium oxide). The ignition temperature depends on whether or not the oxide is protected during the ignition process.

Should ignition occur, several properties affect the ability of the material to damage adjacent construction materials. The heat of combustion, mass, flame propagation characteristics, filler content, char formation and shape stability affect the propensity to ignite surrounding materials.

5.5 Ignition mechanisms and sources

5.5.1 General

Potential ignition mechanisms and ignition sources to consider include

- particle impact,
- mechanical impact,
- pneumatic impact,
- promoted ignition,
- galling and friction,
- resonance,
- electrical arcing,
- oxygen index, and
- threshold pressure.

5.5.2 Particle impact

Heat may be generated from the transfer of kinetic, thermal or chemical energy when small particles moving at high velocity strike a component. This heat, which is adequate to ignite the particle, may be caused by the exposure of non-oxidized metal surfaces or the release of mechanical strain energy. The heat from the burning particle ignites the component. For example, high-velocity particles from assembly-generated contaminants striking a valve body just downstream of the control element of the valve can cause particle impact ignition.

5.5.3 Mechanical impact

Heat may be generated from the transfer of kinetic energy when an object having a relatively large mass or momentum strikes a component. The heat and mechanical interaction between the objects is sufficient to cause ignition of the impacted component. This may be performed in ambient pressure LOX test conditions or in pressurized LOX or GOX test conditions.

Aluminium, tin, lead and titanium alloys have been ignited experimentally in this way, but iron, nickel, cobalt and copper alloys have not. It has been determined for several aluminium alloys that the minimum energy to induce sample fracture is less than or equal to the minimum energy required to induce ignitions by mechanical impact. Therefore, mechanical failure will precede or attend mechanical impact ignitions of these alloys. Mechanical impact testing of contaminated surfaces in oxygen indicates an increase in mechanical impact sensitivity.

5.5.4 Promoted ignition

A source of heat input may occur (perhaps caused by a kindling chain) that acts to start the nearby materials burning. For example, contaminants (oil or debris) ignite, releasing heat that ignites adjacent components.

Several studies regarding promoted ignition have been completed in recent years. These studies have determined the pressure at which sustained upward combustion of 3,2 mm diameter metallic rods occurs.

5.5.5 Galling and friction

Heat may be generated by the rubbing together of two parts in GOX, LOX, air or blends of gases containing oxygen in a chamber capable of maintaining a pressure of up to 69 MPa. A rotating shaft capable of rotating up to 30 000 revolutions per minute is pressed against a stationary test article at loads up to 4 450 N. The heat and interaction of the two parts, along with the resulting destruction of protective oxide surfaces or coatings, cause the parts to ignite. For example, the rub of a centrifugal compressor rotor against its casing may cause galling and friction.

The resistance to ignition by friction is measured in terms of the Pv product, which is the product of the contact pressure and the surface velocity.

5.5.6 Resonance

Acoustic oscillations within resonance cavities may cause a rapid temperature rise. This rise is more rapid and reaches higher values if particles are present or gas velocities are high. For example, a gas flow into a tee and out of a branch port can form a resonant chamber at the remaining closed port.

Results of studies with several types of tee configurations have indicated that temperature increases caused by resonance heating is sufficient to ignite both aluminium and stainless-steel tubes. Tests with aluminium and stainless-steel particles added to the resonance cavity indicated that ignition and combustion may occur at lower temperatures. Some of the tests with stainless-steel particles have resulted in ignition, but ignition appears to depend more on system pressures and system design.

5.5.7 Electrical arcing

Electrical arcing can occur from motor brushes, electrical power supplies and lighting. Electrical arcs can be very effective ignition sources for any flammable material. For example, an insulated electrical heater element can experience a short circuit and arc through its sheath to the oxygen gas, causing an ignition.

5.5.8 Oxygen index

This is a determination of the minimum concentration of oxygen in a flowing mixture of oxygen and a diluent, usually nitrogen, that will just support combustion at atmospheric pressure.

The test system consists of a heat-resistant glass cylinder that is attached to a non-combustible base. The base contains a non-combustible material, usually glass beads, to allow the gases to mix and evenly distribute the diluent. The sample is supported from the bottom and is ignited at the top. The diluent is adjusted until the mixed gas barely supports combustion of the test material. See ISO 4589 for a detailed test method.

5.5.9 Threshold pressure

The threshold pressure is the minimum gas pressure at a specified oxygen concentration and temperature that supports self-sustained combustion of the entire sample. An igniter is placed below the bottom of the test material, which is suspended in a chamber filled with the pressurized test gas. The test conditions are adjusted until self-sustained combustion of the sample does not occur.

6 Metallic materials

6.1 Nickel and nickel alloys

6.1.1 Resistance

Nickel and nickel alloys are very resistant to ignition and combustion. These alloys usually have high strengths with significant low-temperature toughness. Alloys with very high nickel content have not been ignited in particle impact tests.

6.1.2 Nickel/iron (Inconel™) alloys[1)]

The ignition resistance of nickel/iron alloys varies with the specific alloy. Inconel™ 718 is used extensively in high-pressure oxygen systems in recent years because it is a good structural material and is considered significantly less ignitable than stainless steels. Some Inconel™ alloys are used successfully at pressures as high as 69 MPa. Inconel™ alloys appear to resist ignition by particle impact better than most stainless steels, but are similar to stainless steel 440C. Some Inconel™ alloys have exceptional resistance to ignition by frictional heating, but others (including Inconel™ 718) ignite similarly to stainless steel during rubbing frictional tests. Inconel™ MA754, a mechanically alloyed material, has exceptional resistance to ignition by frictional heating and does not support self-sustained combustion at pressures as high as 69 MPa.

Inconel™ 625 is useful for very high-temperature applications where welded materials are required. It may be used as a high-temperature replacement for Monel™ 400, bearing in mind that material strength is reduced and flammability and ignition susceptibility is increased. Inconel™ 718 is useful for very high-temperature applications where high specific strengths are required and welding is permitted. Because it can be heat-treated to enhance mechanical properties, Inconel™ 718 may replace Inconel™ 625; however, flammability and ignition susceptibility is increased.

Nickel 200 alloys are also suitable for use as filter elements.

6.1.3 Nickel/copper (Monel™) alloys[2)]

6.1.3.1 Characteristics

Nickel/copper alloys are generally self-extinguishing in oxygen fires, are available in the necessary ranges of hardness and are typically used for valve stems, bodies and springs.

Copper and copper alloys, but not brass, are generally quite resistant to ignition. Monel™ 400 and K-500 have not ignited in particle impact tests (although some surface melting and burning may be observed) and do not burn in upward flammability tests even at oxygen pressures as high as 69 MPa. Monel™ alloys ignite in frictional heating tests at higher loads than stainless steel, but the burning does not propagate. Ignitions have

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2) Monel™ is the trade name of a suitable product available commercially. This information is given for the convenience of users of this part of ISO 22538 and does not constitute an endorsement by ISO of the product named. Equivalent products may be used if they can be shown to lead to the same results.

occurred in test systems fabricated from nickel/copper alloys, and precautions shall also be taken to minimize ignition sources when designing nickel/copper systems. However, fewer precautions are required when ignition-resistant materials are present than when more ignitable materials are present, and configurational testing is rarely essential.

Monel™ alloys are rarely the materials of choice for flight systems because of the perception that components constructed of them weigh more than those of other alloys. However, these alloys can often be obtained in the necessary range of hardness and specific strengths. Monel™ alloys are recommended for ground-based, manually operated systems when the cost of demonstrating safe operation with other materials is high. In aerospace systems, when weight is a constraint, the use of Monel™ sections or liners in key areas can provide extra protection from ignition and fire propagation without increasing weight. In fact, because of the greater strength-to-weight ratio of Monel™ compared to aluminium, Monel™ components can sometimes be made smaller and lighter.

If an all-Monel™ valve is required, then screw threads shall have one part made of annealed Monel™ 400 and the other made of age-hardened Monel™ K-500 to achieve a large difference in hardness and some difference in chemical composition. Using an annealed 300 stainless steel mated with age-hardened Monel™ K-500 would further reduce galling potential because of the increased disparity in chemical compositions.

Monel™ and Monel™ alloys are flammable in finely divided configurations, such as wire mesh and sintered powder.

6.1.3.2 Monel™ 400

Monel™ 400 is useful as an engineering alloy with high ignition resistance in oxygen. It has particular advantages for welding applications, such as pressure vessels and piping. It is also good for assembly housings where weight is not a design constraint and where environmental corrosion, such as might occur by a seashore, may preclude other alloys.

6.1.3.3 Monel™ K-500

Monel™ K-500 is useful for high strength-to-weight ratios. It is more expensive than Monel™ 400, but it also has improved physical properties that make it a good choice. This material is excellent where relatively high hardness is required, such as bearing load retention and improved galling resistance. Another good application for Monel™ K-500 is on valve and piston shafts. However, Monel™ K-500 shall not be welded for most applications.

6.2 Copper and copper alloys

Copper is suitable for use in oxygen at all operating pressures. It is particularly useful for resisting ignition by particle impact and therefore can be used for impingement plates. Copper is resistant to ignition and combustion, but it also has a low-ductility oxide, which is not tenacious and sloughs off. This can cause contamination in oxygen systems. Sintered bronze is more burn-resistant than Monel™ 400 and stainless steel for filter element material.

Aluminium-bronze, although containing a large amount of copper, is not recommended for use in oxygen systems because of its flammability and ignitability. Copper and some copper alloys are flammable in finely divided configurations (such as wire mesh).

Alloys with very high copper content have not been ignited in particle impact tests.

6.3 Stainless steels

Stainless steels are more ignition- and burn-resistant than titanium and aluminium alloys and are used extensively in high-pressure oxygen systems. The ignition and burn resistance is about the same for most stainless steels; some exceptions exist, such as 440C, which ignites and propagates flame less easily than other stainless steels. Few problems are experienced with the use of stainless-steel storage tanks or lines, but ignitions have occurred in stainless-steel components such as valves in high-pressure and high flow rates. Although stainless steel particulate can ignite materials, it is far less hazardous than aluminium particulate. Stainless steels have high heats of combustion and are ignited quite easily by frictional heating, particle impact and promoters.

The 300 series stainless steel is a very common material for valves, tubing, vessels and fittings. If used in situations where the ignition mechanisms are minimized or eliminated, it provides an effective and relatively low-cost material choice.

6.4 Aluminium and aluminium alloys

6.4.1 General

Aluminium alloys are highly susceptible to ignition and combustion in oxygen, but because of their light weight, designers are tempted to use aluminium in spite of the ignition hazards. An anodizing surface preparation shall be used for aluminium parts subject to conditions that may generate particulate or be subjected to particle impact. Aluminium alloys are attractive candidate materials for pressure vessels because of their high strength-to-weight ratios. It is especially useful for oxygen storage tanks and similar areas where no credible ignition hazard exists.

6.4.2 Frictional heating ignition

A thin, protective oxide surface film provides resistance to aluminium reactions in oxygen. Aluminium’s tough, tenacious oxide, which has a melting point of 2 342 °C, protects the base metal from ignition to a degree under static conditions even above the 660 °C melting point of aluminium. High temperatures above 477 °C, abrasions or stress may cause a loss of film integrity, increasing the tendency of the metal to burn. The use of aluminium alloys in lines, valves and other components shall be avoided whenever possible because they easily ignite in high-pressure oxygen, burn rapidly and have very high heats of combustion. Aluminium is ignited exceptionally easily by friction because wear destroys the protective oxide layer; it shall not be used in systems where frictional heating is possible.

6.4.3 Particle impact ignition

Aluminium is very easily ignited by particle impact. Aluminium particulate is a far more effective ignition source than many other metal particulates tested to date. High-pressure oxygen systems fabricated from aluminium shall be designed with extreme care to eliminate particulate. Filters shall be fabricated from materials less ignitable than aluminium. Nickel, silver, bronze or Monel™ alloys are recommended, although Monel™ wire meshes are known to be flammable in high-pressure oxygen. Aluminium alloys are more suitable for static components with low oxygen flow rates (such as oxygen storage tanks) than for components with internal movement and variable flow (such as valves and regulators). Systems that use large areas of aluminium alloys in oxygen storage tanks shall be designed to ensure that aluminium particulate cannot cause ignition of other metallic materials downstream from the aluminium.

Particle impact tests on anodized aluminium targets have indicated that anodizing the surface increases the resistance to ignition by particle impact.

6.4.4 Mechanical impact tests

No ignitions occurred with specimens of 6061-T6 aluminium of several diameters and thicknesses in liquid and gaseous oxygen at a pressure of 69 MPa. However, reactions did occur when aluminium 6061-T6 specimens were contaminated with cutting oil, engine oil or toolmakers dye. Extensive liquid- and gaseous-oxygen mechanical impact testing was performed at three test facilities in the evaluation of aluminium/lithium alloys and 2219-T851, 2219-T87, 2219-T37, 2090-T81, 8090-T3 and 8090-T771 alloys in the development of lightweight tanks for space vehicles. Reactions occurred in some specimens of all alloys during pressurized tests.

Aluminium and iron metal alloys have been ignited by impact of 1 600 μm and 2 000 μm diameter aluminium particles travelling at velocities greater than 244 m/s, while alloys with very high nickel and copper content have not been ignited. Tests conducted with small quantities of iron powder and inert material impacting against carbon and stainless steels have indicated that when the particle does not ignite, no ignition of the target materials is observed. Ignition of the particle mixture has occurred at velocities greater than 45 m/s and at pressures ranging from 20 MPa to 24 MPa. The data suggest that specimen ignition is independent of pressure between 2 MPa and 30 MPa.

6.4.5 Promoted ignition tests

Promoted ignition tests on aluminium/lithium alloys have indicated that they are less flammable than aluminium. The threshold pressure for aluminium/lithium alloys is approximately 0,17 MPa.

6.5 Iron alloys

Iron alloys are poor candidates for oxygen systems because they easily ignite and offer little weight savings; however, iron alloys are used extensively in cylinders. Iron alloys, like many other alloys, can only be used if the credible sources of ignition are identified and removed.

Alloy steels (Fe-Ni) suitable for use in oxygen systems include 5 % nickel, 9 % nickel and 36 % nickel (Invar™)[3]. The threshold pressure for Invar™ is similar to most stainless steels. In frictional heating tests similar behaviour is noted where the ignition is comparable to that for stainless steels.

6.6 Other metals and alloys

6.6.1 General

Many other metals and alloys exist that have mechanical properties suited to applications in high-pressure oxygen systems; however, their ability to propagate fire after ignition shall be evaluated before determining how suitable they are for use. New alloys are continually being developed, some of which are being designed to resist ignition and not to support self-sustained combustion. Before a new alloy is used in an oxygen system, its use and application shall be reviewed and approved by the organization responsible for material selection.

The use of certain metals in oxygen systems shall be restricted.

6.6.2 Titanium

All titanium alloys tested showed sensitivity to mechanical impact in oxygen. Titanium shall not be used with LOX at any pressure or with GOX at oxygen pressures above 207 kPa. Tests have indicated that titanium, α-titanium and α_2-titanium alloys can be ignited and sustain combustion at oxygen pressures as low as 7 kPa. Frictional heating tests conducted on titanium and titanium alloys have indicated that the Pv product for ignition is extremely low. Recent testing indicated that titanium and its alloys can also be ignited in air in frictional heating tests.

Titanium alloys shall be avoided in storage or test facility systems, since titanium is impact sensitive in oxygen. A reaction in LOX or GOX may propagate and completely consume the metal.

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[3] Invar™ is the trade name of a suitable product available commercially. This information is given for the convenience of users of this part of ISO 22538 and does not constitute an endorsement by ISO of the product named. Equivalent products may be used if they can be shown to lead to the same results.

6.6.3 Magnesium

Magnesium alloys shall not be used except in areas where minimal exposure to corrosive environments can be expected. Reactivity with halogenated compounds constrains its use with lubricants containing chlorine or fluorine. In promoted combustion tests in 100 % oxygen, magnesium and its alloy AZ-91 have shown the ability to sustain combustion even at pressures as low as 7 kPa.

6.6.4 Beryllium, cadmium and mercury

Beryllium, cadmium and mercury and their alloys are highly toxic and are not acceptable for use in oxygen systems under any conditions.

7 Component housings

The mass of the housing contributes the greatest proportion of weight and combustible matter to the component assembly. Consequently, the selection of the housing material is especially important in oxygen systems. There are few weight constraints for ground-based systems. However, portable or flight systems are usually lightweight and lightweight materials such as aluminium have a very limited fire resistance. In such applications, the use of readily flammable materials shall be used only when pressure, flow rates and pressurization rates are low. In such applications, an analysis of adiabatic heating shall be performed to ensure acceptability.

For higher pressures, flow rates or pressurization rates, nickel alloys shall be used. Due to the greater strength-to-weight ratio between aluminium and nickel/copper alloys, the nickel/copper components may be made smaller and lighter for some applications. However, the designer shall use caution when using this technique.

8 Configuration testing

If it is not possible to find materials that meet the functional requirement of a design, it may be possible to provide sufficient protection from ignition to permit the use of a susceptible material. If this design approach is used, then the adequacy of the design shall be demonstrated by configuration testing under conditions more severe than the expected worst-case use environment for the component in question.

For configuration tests to be valid, the tests shall be conducted on hardware identical to the proposed use hardware. The configuration tests shall be at oxygen pressures at least 10 % above the worst-case operational conditions. Expected test temperatures shall be exceeded by at least 25 °C above the use temperature. If the material is to be subjected to rapid changes in pressure, the pressure rise rate used in the configuration test shall be twice that which the component is expected to experience in operation. If cycling or multiple reuse of the component is a design requirement, then the configuration testing shall exceed by a factor of four the expected number of cycles or reuses. Failure of the configuration test article before completion of the required number of cycles would limit the use life of the component to one-fourth the number of cycles actually completed before the failure.

Annex A
(informative)

List of materials

Table A.1 — Heat of combustion of some metals and alloys

Materials	Heat of combustion kJ/g	Source
Beryllium	66,38	See Bibliography [4]
Aluminium	31,07	See Bibliography [4]
Magnesium	24,69	See Bibliography [4]
Titanium	19,71	See Bibliography [4]
Chromium	10,88	See Bibliography [5]
Ferritic and martensitic steels	7,95 to 8,37	Calculated
Austenitic stainless steels	7,74 to 7,95	Calculated
Precipitation-hardened stainless steel	7,74 to 8,16	Calculated
Carbon steels	7,38 to 7,53	Calculated
Iron (Fe_2O_3)	7,385	See Bibliography [4]
Manganese	7,032	Calculated
Molybdenum	6,103	Calculated
Inconel 600™	5,439	Calculated
Aluminium-bronzes	4,60 to 5,86	Calculated
Zinc	5,314	See Bibliography [5]
Tungsten	4,898	Calculated
Tin	4,895	See Bibliography [5]
Cobalt	4,57	See Bibliography [6]
Nickel	4,10	See Bibliography [5]
Monel™	3,64	Calculated
Yellow brass, 60Cu/40Zn	3,45	Calculated
Cartridge brass, 70Cu/30Zn	3,31	Calculated
Red brass, 85Cu/15Zn	2,89	Calculated
Bronze, 10Sn/2Zn	2,74	Calculated
Copper	2,45	See Bibliography [4]
Lead	1,05	See Bibliography [5]
Platinum	0,686	See Bibliography [6]
Silver	0,146	See Bibliography [5]
Gold	0,079	See Bibliography [7]

Table A.2 — Minimum oxygen pressure required to support self-sustained combustion of rods ignited at the bottom, approximately 15 cm (6") in length and 0,32 cm (0,125") in diameter

Material	Threshold absolute pressure [a] MPa	Next lower absolute pressure tested [b] MPa
Silver (commercially pure)	> 68,9 [c]	—
Monel K-500™	> 68,9 [c]	—
Inconel MA 754™	> 68,9 [c]	—
Monel 400™	> 68,9 [c]	—
Brass 360 CDA	> 68,9 [c]	—
Copper beryllium	> 68,9 [c]	—
Nickel 200™	55,2	—
Copper 102	55,2	—
Red brass	48,3	—
Tin bronze	48,3	—
Yellow brass	48,3	—
Haynes 188™	34,5	20,7
Haynes 242™	34,5	20,7
Hastelloy C22™	34,5	6,9
Hastelloy C276™	20,7	6,9
Inconel 600™	20,7	6,9
Stellite 6™	20,7	6,9
Inconel 625™	20,7	6,9
440C stainless steel	17,2	6,9
MP 35N™	13,8	10,4
Elgiloy™	13,8	10,4
Udimet 700™	6,9	3,5
Haynes G3™	6,9	3,5
Inconel 718™	6,9	5,2
Waspaloy™	6,9	3,5
Invar 36™	⩽ 6,9 [d]	—
304 stainless steel	6,9	3,5
Colmonoy™	6,9	3,5
17-4 PH	6,9	3,5
303 stainless steel	⩽ 6,9 [d]	—
321 stainless steel	6,9	3,5
Lead (commercially pure)	⩽ 5,2 [d]	—
Beryllium (commercially pure)	4,1	3,5
316 stainless steel	3,5	0,7
Carbon steel A302B	⩽ 3,5 [d]	—
Ductile cast iron	⩽ 3,5 [d]	—
Nitronic 60™	⩽ 3,5 [d]	—
9% nickel steel	⩽ 3,5 [d]	—
Weldalite 049-T851™	2,1	1,4
Tin (commercially pure)	1,4	1
Aluminium-bronze	1,4	0,7
AMS 6278	1,4	0,7
Iron (commercially pure)	⩽ 0,7 [d]	—
Aluminium 1100	⩽ 0,7 [d]	—
AISI 9310	0,7	0,3
Aluminium 2219	0,2	0,1
Aluminium 5058	⩽ 0,2 [d]	—
Aluminium (commercially pure)	⩽ 0,17 [d]	—

Table A.2 (*continued*)

Material	Threshold absolute pressure [a] MPa	Next lower absolute pressure tested [b] MPa
Hafnium (commercially pure)	$\leqslant$ 0,17 [d]	—
Zirconium	$\leqslant$ 0,07 [d]	—
Titanium, Ti-6Al-4V	$\leqslant$ 0,007 [d]	—
Ti-6A1-4V	$\leqslant$ 0,007 [d]	—

[a] Minimum pressure that supported self-sustained combustion.

[b] Highest pressure tested at which the material self-extinguished.

[c] > indicates that this was the highest pressure tested and that the material did not support self-sustained combustion. The threshold pressure, if it exists, is greater than the stated value.

[d] $\leqslant$ indicates that no tests were conducted at lower pressures and therefore the threshold pressure is less than or equal to the stated value.

Table A.3 — Metal-to-metal friction ignition test data in 6,9 MPa oxygen

Test materials Stator	Test materials Rotor	Pv product at ignition $W/m^2 \times 10^{-8}$
Inconel MA 754™	Inconel MA 754™	3,96 – 4,12
Haynes 214™	Haynes 214™	3,05 – 3,15
Inconel MA 758™	Inconel MA 758™	2,64 – 3,42
Nickel 200™	Nickel 200™	2,29 – 3,39
Tin bronze	Tin bronze	2,15 – 2,29
Hastelloy C-22™	Hastelloy C-22™	2,00 – 2,99
Inconel 600™	Inconel 600™	2,00 – 2,91
Inconel MA 6000™	Inconel MA 6000™	1,99 – 2,66
Glidcop Al-25™	Glidcop Al-25™	1,79 – 2,19
Hastelloy 230™	Hastelloy 230™	1,79 – 2,19
NASA-Z™	NASA-Z™	1,77 – 2,63
CuZr	CuZr	1,68 – 1,73
Inconel 625™	Inconel 625™	1,63 – 1,73
Hastelloy B-2™	Hastelloy B-2™	1,61 – 2,16
Monel K-500™	Hastelloy C-22™	1,57 – 3,72
Waspaloy™	Waspaloy™	1,55 – 2,56
Monel 400™	Monel 400™	1,44 – 1,56
Monel K500™	Hastelloy C-276™	1,41 – 2,70
Haynes 230™	Haynes 230™	1,40 – 1,82
Monel K-500™	Monel K-500™	1,37 – 1,64
Monel K-500™	Hastelloy G-30™	1,34 – 1,62
13-4 PH	13-4 PH	1,31 – 2,06
Ductile cast iron	Monel 400™	1,28 – 1,45
Hastelloy C-276™	Hastelloy C-276™	1,21 – 2,82
Incoloy 903™	Incoloy 903™	1,20 – 1,44
Gray cast iron	410 stainless steel	1,19 – 1,48
Gray cast iron	17-4 PH (H 1150 M)	1,17 – 1,66
Inconel 718™	Inconel 718™	1,10 – 1,19
Copper beryllium	Monel 400™	1,10 – 1,20
AISI 4140™	Monel K-500™	1,09 – 1,35
Ductile cast iron	17-4 PH (H 1150 M)	1,09 – 1,17
Monel 400™	Nitronic 60™	1,03 – 1,69
Inconel 718™	17-4 PH stainless steel	1,02 – 1,06
17-4 PH stainless steel	17-4 PH stainless steel	1,00 – 1,21
Bronze	Monel K-500™	0,99 – 1,84
Tin bronze	304 stainless steel	0,97 – 1,25
Yellow brass	Yellow brass	0,97 – 1,22

Table A.3 (*continued*)

Test materials		**Pv product at ignition** W/m^2 × 10^{-8}
Stator	**Rotor**	
Monel K-500™	Inconel 625™	0,93 – 2,00
Hastelloy X™	Hastelloy X™	0,93 – 1,05
17-4 PH stainless steel	Hastelloy C-22™	0,93 – 1,00
Monel K-500™	304 stainless steel	0,92 – 1,13
Hastelloy G-30™	Hastelloy G-30™	0,90 – 1,28
Inconel 718™	304 stainless steel	0,90 – 1,18
17-4 PH stainless steel	Hastelloy 276™	0,89 – 1,10
Bronze	17-4 PH (H 1150 M)	0,89 – 1,02
316 stainless steel	303 stainless steel	0,89 – 0,90
14-5 PH	14-5 PH	0,88 – 1,40
Inconel 718™	316 stainless steel	0,86 – 0,96
304 stainless steel	304 stainless steel	0,85 – 1,20
17-4 PH stainless steel	17-4 PH stainless steel	0,85 – 1,07
Monel 400™	304 stainless steel	0,85 – 0,94
Ductile cast iron	Stellite 6™	0,84 – 1,16
17-4 PH stainless steel	Hastelloy G-30™	0,84 – 1,02
Monel K-500™	303 stainless steel	0,84 – 1,00
Copper zirconium	316 stainless steel	0,83 – 0,90
Ductile cast iron	Tin bronze	0,81 – 1,69
Inconel 706™	Inconel 706™	0,81 – 1,21
Monel K-500™	17-4 PH stainless steel	0,80 – 1,00
Bronze	410 stainless steel	0,79 – 1,20
Stellite 6™	Stellite 6™	0,79 – 0,82
303 stainless steel	303 stainless steel	0,78 – 0,91
Monel 400™	303 stainless steel	0,76 – 0,93
Monel K-500™	316 stainless steel	0,75 – 0,91
316 stainless steel	316 stainless steel	0,75 – 0,86
Inconel 718™	303 stainless steel	0,75 – 0,85
Brass CDA 360	Brass CDA 360	0,70 – 1,19
304 stainless steel	17-4 PH stainless steel	0,69 – 1,09
316 stainless steel	304 stainless steel	0,68 – 0,91
303 stainless steel	17-4 PH stainless steel	0,66 – 1,53
Stellite 6™	Nitronic 60™	0,66 – 0,77
303 stainless steel	17-4 PH stainless steel	0,65 – 0,88
17-4 PH stainless steel	Inconel 625™	0,64 – 1,09
304 stainless steel	Copper beryllium	0,63 – 1,24
Monel 400™	316 stainless steel	0,62 – 0,91
17-4 PH (Condition A)	17-4 PH (Condition A)	0,61 – 1,05
Invar 36™	Invar 36™	0,60 – 0,94
316 stainless steel	316 stainless steel	0,53 – 0,86
Incoloy MA 956™	Incoloy MA 956™	0,53 – 0,75
Ductile cast iron	Nitronic 60™	0,44 – 0,75
440C stainless steel	440C stainless steel	0,42 – 0,80
Aluminium-bronze	C355 aluminium	0,30 – 0,32
Incoloy 909™	Incoloy 909™	0,29 – 1,15
Nitronic 60™	Nitronic 60™	0,29 – 0,78
Aluminium 6061-T6	Aluminium 6061-T6	0,061
Ti-6Al-4V	Ti-6Al-4V	0,003 5

NOTE See Reference [8].

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