CHAPTER 8.

TRANSPORTATION

CHAPTER 8. TRANSPORTATION

800 GENERAL

Standards and guidelines for the transportation of oxygen are for the protection of people and infrastructure.

a. Standards and Guidelines.

(1) Transportation of GOX or LOX on public thoroughfares is covered by federal and state transportation standards and guidelines (Table E-1, Appendix E). NASA operations for the transport of GOX or LOX shall adhere to these standards.

(2) Transportation of GOX or LOX on thoroughfares controlled by NASA is the responsibility of cognizant site authorities and is covered by federal and state labor standards and guidelines (Tables E-1, Appendix E). Where conditions and requirements of use on site are similar to those of public thoroughfares, federal and state transportation standards and guidelines will be used. NASA operations for the transport of GOX or LOX shall adhere to these standards.

b. Definitions.

Gaseous and liquid oxygen can be transported by means that vary from tanks on barges, railroad cars, and trucks to small cylinders. Transport containers are described according to definitions developed by the DOT (49 CFR 171.8 1986). Basic definitions include the following:

(1) Gaseous oxygen is specified as a compressed gas (UN 1072) with a hazard class of 2.2 (nonflammable gas, oxidizer) by DOT (see 49 CFR 172.101 1986 and 49 CFR 173.115 1986).

(2) Liquid oxygen is specified as a cryogenic liquid (UN 1073) with a hazard class of 2.2 (nonflammable gas, oxidizer) by DOT (see 49 CFR 172.101 1986 and 49 CFR 173.115 1986).

(3) A cargo tank specifies transport dewars designed for highway service, such as over-the-road trailers, tank motor vehicles, compressed gas (CGA) trailers.

(4) A cylinder is a pressure vessel with a circular cross section designed for pressures greater than 275.7 kPa (40 psia).

801 TRANSPORT ON PUBLIC THOROUGHFARES

a. General.

While most NASA commerce on public thoroughfares involves commercial carriers, the responsibility for complying with federal and state transportation laws rests not only with them but also with the organizations that handle and receive oxygen.

b. Training.

Personnel involved in handling, receiving, shipping, and transport of a hazardous material must receive Hazardous Materials (HAZMAT) training (49 CFR 172.700 1986). NASA specific training can be obtained from the Hazardous Materials Coordinator, Transportation Branch, Lyndon B. Johnson Space Center (JSC), Houston TX 77058. Contact 713-483-6509 for further details.

c. Emergency Response.

During all phases of transport emergency response, information is required at facilities where hazardous materials are either loaded, stored, or handled (49 CFR 173.600 1986). Advanced planning for a variety of potentially hazardous and disastrous fires and explosions shall be undertaken with full realization that the first priority is reduction of any risk to the lives of emergency personnel and bystanders. NASA shipments of oxygen are monitored by CHEMTREC (the toll-free emergency telephone number is 800-424-9300). Other emergency information sources include the Dow Chemical USA’s Distribution Emergency Response System (telephone number, 517-634-4400), and the Union Carbide Corporation’s Hazardous Emergency Leak Procedure (HELP), which provides information 24 hours a day (telephone number is 304-744-3487).

d. Transport Requirements for Gaseous Oxygen.

General requirements for the transport of GOX are given in 49 CFR 172.101 (1986), *Hazardous Materials Table*, and 49 CFR 173 (1986), *Shippers-General Requirements for Shipments and Packaging*. The proper shipping name for GOX is oxygen, compressed.

(1) Packaging must be labeled NON-FLAMMABLE GAS, OXIDIZER.

(2) Special packaging requirements are given in 49 CFR 173.302 (1986), *Charging of Cylinders with Nonliquified Compressed Gases*, 49 CFR 173.306 (1986), *Limited Quantities of Compressed Gases*, and 49 CFR 173.3 15 (1986), *Compressed Gases in Cargo Tanks and Portable*

Tanks. Specifications for the qualification, maintenance, and use of cylinders are covered in 49 CFR 173.34 (1986), for the design of cylinders in 49 CFR 178.36 (1986), for the design of cargo tank motor vehicles in 49 CFR 178.337 (1986), and for the loading and unloading of cylinders in 49 CFR 177.840 (1986).

(3) Gaseous oxygen in quantities up to 75 kg (165 lb) may be transported on board passenger aircraft or railcars. Up to 150 kg (330 lb) are permitted aboard cargo aircraft. It may be stowed above or below deck on board ship (49 CFR 1992).

e. Transport Requirements for Liquid Oxygen.

General requirements for the transport of LOX are given in 49 CFR 172.101 (1986), *Hazardous Materials Table*, and 49 CFR 173 (1986), *Shippers-General Requirements for Shipments and Packaging*. The proper shipping name for LOX is Oxygen, refrigerated liquid (cryogenic liquid).

(1) Packaging must be labeled NON-FLAMMABLE GAS, OXIDIZER.

(2) Packaging requirements are given in 49 CFR 173.316 (1986), *Cryogenic Liquids in Cylinders*, 49 CFR 173.318 (1986), *Cryogenic Liquids in Cargo Tanks*, and 49 CFR 173.320 (1986), *Cryogenic Liquids, Exceptions*. Specifications for the qualification, maintenance, and use of cargo tank motor vehicles are covered in 49 CFR 173.33 (1986), for the design of insulated cargo tanks in 49 CFR 178.338 (1986), and for the loading and unloading of cylinders in 49 CFR 177.840 (1986), *Class 2 (gases) Materials*.

(3) Liquid oxygen is not permitted aboard passenger aircraft, passenger railcars, or cargo aircraft. It may be stowed only above deck on cargo ships.

802 TRANSPORT ON SITE CONTROLLED THOROUGHFARES

a. Standard Commercial Operation on Site.

Federal and state transportation guidelines can be applied in lieu of special requirements on NASA-controlled sites where conditions and requirements of use are similar to public thoroughfares.

b. Noncommercial Equipment and/or Special Operations.

Special equipment or operations used for the transport of oxygen must meet federal and state labor requirements (29 CFR 1986) as well as additional requirements of the cognizant NASA authorities.

c. Guidelines for the Design of Noncommercial Transport Equipment.

(1) General guidelines. Where applicable, standard oxygen design practice should be used (Chapters 3 and 4).

(a) The tankage design will be in accordance with accepted design practice (ASME 1995a, b).

(b) Redundant relief protection must be provided to the tank and piping systems.

(c) The design of the undercarriage shall isolate the tank and piping systems from potential collision damage.

(d) Controls should prevent oxygen venting while the vehicle is in motion.

(e) The trailer should use a fail-safe emergency brake system.

(2) Requirements for highway service. The design of noncommercial vehicles must comply with federal and state transportation guidelines (see 801 above) for operation on public thoroughfares. In addition to the general guidelines above, the design must meet highway standards for cargo tank design (49 CFR 178.338 1986 for cryogenic transport and 49 CFR 178.337 1986 for gas carriers).

d. General Operating Procedures.

The following guidelines apply to all oxygen transport operations.

(1) General.

(a) Operational areas should remain clear of nonessential personnel. Appropriate personnel protective equipment should be used. Facilities should maintain necessary deluge systems.

(b) Transport systems should be adequately grounded.

(c) The operational area should be kept free of combustible materials. Spark-producing and electrical equipment that is within the operational area and is not hazard-proof should be turned off and locked out. All tools used shall comply with established safety requirements.

(d) All tank inlets and outlets, except safety relief devices, should be marked to designate whether they are covered by vapor or liquid when the tank is filled.

(e) The temperature of LOX is so low that liquid air will form on uninsulated transfer equipment and vaporizers. Drip pans should be installed under all such equipment. The concern is that LOX will come off separately from LN_2 as the liquid air returns to a gas. Oxygen will vigorously support combustion of any materials such as paint, oils, or lubricants that make up the cargo tank or may be found on the ground.

(f) Trailers shall be equipped with a dry-chemical fire extinguisher. The rating shall not be less than 10 BC.

(g) In the event of a oxygen leak the transfer must be stopped and the leak repaired. In the event of a fire the oxygen sources should be isolated as quickly as possible.

(h) Operational procedural checklists should be used.

Note: LOX forms shock-sensitive explosive compounds with carbonaceous materials. Transfer operations should not be conducted over asphalt surfaces or porous surfaces such as sand that may hide the presence of oils and greases.

(2) Repair operations.

(a) Before any type of maintenance is attempted, the system shall be depressurized; all oxygen lines disconnected, drained, or vented, and purged; the operations area inspected; and the security of all systems verified.

(b) Repairs, alterations, cleaning, or other operations performed in confined spaces in which oxygen vapors or gases are likely to exist are not recommended until a detailed safety procedure is established. As a minimum, this procedure shall include the evacuation and purging requirements necessary to ensure safe entry in the confined space. The personnel engaged in the operations shall be advised of the hazards that may be encountered, and at least one person shall be immediately available while the work is being performed to administer emergency rescue, should it be necessary.

(3) Venting operations.

(a) Where possible, facility venting should be used.

802d

(b) In the field, a safe location, remote if possible, should be selected for venting. Consideration should be given to the wind direction so that vented gas will be carried away safely.

e. Inspection. Certification. and Recertification of Mobile Vessels.

(1) Mobile vessels require periodic recertification.

(2) Mobile Vessels recertified for public thoroughfares.

(a) Department of Transportation specifications require periodic pressure retests of LOX vessels and of pressure-relief valves (49 CFR 173.31 and 173.33 1986).

(b) Testing. See 49 CFR 178.331 (1986) for GOX and 49 CFR 178.338 (1986) for LOX tankage.

803 TRANSPORTATION EMERGENCIES

a. Initial Actions.

The first concern shall be to prevent death or injury. In an accident or emergency try to get the dewar off the road if possible, preferably to an open location. Shut off the tractor-trailer electrical system. Post warning lights and signs and keep people at least 152 m (500 ft) away for GOX or 800 m (½ mile) away for LOX. Contact authorities and obtain help:

CHEMTREC (800-424-9300)

b. Emergency Actions.

Emergency actions to combat leaks and fires involving oxygen tractor-trailers include pulling the vehicle into the least hazardous area and turning the ignition off. For fires originating near the engine, use a fire extinguisher; for tire fires, use water or chemical fire extinguishers or both. Tires may reignite 20 to 30 minutes after the initial fire has been extinguished, so the driver should not leave the scene until the tire temperature is lowered sufficiently. The driver also should not leave the scene until the fire has been completely extinguished and the burning materials cooled. Aid should be requested from the nearest fire or police department or both. On the highway, the environment in which a fire and subsequent damage may occur is difficult to control. An accident may occur at any time and at any place along the route. A controlled release of oxygen from the trailer through venting should take into account all possible ignition sources, vapor dispersion, population exposure, and general safe operations. Flares normally used for highway vehicular accident identification should not be used in close proximity to upset or damage LOX tanks.

CHAPTER 9.

EMERGENCY PROCEDURES

CHAPTER 9: EMERGENCY PROCEDURES

900 TYPES OF EMERGENCIES

a. Leaks and Spills.

(1) Primary Danger. The primary danger from oxygen leaks and spills is a fire or explosion caused by combustible materials in the presence of a high concentration of oxygen. Oxygen-enriched environments greatly increase the rate of combustion of flammable materials.

(2) Gaseous Oxygen. GOX leaks can result in oxygen-enriched environments, especially in confined spaces. Impingement of GOX onto an organic material such as grease can cause a fire. When leaks are detected, the source of the oxygen should be halted or disconnected. Any equipment inherently heat- or spark-producing should be turned off or disconnected. Disassembly and repair of leaking lines should begin only after the area has been properly ventilated.

(3) Liquid oxygen.

(a) Liquid oxygen spills and leaks cause oxygen enrichment of the immediate vicinity as the liquid vaporizes. When a spill or leak is detected, the source of the supply should be immediately halted or disconnected. Any equipment inherently heat- or spark-producing should be turned off or disconnected. Affected areas should be completely roped off or otherwise controlled to limit personnel movement. The equipment or piping should be thoroughly vented and warmed before repair of the leak is attempted.

(b) Liquid oxygen spills on pavements such as asphalt have resulted in impact-sensitive conditions that caused explosions from traffic or dropped items (Weber 1966). The same condition can occur from LOX leakage onto concrete that is contaminated with oil, grease, or other organic materials. The affected areas should be completely roped off or otherwise controlled to limit vehicle and personnel movement. Electrical sources should be turned off or disconnected. No attempt should be made to hose off the affected area, and the area should not be cleared for access until the oxygen-rich cold materials are adequately warmed and absorbed oxygen has evaporated.

900b

b. Overpressurization.

Oxygen cannot be kept liquid if its temperature rises above the critical temperature of -118.6 °C (-181.4 °F). Consequently, if LOX is trapped in a closed system and allowed to warm, extreme pressures can overpressurize the system. For example, LOX trapped between valves can rupture the connecting pipe. Pressure relief of some kind must be provided where trapping might occur. Moreover, relief and vent systems must be sized to accommodate the flow so that excessive backpressures will not occur. Cryogenic liquid storage vessels are protected from overpressurization by a series of pressure relief devices. These relief devices are designed to protect the inner vessel and the vacuum-insulated portion of the tank from failures caused by inner and outer shell damage, overfilling, and heat load from insulation damage or from a fire.

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

(2) Frost appearing on the outer wall of an insulated cryogenic vessel is indicative of vessel insulation loss. Frost appearance is only a clue to the type of insulation loss. This insulation loss could be caused by a movement of the insulation in the annular area of the tank, by loss of vacuum in the annular area, or by inner vessel failure. Assistance from knowledgeable and responsible pressure-systems personnel should be obtained.

(a) Personnel should listen and watch for indication of pressure-relief device actuation. Constant relief actuation is an indication that a major problem has occurred. Special care should be taken if the sound of the relief device changes and becomes higher pitched while operating.

(b) Continued pressure rise while the relief device is actuated indicates a major system malfunction. If constant relief device actuation is occurring, immediately evacuate the area and physically rope off and control the area if this can be performed safely. Venting the vessel is recommended, if possible. Do not apply water, as this would only act as a heat source to the much colder oxygen and aggravate the boiloff.

c. Transportation Emergencies.

Vehicular accidents involving oxygen transports can result in leaks, spills, and container rupture. Spills and leaks may result in fires and explosions. The first priority in an emergency situation is to protect personnel from hazards resulting from a spill or release of oxygen. The next priorities are protection of property and the environment, which should occur only after personal safety hazards have been mitigated.

(1) Consult the DOT Emergency Response Guidebook (DOT P5800.5 1993) and other references shown below for information regarding the emergency action to take in the event of an accident involving LOX or GOX.

(2) Additional information can be obtained 24 hours a day by calling the Chemical Transportation Emergency Center (CHEMTREC) at **800-424-9300**.

(3) Other emergency procedure information can be obtained from the Association of American Railroads (AAR), Bureau of Explosives, *Emergency Handling of Hazardous Materials in Surface Transportation*, and the National Response Center, US Coast Guard Headquarters, Room 2611, 2100 Second Street, SW, Washington, DC 20593-0001, telephone **800-424-8802** or **202-267-2675**.

d. Personal Exposure to Cryogenic Liquid or Cold Vapor (Cold Injury).

Note: This information represents the most current NASA Headquarters stand on cold injuries. It may change, and anyone dealing with oxygen systems should keep informed on the latest recommended procedures. This entire section is referenced by a letter from the director of the NASA Occupational Health Office.[1]

Direct physical contact with LOX, cold vapor, or cold equipment can cause serious tissue damage. Medical assistance should be obtained as soon as possible for any cold injury. First aid procedures to be administered by medical professionals are beyond the scope of this handbook. However, proper immediate bystander response should be as follows:

(1) If it is safe to do so, remove the patient from the source of the cold.

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[1] Letter from Marshall S. Levine, Director, Occupational Health Office, NASA Headquarters, 1991.

(2) In the event of limb-size or smaller cryogenic exposure, appropriate response may include an attempt to rapidly warm the affected area with moist heat from a shower, eyewash or warm water bath, not to exceed 38.9 °C (102 °F).

Note: Do not allow a heavy stream of water to impinge directly on frozen skin. In some cases, it is safest to do nothing other than cover the involved area until professional medical help is available.

(3) Massive full-body cryogenic exposures present significant additional concerns, but removal of the victim from the exposure atmosphere and keeping the victim’s airway open are important. Loosely wrapping the victim in a blanket until the arrival of the ambulance team is also advised.

(4) Some important **don’ts**:

(a) **Don’t** remove frozen gloves, shoes, or clothing. Salvageable skin may be pulled off inadvertently.

(b) **Don’t** massage the affected part.

(c) **Don’t** expose the affected part to temperatures higher than 44°C (112 °F), such as a heater or a fire. This superimposes a burn and further damages already injured tissues.

(d) **Don’t** apply snow or ice.

(e) **Don’t** apply ointments.

(f) **Don’t** allow any smoking, open flames, or other hazardous conditions near the victim.

901 EMERGENCY ASSISTANCE PLANS AND PROCEDURES

a. Policy.

(1) Each NASA center is responsible for the preparation of emergency plans and implementing emergency procedures. Evacuation routes and requirements and responsibilities of site personnel are included in these plans. Dry runs of safety procedures should be conducted using both equipment and personnel and periodic safety inspections, and surveys should be performed to ensure that emergency procedures are being performed safely.

(2) Fire drills, general safety meetings, and facility inspections should be held to develop and evaluate emergency plans and procedures.

(3) Training should familiarize personnel with the physical, chemical, and hazardous properties of LOX and GOX and with the nature of the facility's major process systems. Operator training should include oxygen handling practice and emergency training in handling spills and fires. Supervisors should keep operators informed of any operational or safety procedure changes.

(4) Supervisors shall periodically monitor oxygen-handling operations to ensure that all safety precautions are taken during transfer, loading, testing, and disposal. Local fire or other emergency personnel should be informed of any unusual or unplanned operations. Also, the accessibility and useability of fire protection and spill response equipment shall be verified before oxygen-handling operations commence.

(5) Written emergency procedures should be included in all operating procedures involving oxygen.

902 FIRE-FIGHTING TECHNIQUES

a. General.

When fighting a fire involving oxygen-enriched atmospheres, the first step should be to shut off the oxygen supply and, if possible, to shut off and remove fuel sources. Combustible materials must be cooled below their ignition temperatures to stop the fire. Water has been shown to be an effective extinguishing agent for fires involving oxygen-enriched atmospheres.

In some cases, when the oxygen supply cannot be shut off, the fire may burn so vigorously that containment and control is more prudent than trying to put out the fire.

(1) If fuel and LOX are mixed but not burning, quickly isolate the area from ignition sources, evacuate personnel, and allow the oxygen to evaporate. Mixtures of fuel and LOX are an extreme explosion hazard.

(2) If a fire is supported by LOX flowing into large quantities of fuel, shut off the oxygen flow. After the excess oxygen is depleted, put out the fire with the extinguishing agent recommended for the particular fuel.

(3) If a fire is supported by fuel flowing into large quantities of LOX, shut off the fuel flow and allow the fire to burn out. If other combustible material in the area is burning, water streams or fogs may be used to control the fires.

(4) If large pools of oxygen and water-soluble fuels, such as hydrazine or alcohol, are burning, use water to dilute the fuel and reduce the fire’s intensity.

CHAPTER 10.

REFERENCES

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APPENDIX A.

CHEMICAL AND PHYSICAL PROPERTIES

APPENDIX A

CHEMICAL AND PHYSICAL PROPERTIES

A.1 LIQUID OXYGEN (LOX)

a. Physical and Chemical Properties.

(1) High-purity LOX is a light blue, odorless, transparent liquid. LOX is chemically stable, is not shock-sensitive, and will not decompose. It is a cryogenic liquid which boils vigorously at ambient temperature.

(2) The physical and chemical properties of LOX are listed in Roder and Weber (1972). These include atomic weight 16, molecular weight 31.9988, density (at the boiling point and 1 atmosphere) 1.141 kg/l (71.2311 lb/ft^3), boiling point -182.97 °C (-297.35°F), heat of fusion and vaporization 444.8 J/mol (5.976 BTU/lb) and 6812.3 J/mol (91.568 BTU/lb), and specific heat at constant pressure (C_p) 54.28 J/mol-K (0.405 BTU/lb-°R).

(3) Liquid Oxygen is a strong oxidizer that vigorously supports combustion.

(4) Most common solvents are solid at LOX temperatures (-218.8 °C to -183.0 °C (-361.8 °F to -297.4 °F)). LOX is completely miscible with liquid nitrogen and liquid fluorine. Methane is highly soluble in LOX, light hydrocarbons are usually soluble, and acetylene is soluble only to about 4 ppm.

A.2 GASEOUS OXYGEN (GOX)

a. Physical and Chemical Properties.

(1) Gaseous oxygen is an odorless, colorless, transparent gas.

(2) The physical and chemical properties of GOX are included in Roder and Weber (1972). They include density 1.43x10^3 kg/1 (0.0892 lb/ft^3) at STP, specific heat at constant pressure C_p = 30.77 J/mol-K (0.230 BTU/lb-°R), and specific heat at constant volume C_v = 21.28 J/mol-K (0.150 BTU/lb-°R).

(3) Gaseous oxygen is a strong oxidizer that vigorously supports combustion.

A.3 REFERENCES

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APPENDIX B.

MATERIALS TESTING METHODS AND TEST DATA

APPENDIX B

MATERIALS TESTING METHODS AND TEST DATA

B.1 Many tests have been developed for evaluating materials for oxygen systems, including studies of ignition and burning characteristics and the causes of oxygen-related failures (Bryan and Lowry 1986; Steinthal 1982; Ordin 1973; NHB 8060.1C (1991); Stoltzfus and Benz 1984). These tests provide a means to rank materials.

Experimental methods used for determining and evaluating the ignition and combustion of materials include:

a. Ignition Tests.

  (1) Mechanical impact

  (2) Pneumatic impact

  (3) Autoignition

  (4) Friction

  (5) Particle impact

  (6) Resonance cavity

b. Combustion Tests.

  (1) Calorimeter

  (2) Limiting oxygen index (LOI)

  (3) Upward flammability of materials in gaseous oxygen (GOX)

B.2 IGNITION TESTS

a. Mechanical Impact Test Method (ASTM G 86 1991: ASTM D 2512 1991: NHB 8060.1C 1991).

This test method is to determine the sensitivity of materials to ignition by mechanical impact in liquid oxygen (LOX) or GOX at pressures from 0.1 to 68.9 MPa (14.7 to 10 000 psia).

The mechanical impact tester consists of a test chamber with a striker pin and striker pin counterloader. It also includes the necessary test chamber purge, pressurization and vent systems; a plummet, plummet guide tracks, plummet hold-release mechanism and a plummet rebound limiter; and controls and instrumentation necessary for performing the test and monitoring the test chamber for evidence of reaction. For LOX compatibility, the test system and samples should be configured as described in ASTM D 2512 (1991). For GOX compatibility, the test system and samples should be configured as described in ASTM G 86 (1991).

b. Autoignition Temperature (AIT) Test Method (ASTM G 72 1991).

This test measures the minimum sample temperature at which a material will spontaneously ignite when heated in an oxygen or oxygen-enriched atmosphere. AIT's of nonmetals are commonly measured by methods such as in ASTM G 72 (1991). Metals autoignite at much higher temperatures than nonmetals. These temperatures are much higher than those that normally would occur in actual oxygen systems. The temperature at which a material will ignite spontaneously varies with the system geometry and heating rate.

The test system consists of a reaction vessel (bomb), a sample holding assembly, and a system whereby this reaction vessel can be charged with oxygen and heated. Thermocouples and/or pressure transducers may be used to determine the temperature at the time ignition occurs.

c. Pneumatic Impact Test Method (NHB 8060. lC 1991: ASTM G 74 1991).

This test method provides reaction sensitivity of materials to dynamic pressure impacts by gases such as oxygen, air, or gas blends containing oxygen.

The test system (ASTM G 74 1991) consists of a high-pressure accumulator capable of being pressurized with oxygen or nitrogen to 69 MPa (10000 psia), a quick-opening valve, and a test chamber with a test sample.

d. Frictional Heating Test Method.

This test method provides the susceptibility of materials to ignition by friction in GOX and LOX, air, or blends of gases containing oxygen. The ends of two hollow cylinders are rubbed against one another in an oxygen-enriched atmosphere. Test variables include oxygen pressure, normal loads, and rubbing velocity. At standard test conditions, a material is ranked based on the Pv product at ignition (where P is load divided by the initial cross-sectional area of the sample and v is the relative surface velocity).

(1) The GOX frictional heating apparatus described here is also described in Benz and Stoltzfus (1986). It consists of a high-pressure test

chamber, an electrical motor and transmission assembly, and a pneumatic actuation cylinder. The high-pressure test chamber, fabricated of Monel®, consists of a cylindrical chamber with a replaceable nickel sleeve inside. The chamber contains a rotating shaft that extends through the chamber by a series of bearings and seals. The shaft is connected at one end to a drive motor/transmission assembly that is capable of rotating the shaft up to 30 000 rpm. The other end of the shaft is connected to a pneumatically actuated cylinder that allows axial movement of the shaft to apply up to 4450 N (1000 lbf) normal load on the test specimens. The rotating test specimen is mounted on the shaft, and the stationary test specimen is affixed to the test chamber.

(2) The LOX frictional heating test system is similar to the GOX frictional heating test system, except the LOX frictional heating test system is configured in a vertical position and has a fluid piping system for LOX.

e. Particle Impact Test Method.

This test method provides the susceptibility of a material to ignition by particle impact. A stream of oxygen with one or more entrained particles is impinged on a metal target. The particles may be capable of igniting themselves upon impact. Test variables include oxygen pressure, oxygen temperature, oxygen velocity; and number, size, quantity, and material of the particles.

(1) Supersonic Particle Impact Test System. The supersonic particle impact test system is essentially the same as that described in Benz, Williams, and Armstrong (1986). It consists of

(a) A gas inlet and flow straightener

(b) A particle injector and converging nozzle

(c) A diverging nozzle and test sample holder

GOX and the particle, injected just upstream of the converging nozzle, enter through the inlet section of the chamber and are accelerated to supersonic velocity as they pass through the converging and diverging nozzle. After the diverging nozzle, the fluid enters a short section with a constant cross-sectional area to establish the fluid velocity before impact. The particle impacts a target made of the test material.

(2) Subsonic Particle Impact Test System. The subsonic particle impact test system is essentially the same as the one described in Williams, Benz, and McIlroy (1988). It consists of a particle impact chamber, in which particles up to 5 g (0.01 lb) can be injected in flowing oxygen

upstream of a target specimen. The particles entrained in the oxygen are carried through the test chamber where they impact the target made of the test material. The oxygen and particles flow through holes on the periphery of the target and finally are vented to the atmosphere through the flow control orifice.

f. Resonance Cavity Ignition Test Method.

This test method was used to determine if resonance ignition could occur (Phillips 1975). It was developed in 1975, but was not maintained after the early tests were completed. The test flow system consists of high-pressure gaseous nitrogen and oxygen sources, stainless steel flow lines, pressure controllers, fire valves, and an exit flow control valve. The controllers establish and maintain the constant pressure delivered to the resonance apparatus. The resonance test apparatus used is described in detail in Phillips (1975); it consists of an inlet tube, an exit tube, and a resonance tube forming a tee. The temperatures generated at the base of the resonance tube are in excess of 538 °C (1000 °F) for both GOX and nitrogen.

B.3 COMBUSTION TESTS

a. Calorimeter Test (ASTM D 2382 1991: ASTM D 2015 1991).

This test measures the heat evolved per unit mass (the heat of combustion) when a material is completely burned in 2.5 to 3.5 MPa (368 to 515 psia) of oxygen at constant volume. Several procedures such as those listed in ASTM D 2382 (1991) and ASTM D 2015 (1991) are used. For many fire-resistant materials useful in oxygen systems, measured amounts of combustion promoter must be added to ensure complete combustion.

b. Limiting Oxygen Index Test (ASTM D 2863 1991).

This is a determination of the minimum concentration of oxygen in a flowing mixture of oxygen and a diluent that will just support propagation of combustion. ASTM D 2863 (1991) applies to nonmetals at atmospheric pressure. The test method for metals has not been standardized; it is being reviewed by the ASTM G 4 Committee.

c. Upward Flammability of Materials in GOX (NHB 8060. lC 1991).

This test determines the flammability of materials in GOX. In it, a material specimen is exposed to a standardized promoter (easily ignited material) or other ignition source. With a standardized promoter, the results give the relative ranking of the materials.

The promoted combustion test system described here is similar to the one described by Stoltzfus et al. (1988). The test system consists of a cylindrical stainless steel chamber with an internal volume of approximately 740 cm^3 (45 $in.^3$). The chamber can be pressurized to 68.9 MPa (10 000 psia). The chamber has a copper liner and a copper base plate to protect it from the burning material. The test specimen, with an aluminum promoter at the bottom, is held at the top by the specimen mount. The ignition of the aluminum promoter is accomplished by electrically heating an aluminum-palladium wire wrapped around the promoter.

B.4 METAL TEST DATA

Several tests for metallic materials' ignition and flammability have been developed in recent years. These tests provide a good indication of the relative ranking of metallic materials for ignitability, but rarely provide absolute information on ignitability in a specific application. Configurational tests have to be conducted if such information is required. Additional tests that are more suitable for the specific application of a metallic material may become available in the future. The relative ranking of materials is partially dependent on the test method used. Three tests commonly used by NASA are the promoted combustion test (upward flammability test), the frictional heating test, and the particle impact test. At present, the upward flammability test (NHB 8060.1C 1991) is used to obtain a basic ranking of metallic materials' flammability. Particle impact and frictional heating tests are valuable for assessing ignitability when particle impact or friction between moving parts can occur.

a. Ignition Test Data.

(1) Mechanical Impact Test. Mechanical impact test methods (NHB 8060. 1C Tests 13A and 13B, "Mechanical Impact for Materials in Ambient Pressure LOX" and "Mechanical Impact for Materials in Variable Pressure GOX and LOX" (1991)) have been used for evaluating the ignition characteristics of metallic materials in oxygen systems. While mechanical impact tests are not presently used to evaluate metals for oxygen service, a large body of data for mechanical impact of metals exists; some can be found in Key and Riehl (1964).

(2) Autoignition Temperature Test. AIT's as described in ASTM G 72 (1991) are not available; however, some AIT's of solid metals are given in Table B-1. Ignition temperature of metals are dependent on the test procedure, material configuration, and presence or lack of oxide layers.

(3) Pneumatic Impact Test. Metals have been shown not to ignite because of gaseous pneumatic impact.

(4) Friction.

(a) Ignition by frictional heating is very sensitive to the characteristics of the metallic surfaces. This test is appropriate for materials selection only if frictional heating is a possible concern.

(b) Data on the ignitability of metallic materials by frictional heating are shown in Tables B-2 and B-3. The *Pv* product is a measure of the energy absorbed per unit area of rubbing surface per unit time; metals and alloys with low *Pv* products at ignition are more easily ignited than those with high *Pv* products at ignition. Relative rankings of metallic materials for ignitability by frictional heating show some differences from the relative rankings by promoted combustion tests. These differences are significantly reduced if the friction coefficient μ of the metallic surface is considered and relative rankings are based on the product μ*Pv* (Stoltzfus, Benz, and Homa 1989).

(c) Ignition of metallic, materials by frictional heating can occur in LOX systems as well as in GOX. The ignitability of metallic materials is lower in LOX than in GOX because of the low initial temperatures. However, once ignition takes place, propagation is inevitably more extensive because of the large quantity of oxygen present in the condensed phase. Combustion occurs in oxygen gas caused by frictional heating vaporizing the liquid. Therefore, the relative ranking of metallic materials in LOX is essentially the same as that in ambient temperature GOX.

(5) Particle Impact.

(a) Data on the ignitability of metallic target materials by impact of single, large, supersonic, aluminum particles in the supersonic particle impact test system are provided in Figures B-la and B-lb. The figure presents ignition (recorded as ignition, partial burn, or no ignition) as a function of target temperature for a supersonic particle impact tester inlet pressure of 27.5 MPa (4000 psig); 1600-μ particles were used for the testing. Under these conditions, both particle velocity and the pressure at the target increased slowly with target temperature; the pressure at the target varied from approximately 3.6 to 4.0 MPa (520 to 580 psia), and the particle velocity at the target varied from approximately 370 to 430 m/s (1200 to 1400 ft/s). The data provide a rough relative ranking of the resistance of metallic materials to ignition by particle impact; however, the test parameters are too arbitrary for the data to provide absolute pass/fail criteria in use conditions.

(a) Other metallic materials have been used as the particles, but ignitions have not been observed except with aluminum 6061 targets and 304 stainless steel particles (Benz, Williams, and Armstrong 1986). The 304 stainless steel particles imbedded in the aluminum 6061 targets but did not ignite (Benz, Williams, and Armstrong 1986). Data from subsonic particle impact tests, conducted at WSTF and elsewhere, indicate that fine iron particles may be ignited by impact on static targets at flow velocities as low as 35 m/s (115 ft/s), although such burning iron particles were not found to ignite iron or steel targets at flow velocities below about 40 m/s (150 ft/s) (Williams, Benz, and McIlroy 1988). Results from this test program indicate that ignition may occur at higher iron particle concentrations. Data on subsonic particle impact by particulate from other metallic materials and polymeric materials are lacking at this time. The data obtained to date suggest that metallic powders are more likely to cause particle impact ignition than large, single particles.

(b) The relative ranking of metal target materials is assumed to be similar for ignition by large, single particles and by powders, but no definitive study has been conducted. Similarly, the worst-case pressure is believed to be the highest system pressure, but this assumption has not been verified experimentally. Temperature effects are believed to depend on the size and ease of oxidation of the particulate. Usually, ignitability increases with increasing temperature; however, particulate oxidation without ignition at high temperatures can reduce the ignitability.

(6) Resonance Cavity. Data from resonance testing are described by Phillips (1975).

b. Combustion Test Data.

(1) Calorimeter. The heats of combustion for selected metals and alloys are shown in Table B-4.

(2) Limiting Oxygen Index. The ASTM D 2863 (1991) standard limiting oxygen index test is not commonly used for metals. However, some data for some aluminum alloys and bronzes are reported by Benning, Zabrenski, and Ngoc (1988).

(3) Upward Flammability of Materials in GOX.

(a) The promoted combustion test has been adopted as a standard metals flammability test for NHB 8060. 1C (1991). This test determines the ability of a metallic rod to propagate flame upward when ignited at the bottom by an ignition source. Threshold pressure is the minimum pressure required for self-sustained combustion. For any metallic material, the flammability increases with increasing pressure and decreases with increasing thickness (the standard sample for the test is 0.32 cm (0.125 inch) thick); the quantity of promoter does not affect the flammability. Table B-5 shows threshold pressures of some common metallic materials. It should be noted that upward flame propagation is used for this test because it provides more repeatable data and better distinguishes the performance of different materials than does downward propagation. However, metallic materials burn downward more readily than upward and materials that are self-extinguishing in upward propagation may burn completely in the downward configuration. Nevertheless, the test severely evaluates metallic materials because the aluminum promoter is a far more intense ignition source than typical ignition sources in real systems (such as burning polymeric materials). Details of this test are given in NHB 8060. 1C (1991), Stoltzfus, Benz, and Homa (1989), and Stoltzfus, Lowrie, and Gunaji (1991).

(b) Relative rankings from promoted combustion and particle impact tests appear to be similar, although the scarcity of particle impact data makes this conclusion somewhat tentative. A rough correlation exists between heat of combustion and ignitability and flammability in these two tests. Thus, the materials that ignite least easily and propagate fire least readily are usually those with the lowest heats of combustion or those containing elements with low heats of combustion. Specific exceptions to this general rule do exist. For example, aluminum bronzes containing 93-percent copper (low heat of combustion and relatively nonflammable) and only 7-percent aluminum (high heat of combustion and highly flammable) are highly flammable in high-pressure oxygen.

B.5 NONMETALS TEST DATA

a. Test data on reactions of nonmetals with high-pressure oxygen have been obtained principally from NHB 8060.1 Tests 13b and 14, “Mechanical Impact for Materials in Variable Pressure GOX and LOX” and “Pressurized Gaseous

Oxygen Pneumatic Impact for Nonmetals," (NHB 8060. 1C 1991). In an operating high-pressure oxygen system, the potential for pneumatic impact ignition is greater than that for mechanical impact ignition (Moffett et al. 1988). The standard pneumatic impact test is not mandatory for nonmetals. The statistical base on which materials decisions are made for both tests is weak; specifically the ability of these tests to distinguish batch differences in materials has been disputed (Bryan 1983). Test data on reactions of nonmetals with LOX have been obtained with NHB 8060. lC Test 13A (Bryan 1983). GOX mechanical impact usually provides a more sensitive materials test than LOX mechanical impact; the sensitivity is known to increase with increasing pressure (Bryan 1983). The LOX mechanical impact test, however, has provided a large database for nonmetals and provides valuable information on their suitability for oxygen service.

b. The mechanical impact test and the pneumatic impact test generally give similar results for a given material. Polymeric materials are rarely ignited by pneumatic impact at pressures below 1.7 MPa (250 psia), because the temperatures reached by adiabatic compression are below the AIT of most polymeric materials. However, they may react as a result of mechanical impact at pressures below 1.7 MPa (250 psia).

c. Mechanical impact and pneumatic impact test conditions are usually more severe than those in actual use. Data obtained are conservative and allow a reasonable margin of safety. However, ignition by adiabatic compression heating is very configuration-dependent, and configurational testing or additional analysis should be conducted for systems. For example, flexible hose materials may not react in the standard NHB 8060. 1C Test 14 at 41 MPa (6000 psia), but a flexible hose constructed of these materials has been shown to ignite when pressurized to only 6.9 MPa (1000 psia) through a quick-opening valve similar to that used in the pneumatic impact test (Janoff et al. 1989). The flexible hose can still be used at 41 MPa (6000 psia) if the system is designed so that pressurization is slow and the downstream end of the hose is not closed (see Chapter 4).

d. The potential for ignition by adiabatic compression can be assessed as follows (ASTM G 63 1991):

(1) Calculate the maximum temperature the oxygen can reach with the following equation:

$$\frac{T_f}{T_i} = \left[\frac{P_f}{P_i}\right]^{\frac{n-1}{n}}$$

where:

T_f = final temperature (abs)
T_i = initial temperature (abs)
P_f = final pressure (abs)
P_i = initial pressure (abs)
n = ratio of specific heats (1.40 for oxygen)

Thus, for a final pressure of 34.5 kPa (5000 psia) from ambient conditions (10 °C (67.7 °F), 101.4 kPa (14.7 psia)), the maximum theoretical temperature is 1277 °C (2330 °F).

(2) Table B-6 shows polymer properties relating to ignition and combustion. If the calculated temperature exceeds the AIT of the polymer, then the potential for ignition exists.

(3) If ignition can occur, the potential for igniting adjacent materials must be considered. Calculation of adiabatic flame temperature will give an indication of this potential. Representative values of polymeric adiabatic flame temperature are given in Table B-6 for three different pressures. Polymers are also ranked according to heat of combustion and the AIT (Lockhart, Hampton, and Bryan 1989). Polymers with high heats of combustion and high carbon black-filler content are more likely to ignite adjacent materials (Shelley 1991).

Note: The polymers in the tables are representative of available polymeric materials.

(4) The ignition of adjacent materials is dependent on the heat transfer from the burning polymer to those materials. This can only be assessed for a specific configuration.

e. Other tests exist that may provide useful information on the relative ignitability of nonmetals in high-pressure oxygen. Autoignition tests have been conducted in high-pressure oxygen using ASTM G 72 (1991) and Steinthal (1982). Frictional heating (Benz and Stoltzfus 1986) has been used as an ignition test. Additional test methods for assessing the ignition potential of nonmetals are under development (Tapphorn, Shelley, and Benz 1991).

f. Combustion tests for polymers are the calorimeter (ASTM D 2015 1991), limiting oxygen index (ASTM D 2863 1991) and the upward flammability of polymers (NHB 8060. 1C 1991). The oxygen index data in Table B-6 indicate that the majority of polymeric materials are flammable at ambient pressures (0.1 MPa (14.7 psia)) in 100-percent oxygen. These data emphasize the need for careful system design, because polymers are often used in systems that are at higher than ambient pressures.

Table B-1

Selected Values for Ignition Temperatures of Solids[a]

Metal	Ignition Temperature	
	(K)	(ºF)
Mild Steel	4248 to 4410	2240 to 2330
W	4302 to 4446	2270 to 2350
Ta	4284 to 4428	2260 to 2340
Ti Alloys		
RC-70	5400 to 5544	2880 to 2960
RS-70	5418 to 5508	2890 to 2940
RS-110-A	5364 to 5454	2860 to 2910
RS110-BX	5346 to 5472	2850 to 2920
Stainless Steels		
430	4644 to 4698	2460 to 2490
Berylco® 10	3366 to 3384	1750 to 1760
Mg	2323	1171
Mg Alloys		
20% Al	1900	936
70% Zn	2023	1004
25% N	1897	934
20% S	2194	1099
63% Al	1767	862
Fe	3286	1706
Sr	2606	1328
Ca	2055	1022
Th	1893	932
Ba	840	347
Mo	2736	1400
U	1310	608
Ce	1310	60

[a] Reynolds (1959)

Table B-2

Friction Ignition Test Data for Similar Pairs[a,b]

Test Materials		*Pv* Product at Ignition	
Stator	Rotor	$W/m^2 \times 10^{-8}$	($lbf/in^2 \times ft/min \times 10^{-6}$)
Inconel® MA 754	Inconel® MA 754	3.96 – 4.12[c]	11.30 – 11.75
Haynes® 214	Haynes® 214	3.05 – 3.15	8.73 – 8.96
Inconel® MA758	Inconel® MA758	2.64 – 3.42	7.53 – 9.76
Nickel 200	Nickel 200	2.29 – 3.39	6.54 – 9.66[d]
Tin Bronze	Tin Bronze	2.15 – 2.29	6.15 – 6.55[e]
Hastelloy® C-22	Hastelloy® C-22	2.00 – 2.99[f]	5.72 – 8.52
Inconel® 600	Inconel® 600	2.00 – 2.91	5.70 – 8.30[d]
Inconel® MA6000	Inconel® MA6000	1.99 – 2.66	5.68 – 7.59
Glidcop A1-25	Glidcop A1-25	1.95 – 3.59	5.56 – 10.2
Hastelloy® 230	Hastelloy® 230	1.79 – 2.19	5.10 – 6.24
NASA-Z	NASA-Z	1.77 – 2.63	5.05 – 7.52
Cu Zr	Cu Zr	1.68 – 3.19	4.81 – 9.11
Inconel® 625	Inconel® 625	1.62 – 1.73[f]	4.65 – 4.94
Hastelloy® B-2	Hastelloy® B-2	1.61 – 2.16[f]	4.60 – 6.12
Waspaloy	Waspaloy	1.55 – 2.56	4.45 – 7.31
Monel® 400	Monel® 400	1.44 – 1.56	4.12 – 4.46[d]
Monel® 400	Monel® 400	1.42 – 1.55[g]	4.05 – 4.43
Haynes® 230	Haynes® 230	1.40 – 1.82	4.00 – 5.20
Monel® K-500	Monel® K-500	1.37 – 1.64	3.91 – 4.68[d]
13-4 PH	13-4 PH	1.31 – 2.06	3.74 – 5.88[e]
Hastelloy® C-276	Hastelloy® C-276	1.21 – 2.82[f]	3.45 – 8.06[f]
Incoloy 903	Incoloy 903	1.20 – 1.44	3.41 – 4.11
Inconel® 718	Inconel® 718	1.10 – 1.19	3.13 – 3.37
17-4 PH (H 900)	17-4 PH (H 900)	1.00 – 1.21	2.87 – 3.45
Yellow Brass	Yellow Brass	0.97 – 1.22	2.77 – 3.49
Hastelloy® X	Hastelloy® X	0.93 – 1.05	2.66 – 3.02[d]

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

[b] All unreferenced data are from previously unpublished frictional heating tests performed at NASA White Sands Test Facility.

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

[d] Benz and Stolzfus (1986)

[e] Stolzfus et al. (1988)

[f] Bryan, Stoltzfus, and Gunaji (1993)

[g] Bryan, Stolzfus, and Gunaji (1991)

Table B-2

Friction Ignition Test Data for Similar Pairs (continued) [a,b]

Test Materials		*Pv* Product at Ignition	
Stator	Rotor	$W/m^2 \times 10^{-8}$	$(lbf/in^2 \times ft/min \times 10^{-6})$
Hastelloy® G-30	Hastelloy® G-30	0.90 – 1.28[c]	2.58 – 3.68
14-5 PH	14-5 PH	0.88 – 1.04	2.51 – 2.96
304 SS	304 SS	0.85 – 1.20	2.43 – 3.41
17-4 PH	17-4 PH	0.85 – 1.07	2.42 – 3.05
Inconel® 706	Inconel® 706	0.81 – 1.21	2.33 – 3.45
303 SS	303 SS	0.78 – 0.91	2.25 – 2.60
Stellite® 6	Stellite® 6	0.79 – 0.82	2.25 – 2.35
316 SS	316 SS	0.75 – 0.86[d]	2.14 – 2.46
Brass CDA 360	Brass CDA 360	0.70 – 1.19	1.98 – 3.41[f]
17-4 PH (Condition A[e])	17-4 PH (Condition A)	0.61 – 1.05	1.75 – 2.99
Invar® 36	Invar® 36	0.60 – 0.94	1.71 – 2.68[f]
Incoloy MA 956	Incoloy MA 956	0.53 – 0.75	1.51 – 2.14
316 SS	316 SS	0.53 – 0.86	1.50 – 2.46[f]
440C SS	440C SS	0.42 – 0.80	1.19 – 2.28
Nitronic 60	Nitronic 60	0.29 – 0.78	0.82 – 2.22
Incoloy 909	Incoloy 909	0.29 – 1.15	0.85 – 3.30
Aluminum 6061-T6	Aluminum 6061-T6	0.061	0.18[f]
Ti-6A1-4V	Ti-6A1-4V	0.0035	0.01[f]

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

[b] All unreferenced data are from previously unpublished frictional heating tests performed at NASA White Sands Test Facility.

[c] Bryan, Stoltzfus, and Gunaji (1993)

[d] Bryan, Stolzfus, and Gunaji (1991)

[e] Solution Annealed

[f] Stolzfus et al. (1988)

Table B-3
Friction Ignition Test Data for Dissimilar Pairs[a,b]

Test Materials		*Pv* Product at Ignition	
Stator	Rotor	W / m^2 x 10^{-8}	(lbf/in^2 x ft/min x 10^{-6})
Monel® K-500	Hastelloy® C-22	1.57 – 3.72	4.51 – 10.61
Monel® K-500	Hastelloy® C-276	1.41 – 2.70	4.00 – 7.70[c]
Monel® K-500	Hastelloy® G-30	1.34 – 1.62	3.81 – 4.63
Ductile cast iron	Monel® 400	1.28 – 1.45	3.65 – 4.13[c]
Gray cast iron	410 SS	1.19 – 1.48	3.39 – 4.24[c]
Gray cast iron	17-4 PH (H 1150 M)	1.17 – 1.66	3.35 – 4.75[c]
Cu Be	Monel® 400	1.10 – 1.20	3.14 – 3.42
Ductile cast iron	410 SS	1.10 – 1.23	3.12 – 3.43[c]
AISI 4140	Monel® K-500	1.09 – 1.35	3.10 – 3.85[c]
Ductile cast iron	17-4 PH (H 1150 M)	1.09 – 1.17	3.00 – 3.35[c]
Monel® 400	Nitronic 60	1.03 – 1.69	2.93 – 4.78
Inconel® 718	17-4 PH SS	1.02 – 1.06[d]	2.91 – 3.03
Bronze	Monel® K-500	0.99 – 184	2.82 – 5.26[c]
Tin bronze	304 SS	0.97 - 1.25	2.78 – 3.56[c]
Monel® K-500	Inconel® 625	0.93 – 2.00	2.67 – 5.70
17-4 PH SS	Hastelloy® C-22	0.93 – 1.00	2.65 – 2.86
Monel® K-500	304 SS	0.92 – 1.13[d]	2.63 – 3.24
Inconel® 718	304 SS	0.90 – 1.18[d]	2.58 – 3.37
17-4 PH SS	Hastelloy® G-276	0.89 – 1.10	2.55 – 3.14
Bronze	17-4 PH (H 1150 M)	0.89 – 1.02	2.55 – 2.90[c]
316 SS	303 SS	0.89 – 0.90[d]	2.53 – 2.57
Inconel® 718	316 SS	0.86 – 0.96[d]	2.44 – 2.73
Monel® 400	304 SS	0.85 – 0.94[d]	2.43 – 2.69
17-4 PH SS	Hastelloy® G-30	0.84 – 1.02	2.41 – 2.90
Monel® K-500	303 SS	0.84 – 1.00[d]	2.41 – 2.88
Ductile cast iron	Stellite® 6	0.84 – 1.16	2.39 – 3.32[c]
Cu Zr	316 SS	0.83 – 0.90	2.39 – 2.58
Ductile cast iron	Tin bronze	0.81 – 1.69	2.32 – 4.82[c]

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

[b] All unreferenced data are from previously unpublished frictional heating tests performed at NASA White Sands Test Facility.

[c] Benz, Bishop, and Pedley (1989)

[d] Bryan, Stolzfus, and Gunaji (1991)

Table B-3

Friction Ignition Test Data for Similar Pairs (continued) [a,b]

Test Materials		*Pv* Product at Ignition	
Stator	Rotor	W / m^2 x 10^{-8}	(lbf/in^2 x ft/min x 10^{-6})
Monel® K-500	17-4 PH SS	0.80 - 1.00[d]	2.27 - 2.39
Bronze	410 SS	0.79 - 1.20	2.25 - 3.60[c]
304 SS	303 SS	0.77 - 0.79[d]	2.21 - 2.26
Tin bronze	Aluminum bronze	0.77 - 0.84	2.20 - 2.38[b]
316 SS	17-4 PH SS	0.77 - 0.85[d]	2.18 - 2.41
Monel® 400	303 SS	0.76 - 0.93	2.17 - 2.67
Inconel® 718	303 SS	0.75 - 0.87[d]	2.14 - 2.48
Monel® K-500	316 SS	0.75 - 0.91[d]	2.10 - 2.61
304 SS	17-4 PH SS	0.69 - 1.09[d]	1.97 - 3.11
316 SS	304 SS	0.68 - 0.91[d]	1.93 - 2.60
Stellite® 6	Nitronic 60	0.66 - 0.77	1.90 - 2.18[b]
Monel® 400	17-4 PH SS	0.66 - 1.53[d]	1.89 - 4.38
303 SS	17-4 PH SS	0.65 - 0.88	1.86 - 2.51
17-4 PH SS	Inconel® 625	0.64 - 1.09	1.83 - 3.11
304 SS	Cu Be	0.63 - 1.24	1.81 - 3.54
Monel® 400	316 SS	0.62 - 0.91[d]	1.75 - 2.59
Ductile Cast iron	Nitronic 60	0.44 - 0.75	1.25 - 2.15[b]
Aluminum bronze	C355 Aluminum	0.30 - 0.32	0.85 - 0.91[b]
Nitronic 60	17-4 PH (H 1150 M)	0.28 - 0.61	0.80 - 1.75[b]
Babbitt on bronze	17-4 PH (H 1150 M)	0.09 - 0.21	0.25 - 0.60 [b]
Babbitt on bronze	Monel®K-500	0.09 - 0.19	0.25 - 0.55 [b]
Babbitt on bronze	410 SS	0.08 - 0.09	0.24 - 0.27[b]

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

[b] All unreferenced data are from previously unpublished frictional heating tests performed at NASA White Sands Test Facility.

[c] Benz, Bishop, and Pedley (1989)

[d] Bryan, Stolzfus, and Gunaji (1991)

Table B-4
Heat of Combustion of Metals and Alloys

Material	ΔH_c cal/g[a]	Source
Beryllium (BeO)	15865	JANNAF (1971)
Aluminum ($A1_2O_3$)	7425	JANNAF (1971)
Magnesium (MgO_2)	5900	JANNAF (1971)
Titanium (TiO_2)	4710	JANNAF (1971)
Chromium (Cr_2O_3)	2600	Smithells (1976)
Ferritic and Martensitic Steels	1900-2000	Calculated
Austenitic Stainless Steels	1850-1900	Calculated
Precipitation Hardening Stainless Steels	1850-1950	Calculated
Carbon steels	1765-1800	Calculated
Iron (Fe_2O_3)	1765	JANNAF (1971)
Inconel® 600	1300	Calculated
Aluminum bronzes	1100-1400	Calculated
Zinc (ZnO)	1270	Smithells (1976)
Tin (SnO_2)	1170	Smithells (1976)
Nickel (NiO)	980	Smithells (1976)
Monel® 400	870	Calculated
Yellow brass, 60 Cu/40 Zn	825	Calculated
Cartridge brass, 70 Cu/30 Zn	790	Calculated
Red brass, 85 Cu/15 Zn	690	Calculated
Bronze, 10 Sn/2 Zn	655	Calculated
Copper (CuO)	585	JANNAF (1971)
Lead (PbO)	250	Smithells (1976)
Silver (Ag_2O)	35	Smithells (1976)

Table B-5
Minimum Oxygen Pressure Required to Support Self-Sustained Combustion of Approximately 15-cm (6-in.) long, 0.32-cm (0.125-in.)-Diameter Rods Ignited at the Bottom

Material	Threshold Pressure		Next Lower Pressure Tested (psia)
	(MPa)	(psia)	
Commercially pure Ag	>[a]68.9	>[a]10 000	
Monel® K-500	>[a]68.9	>[a]10 000	
Inconel® MA 754	>[a]68.9	>[a]10 000	
Monel® 400	>[a]68.9	>[a]10 000	
Brass 360 CDA	>[a]68.9	>[a]10 000	
Cu-2 Be	>[a]68.9	>[a]10 000	
Nickel 200	>[a]55.2	>[a] 8 000	
Copper 102	>[a]55.2	>[a] 8 000	
Red Brass	>[a]48.3	>[a] 7 000	
Tin Bronze	>[a]48.3	>[a] 7 000	
Yellow Brass	>[a]48.3	>[a] 7 000	
Haynes® 188	34.5	5 000	3 000
Haynes® 242	34.5	5 000	3 000
Hastelloy® C22	34.5	5 000	1 000
Hastelloy® C276	20.7	3 000	1 000
Inconel® 600	20.7	2 500	1 000
Stellite® 6	20.7	2 500	1 000
Inconel® 625	20.7	2 500	1 000
440C SS	17.2	2 500	1 000
MP 35N	13.8	2 000	1 500
Elgiloy®	13.8	2 000	1 500
Udimet 700	6.9	1 000	500
Haynes ® G3	6.9	1 000	500
Inconel® 718	6.9	1 000	750
Waspaloy	6.9	1 000	500
Invar® 36	≤[b]6.9	≤[b]1 000	None
304 SS	6.9	1 000	500
Colmonoy®	6.9	1 000	500
17-4 PH	6.9	1 000	500
303 SS	≤[b]6.9	≤[b]1 000	None

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

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

Table B-5
Minimum Oxygen Pressure Required to Support Self-Sustained Combustion of Approximately 15-cm (6-in.) long, 0.32-cm (0.125-in.)-Diameter Rods Ignited at the Bottom (continued)

Material	Threshold Pressure		Next Lower Pressure Tested (psia)
	(MPa)	(psia)	
321 SS	6.9	1000	500
Commercially pure Pb	≤[b]5.2	≤[b]750	None
Commercially pure Be	4.1	600	500
316 SS	3.5	500	100
Carbon Steel A302B	≤[b]3.5	≤[b]500	None
Ductile Cast Iron	≤[b]3.5	≤[b]500	None
Nitronic 60	≤[b]3.5	≤[b]500	None
9% Nickel Steel	≤[b]3.5	≤[b]500	None
Welda-lite 049-T851	2.1	300	250
Commercially pure Sn	1.4	300	200
Al-Bronze	1.4	250	100
AMS 6278	1.4	200	100
Commercially pure Fe	≤[b]0.7	≤[b]100	None
Aluminum 1100	≤[b]0.7	≤[b]100	None
AISI 9310	0.7	100	50
Aluminum 2219	0.2	25	20
Aluminum 5058	≤[b]0.2	≤[b]35	None
Commercially pure Al	≤[b]0.17	≤[b]50	None
Commercially pure Hf	≤[b]0.17	≤[b]25	None
Zr	≤[b]0.07	≤[b]10	None
Commercially pure Ti	≤[b]0.007	≤[b]1	None
Ti-6A1-4V	≤[b]0.007	≤[b]1	None

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

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

Table B-6
Polymer Properties Realted to Ignition and Combustion

Material	Autoignition Temp (°C)	Oxygen Index (OI)	Heat of Combustion (j/g)	LOX Mechanical Impact	Solubility S, cm^3/cm^3 O$_2$	Permeability Q, 10^{-8} cm^2, s^{-1} atm^{-1} O^2	Flame Temperature °C[a] Pressure (psia) A-amb, B-3000, C-10000
FEP		77[b]	10467[c]	0/20 (98J)[g]		4.47	2464(A) 3439(B) 3761(C)
Polyether sulphone							3153(A) 3978(B) 4192(C)
PEEK		35[d]					3155(A) 3988(B) 4206(C)
Polyethylene Terepthatlate		22.7[e]	23825[f]	6/51 (98J)[f]		0.02	3145(A) 3970(B) 4185(C)
Polystyrene		17.8[f]	41380[f]	20/20 (98J)[g]		18.94	3130(A) 3942(B) 4152(C)
Polyacetal		14.2 - 16.1[f]		12/20 (98J)[g]		0.39	3013(A) 3687(B) 3841(C)
Polycarbonate		22.5 - 39.7[f]	30783[f]	20/20 (19.5J)[f] 0/20 (19.5J)[f]		1.29	3134(A) 3948(B) 4159(C)
ABS		18.8 - 33.5[f]	35575[f]				
Polymethyl Methacrylate		16.7-17.7[f]	25080[f]	2/2 (98J)[f]			3008(A) 3677(B) 3830(C)
Polyphenylene Sulphide	533[e]	43[e]	28692[e]				3164(A) 3993(B) 4209(C)
PolyPhenylene Oxide		28-29[b]		20/20 (98J)[f]			3105(A) 3891(B) 4090 (C)
Polysulphone		32[e]					3194(A) 4053(B) 4279(C)
Nylon 11/12						0.03	3077(A) 3827(B) 4011(C)
Nylon 6		24[e]				0.03	3072(A) 3815(B) 3997(C)
Nylon 66	339[h]	22[e]	31400[c]	3/100 (98J)[g]		0.03	3118(A) 3845(B) 3897(C)
Polypropylene	231-262[e]	17.5[f]	46050[e]	17/20 (98J)[g]			

[a] Gordon and McBride (1971) [b] Werely (1988) [c] Lowrie (1983) [d] Information supplied by manufacturer. [e] Ikeda (1983) [f] ASTM G 63 (1991)
[g] Bryan (1983) [h] Testing performed at WSTF.

Table B-6

Polymer Properties Realted to Ignition and Combustion (continued)

Material	Autoignition Temp (°C)	Oxygen Index (OI)	Heat of Combustion (j/g)	LOX Mechanical Impact	Solubility S, cm^3/cm^3 O^2	Permeability Q, 10^{-8} cm^2, s^{-1} atm^{-1} O^2	Flame Temperature °C[a] Pressure (psia) A-amb, B-3000, C-10000
HDPE	255[b] 485[c]	17.5[b]	46500[b]	30/80 (98J)[d] 30/80 (83J) 3/20 (9.8J)[d]		4.18	3070(A) 3814(B) 3996(C)
Pine wood			19678[e]				
Natural Rubber			39778[e]		0.112[f]	17.7[f]	3099(A) 3876(B) 4072(C)
Styrene Butadiene Rubber	160[d]				0.094[f]	13.0[f]	3132(A) 2948(B) 4156(C)
Silicone Rubber	460-473[b]	21-32[b]	12895-15440[b]			400[f]	2995(A) 3909(B) 4189(C)
Polytetrafluoro ethylene	512-527[b]	100[b]	5334[b]	0/20 (98J)[d]			2543(A) 3507(B) 2831(C)
PCTFE (Kel-F81)	384[b]	100[b]	7858-9785[b]	0/20 (98J) [d]		0.07	2487(A) 3406(B) 3705(C)
Butyl	380[g]				0.122[f]	1.0 [f]	3091(A) 3860(B) 4052(C)
Ethylene Propylene		25.5 [d]	38460	7/20(98J)[h]	0.13[f]	19.0[f]	3083(A) 3842(B) 4029(C)
Chloroprene (Neoprene)	306-317 [b]	32 - 35[b]	26737-27310 [b]	16/20 (98J)[l]	0.075[f]	3.0[f]	3086(A) 3865(B) 4062(C)
Nitrile or Buna N	489[b]	22[b]	34900[b]	2/3 (98J)[d]	0.068[f]	2.9[f]	3097(A) 3867(B) 4060(C)

[a] Gordon and McBride (1971)
[b] Ikeda (1983)
[c] Tapphorn, Shelley, and Benz (1991)
[d] ASTM G 63 (1991)
[e] Lowrie (1983)
[f] Blow and Hepburn (1985)
[g] Testing performed at WSTF.
[h] Key (1972)
[i] Bryan (1983)

Table B-6
Polymer Properties Realted to Ignition and Combustion (continued)

Material	Autoignition Temp (°C)	Oxygen Index (OI)	Heat of Combustion (j/g)	LOX Mechanical Impact	Solubility S, cm^3/cm^3 O_2	Permeability Q, 10^{-8}, cm^2, s^{-1} atm^{-1} O^2	Flame Temperature °C[a] Pressure (psia) A-amb, B-3000, C-10000
Chlorosulponate Polyethylene (Hypalon)		27[b]	28470[b]	4/5 (98J) 1/15 (19.5J)[e]		2.1[c]	3048(A) 3778(B) 3956(C)
Polyurethane (foam)		25-28[b]	31771-27214[d]			2.4	
Fluorinated Elastomer (Viton®)	461-484[b]	56-100[b]	12912-18614[b]	3/20 (98J)[e]		1.2	2997(A) 3774(B) 4005(C)
Polyimide Vespel®	562[b]	49	26109[b]	0/20 (98J)[f]			3147(A) 3965(B) 4179(C)
SP21		65[e]	25522[e]	0/20 (98J)[g]			
Vespel SP 21®			6071[d]	0/20 (98J)[g]			
Rulon A reinforced PTFE	427[e]		5338[d]				
Rulon LD reinforced PTFE			7118[d]	0/120 (98J)[g]			
Fluorogold reinforced PTFE							
Fluorogreen® E600			10048[d]	0/20 (98J)[f]			

[a] Gordon and McBride (1971) [b] Ikeda (1983) [c] Blow and Hepburn (1985) [d] Lowrie (1983) [e] ASTM G 63 (1991) [f] Key (1966)
[g] Bryan (1983)

Table B-6

Polymer Properties Realted to Ignition and Combustion (continued)

Material	Autoignition Temp (°C)	Oxygen Index (OI)	Heat of Combustion (j/g)	LOX Mechanical Impact	Solubility S, cm^3/cm^3 O^2	Permeability Q, 10^{-8} cm^2 s^{-1} atm^{-1} O^2	Flame Temperature C[a] Pressure (psia) A-amb, B-3000, C-10000
Kalrez® Perfluoro elastomer	429[b]	100[b]	6552[b]				2543(A) 3506(B) 3831(C)
Polyvinylidene chloride		60[c]	20900[d]			0.004	2908(A) 3549(B) 3707(C)
Polyvinyl chloride	402[b]	37[b]	20855[b]	2/2 (98J) 0/20 (9.8J)		0.09	3048(A) 3798(B) 3987(C)
Carbon Black		35[b]	32750[b]				
Krytox® 240AC Fluorinated lubricant	427[d]	>100[c]	3768-4187[e]	0/200 (98J)[f]			2428(A) 3389(B) 3702(C)
Torlon® Polyamide imide (AMOCO)		42					
Fomblin LC Fluorinate Lubricant (AUSIMONT)	427[d]	>100[c]					2434(A) 3370(B) 3674(C)
Halar ECTFE			16329[e]				3215(A) 4032(B) 4239(C)
ETFE Tefzel (DuPont)		30[d]					3314(A) 4178(B) 4400(C)
PVdF Kynar®		43.7[d]	13710[d]	79/100 (98J) [d]			

[a] Gordon and McBride (1971) [b] Ikeda (1983) [c] Fenimore and Martin (1966) [d] ASTM G 63 (1991) [e] Lowrie (1983)

[f] Bryan (1983)

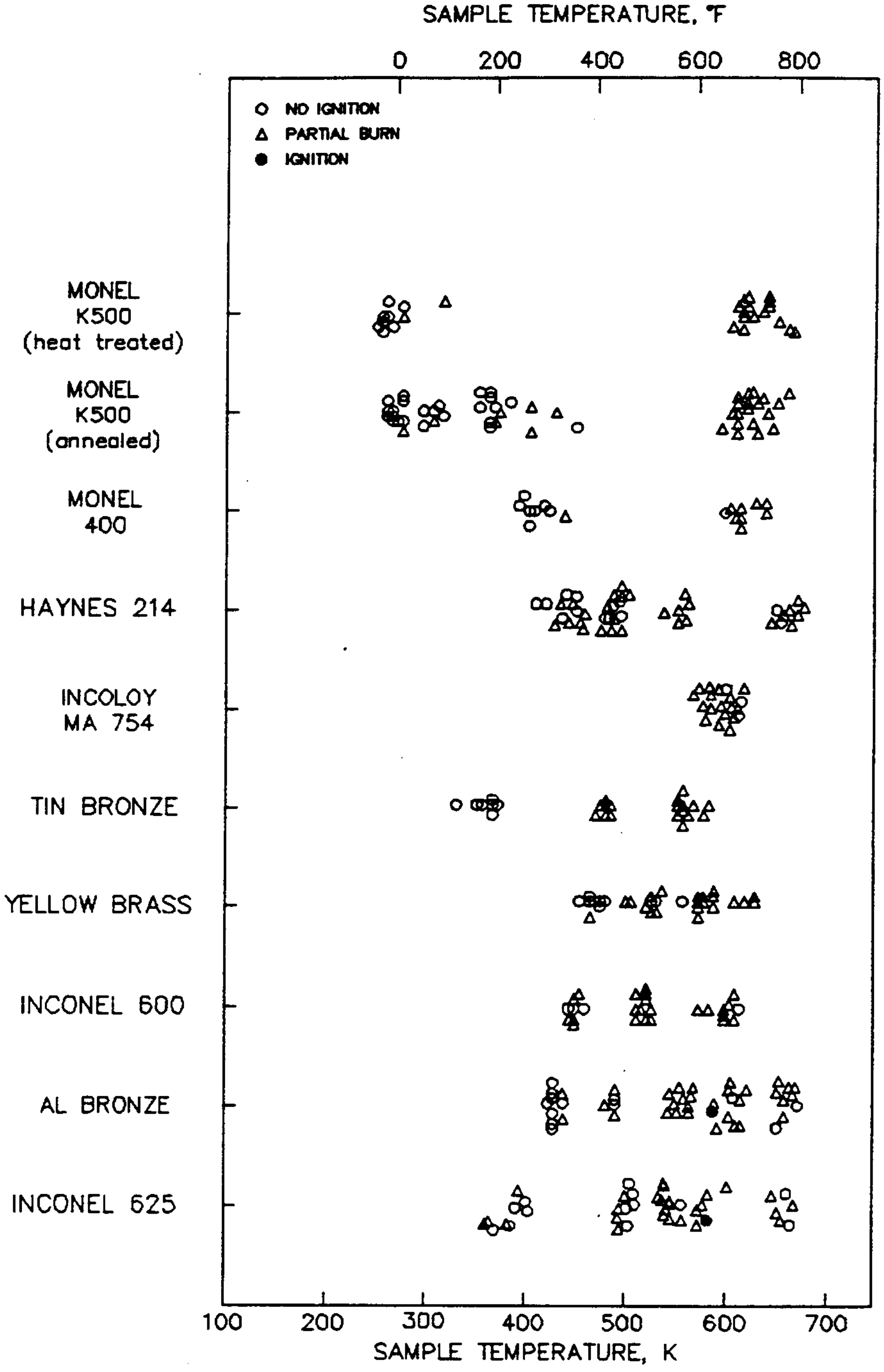

Figure B-1a
Ignitability of Metals in Supersonic Particle Impact Test with 2000-*m* Aluminum Particles in 3900-psi Oxygen (Increases from Top Right to Bottom Left)

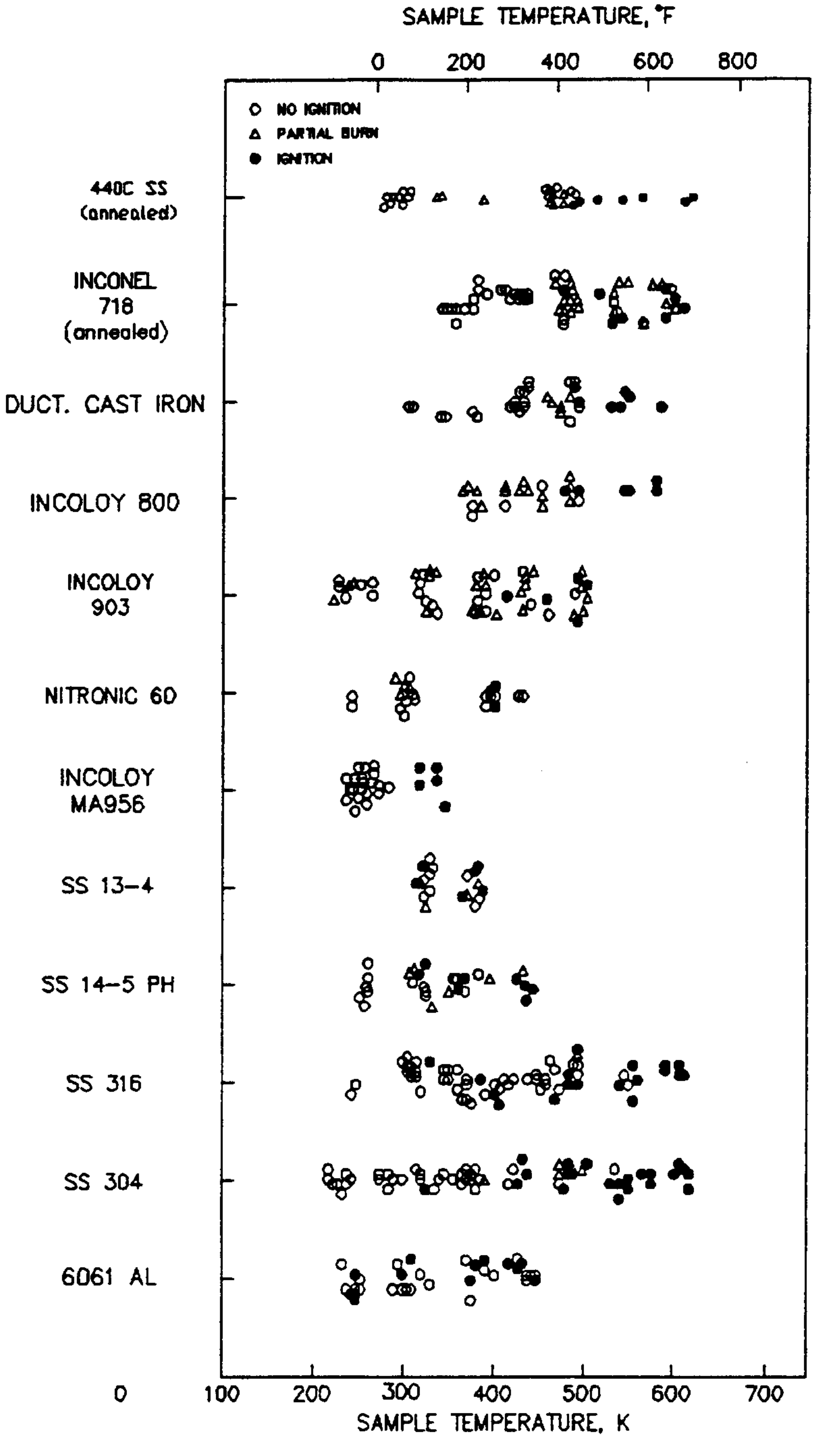

Figure B-1b

Ignitability of Metals in Supersonic Particle Impact Test with 2000-*m* Aluminum Particles in 3900-psi Oxygen (Increases from Top Right to Bottom Left)

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APPENDIX C.

DESIGN EXAMPLES

APPENDIX C

DESIGN EXAMPLES

C. 1 This appendix expands on the concepts presented in Chapter 4, which designers must adhere to when designing oxygen systems and components. The examples detailed below will aid the designer in combining the use of the various design techniques to design simple, reliable, ignition-resistant equipment. Refer to ASTM G 88 (1985) for additional design guidelines.

C.2 SAMPLE MATERIAL APPLICATIONS

Refer to Chapter 3, ASTM G 63 (1985), and ASTM G 94 (1990) for information on materials ignition and combustion. The following information provides guidelines for the designer, but it is not intended to supersede specific data found in Appendix B. The materials identified in the following sections are roughly in descending order of resistance to ignition and combustion in oxygen. Components fabricated from Monel® without thin cross sections are generally safe from ignition mechanisms. Ignition sources must be avoided when using materials known to be flammable in the use environment.

a. Metals.

(1) Monel® 400 is useful as an engineering alloy with high ignition resistance in oxygen. It has particular advantages for welding applications, such as in 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 such metals as aluminum.

(2) Monel® K-500 is useful for high strength-to-weight ratios (specific strengths). Monel® K-500 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.

Note: Monel® K-500 should not be welded for most applications.

(3) Bronze has been shown to be an excellent material for sintered filter elements.[1] It may also be used for valve bodies and other components where material strength is not a prime design criterion.

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[1] Recent tests on initability of filter materials at WSTF.

(4) Beryllium-copper may be used for springs and other applications where high strength and the ignition resistance of copper-based alloys is desired. Inconel® X-750 may be used for high-strength springs, Inconel® 600 for low-strength springs, and MP-35N and Elgiloy® for very high-strength springs and high spring rates. Ignition resistance and high-temperature properties of these materials vary.

(5) Inconel® 625 is useful for very high-temperature applications where welded materials are required. In essence, it may be used as a high-temperature replacement for Monel® 400, keeping in mind that material strength is reduced and flammability and ignition susceptibility is increased.

(6) Hastelloy® C-22 and C-276 are Ni-Cr-Mo alloys that can withstand high-temperature oxidizing environments up to 1090 °C (2000 °F). They are also resistant to mineral acids, solvents, wet and dry chlorine, or hydroflouric acids. However, in high-pressure oxygen environments these alloys have flammable traits similar to Inconel® 625. C-22 alloy, however, is known to be markedly less flammable than C-276. Both of these alloys are available in cast, wrought, and forged configurations.

(7) 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.

(8) 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.

(9) Galling potential increases with materials of similar chemical composition and hardnesses. If an all-Monel® valve is required, then screw threads should have one mating part made of annealed Monel® 400 and the other of age-hardened Monel® K-500 to achieve a large difference in hardnesses and some difference in chemical composition. Using an annealed 300 series stainless steel mated with age-hardened Monel® K-500 would further reduce galling potential because of the increased disparity in chemical compositions.

(10) Aluminum alloys are highly susceptible to ignition and combustion in oxygen, but because of their lightweight, designers are tempted to use aluminum in spite of the ignition hazards. An anodizing surface preparation should be used for aluminum parts subject to conditions that

may generate particulate or be subjected to particle impacts (Bahk et al. 1992). Examples include bends or restrictions in aluminum flow lines, valve bodies, and piston housings.

b. Polymers.

In general, all polymers are flammable in 100-percent oxygen; therefore, care must be taken to minimize or eliminate ignition sources. The materials listed below appear roughly in descending order of preference.

(1) Teflon® is the most compatible soft good in terms of ignition resistance in oxygen-enriched environments. For this reason, it is preferred for a wide variety of seals and miscellaneous components. Teflon® does not have any appreciable resilience, which is a very desirable property for seal materials. Because of this, the designer must ensure that “cold flow” of Teflon® can be tolerated for long-term mechanical loading, pressure-induced loading, and thermal cycling. Additionally, the designer must avoid situations where extrusion creates fine Teflon® particles that can promote combustion of other components. The designer must also avoid seal leakage that could create an oxygen-enriched environment around pressurized components and/or high-velocity flow, which could create particle impact ignition hazards. Teflon® may also be used as a solid lubricant coating on rubbing surfaces, but it will create contamination as the equipment is operated. Designers should be aware that fillers may adversely affect ignition and combustion effects of Teflon®.

(2) Kalrez®/Chemraz® may replace Viton® or silicone when applications call for an elastomer at lower and/or higher operating temperatures than Viton®.

(3) Kel-F® is a fluorinated material that may sometimes be substituted for Teflon® because of its increased rigidity and a slight resiliency. However, Vespel® is usually preferred over Kel-F® in applications where material strength is important.

(4) Viton® is the most recommended elastomer for oxygen usage. Unlike Teflon®, it has “shape memory,” which allows it to withstand various loads and still return to its original shape. Because of this property, Viton® may be preferred over Teflon® for certain applications, even though it has reduced ignition resistance.

(5) Vespels®, especially Vespel®SP-21, are excellent choices for bearings, bushings, valve seats, and seals. These materials have good ignition resistance, lubricity, machinability, and creep resistance.

(6) Silicone is a common material for seals and diaphragms when ductility and low hardness are required to provide excellent sealing ability at low operating temperatures (not cryogenic) and moderate pressures. However, silicone is not a material of choice for oxygen service because of its low ignition threshold in oxygen-enriched environments and its high heat of combustion. Therefore, if silicone is used, the designer must ensure that all ignition sources are eliminated. Fluorosilicone is not recommended in place of standard silicone, because the mechanical properties are not enhanced, ignition/flammability characteristics are similar to silicone, and possible health risks from combustion byproducts are increased.

(7) Adhesives and bonding agents should be avoided because of their high reactivity with oxygen.

c. Composites.

Polymeric composites may have increased mechanical or physical properties over standard materials. A simple example of this is glass fiber-filled Teflon®. The enhanced properties are desirable, but the disadvantage is that the matrix material and often the sizings are more flammable in oxygen. When attempting to use any composites, complete ignition sensitivity testing must be performed.

d. Ceramics and Glass.

(1) Ceramics are not generally flammable in oxygen, so they can serve as effective thermal and electrical insulators. However, although they may not burn, they may be severely degraded by contact with molten metal slag, and their ability to act as a fire stop or an insulator may be compromised. Care should also be taken in their use, because they are typically brittle and susceptible to fracture from manufacturing-induced defects and impact loading. High safety factors and compressive loading are design requirements.

(2) Glasses may be used for many applications including pressure vessel windows and valve seals. Pressure vessel codes generally require glass-retaining pressure differentials to have safety factors of ten or greater. Special design features must also be incorporated per ASME (1987). Sapphire glass is often used for windows as well as for valve ball seals where they mate against seats.

C.3 GENERAL DESIGN REQUIREMENTS

The key to successful designs is to integrate the concepts presented in Chapter 4. Several potential hazards can be reduced or eliminated by judicious design. Additionally, it is wise to spend time at the initial design stage to simplify designs. By simplifying, potential failure points and ignition sources can be eliminated, parts can often be made sturdier and more ignition-resistant, and flow paths can be made straighter.

The following gives some examples of how to apply the concepts in Chapter 4 to real systems to avoid specific problems.

a. <u>Particle Impact</u>.

An ideal design to eliminate particle impact ignition sources would limit fluid velocities, minimize contamination, reduce the potential for particle impacts on blunt surfaces, and avoid burrs and small parts susceptible to kindling chain ignition and combustion. In a best-case example, flow would approximate clean, low-velocity flow through a straight section of tubing. A worst-case example of how <u>not</u> to design for particle impact ignitions may be found in Figure C-1, which illustrates several design problems.

(1) The blunt drill point at the end of the horizontal hole could provide a place for impact to occur, thus resulting in ignition of metallic particles entrapped in the flow stream. The drill point is located immediately downstream from the maximum (near sonic) fluid velocity.

(2) The drill point allows particles to concentrate at the ignition site, thereby increasing the chance of ignition.

(3) The sharp edge at the intersection of the drilled holes provides a site for ignited particles to promote combustion, which could in turn promote the combustion of the bulkier portion of the housing.

b. <u>Pneumatic Impact</u>.

Soft goods must be protected from ignition sources, because they are more easily ignited than metals. An ideal example of a design to eliminate pneumatic impact ignitions would limit pressurization through the use of “slow” actuators or flow restricters. It would avoid manifold designs that allow fluid hammer situations to occur during flow transient situations. Additionally, any small, drilled holes or crevices that are difficult to clean can accumulate nonmetallic contaminants, which can be easily ignited from compressive heating or resonant fluid vibrations. Similarly, soft goods exposed to these heat sources can also be ignited, so all O-rings, seals, and valve seats must be protected from the fluid flow by metallic parts wherever practical. Figure C-2 illustrates soft goods that are minimized and protected from the flow by metallic parts. As shown, there is a tortuous flow path which reduces the pressurization rate and compressive heating of the seals.

c. <u>Mechanical Impact</u>.

Any situation where mechanical components can impact against each other should be avoided. Examples of situations where this can occur are relief valves, shut-off valves, and regulators. Spring-loaded seats in these devices react against fluid pressures, and, during transient flow situations, the seal and seat can impact against each other caused by the imposed force imbalances. Refer to Figure C-3, which demonstrates a place where mechanical impact could occur.

d. <u>Frictional Heating</u>.

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

Frictional heating has also been found to ignite materials in cryogenic applications. The frictional heat can vaporize the LOX and form a vapor-rich fluid surrounding the heat source. Once this occurs, the ignition and combustion situation resembles that of a GOX situation. The force imbalances across the valve seat configuration shown in Figure C-2 could create friction when closing the valve stem.

e. <u>Electrical Arcing</u>.

Electrical arcs in oxygen-enriched environments can lead to heating and subsequent ignition. An example of good design practice is found in Figure C-4, which demonstrates the proper method to insulate electrical components and reduce the possibility of arcing. Arcing can rapidly heat wire insulation, creating fuel and heating in the presence of oxygen and causing ignition.

f. <u>Eliminate Burrs and Sharp Edges</u>.

Although the elimination of burrs and sharp edges should be the goal of all designers and machine shops, this becomes especially important in oxygen systems where small, thin portions of metal can become the site for kindling chain combustion. If an ignition source such as particle impact is able to ignite a burr, this may promote the combustion of the bulkier material surrounding it, which would otherwise have been substantially more difficult to ignite (Figure C-5).

g. Minimize Use-Generated Particulate.

Threaded connections can generate contaminants in oxygen systems as they are engaged and tightened (Figure C-6a). This problem can be eliminated by redesigning the threaded members so the smooth portion of the plug interfaces with the seal before the threads engage (Figure C-6b). However, this solution involves rotating a part against its seal and may cause seal damage. Alternatively, the in-line threaded connection can be replaced with a flanged and bolted connection in which the threaded portions are outside the fluid stream (Figure C-6c). The function of the threaded connection can also be performed by a separate locking nut and sealing plug; the locking nut is inserted after the sealing plug has been pushed into the seal (Figure C-6d). A fifth option is to install a barrier ring to block the particulate (Figure C-6e).

h. Avoid Rotating Valve Stems.

A manual, screw-type valve with a rotating stem (Figure C-7a) might seem desirable in a high-pressure oxygen system because such a valve can provide a slow actuation rate. However, a rotating-stem valve presents contamination problems. A nonmetallic seat can easily be damaged by excessive closing torque, shredding, or gas erosion during opening and closing. Furthermore, solid contaminants can become embedded in soft seat material. If the seat is made of metal, it must be hardened to prevent galling when the valve stem rotates against the seat. Such hardened materials can fracture or even fragment as a result of excessive closing torque or closure onto hard contaminants such as silica.

A manual valve with a nonrotating stem (Figure C-7b) and a metallic seat can be used to achieve the desired slow actuation rate. In this case, the metal seat can be made of a much softer material and the seat can be formed by “coining” (pressure molding by the stem itself to create a perfect match). Contaminants will not cause fragmentation of such a seat. Galling cannot occur unless the nonrotating feature is compromised (therefore, care should be exercised when cleaning). The seat and body of such a valve can be fabricated from many metals that are comparatively unreactive with oxygen.

i. Eliminate Blind Passages and Crevices.

A stagnant area at the end of a drilled passage tends to collect debris either from manufacture or from normal use. During rapid pressurization of GOX and its attendant compression heating, the debris becomes fuel for ignition. When an underexpanded jet impinges on (or flows across) a stagnant cavity, a periodic pressure wave may be formed that oscillates in the cavity, heating the gas within it (cavity resonance). If particles are present in regions of rapid gas flow, they can impact the end of the passage and cause ignition of the component; drill points can collect particulate at their center and significantly increase the chance of ignition. Blind passages and dead-end cavities also increase cleaning difficulty, requiring that the part be turned during soaking to eliminate air pockets. Special nozzles or extensions must be used to flush such areas. Figure C-8a depicts a blind passage created by plugging a drilled passage. Figure C-8b depicts a dead-end cavity created by overdrilling an intersecting passage.

GOX components should be designed so that a jet will not impinge on or flow across a stagnant cavity. Jets should be gradually expanded and stagnant cavities should be eliminated or kept as shallow as possible. In Figure C-8a, the blind passage could be eliminated by making the counterbore for the plug much deeper and installing the plug closer to the regulator stem. The cavity may not be completely eliminated, but the total dead volume would be significantly reduced. The cavity shown in Figure C-8b can be eliminated by paying careful attention to dimensions and tolerances or, preferably, by redesigning to eliminate the intersecting holes. If particle impact ignition is a concern, the drill point should be eliminated as part of the redesign. Inspection with a borescope can be conducted to verify that passageway lengths are within tolerance.

j. Prevent Rotation of Seals and Rotation Against Seats.

Sealed parts that require rotation at assembly (such as O-rings on threaded shafts) can generate particles which may migrate into the flow stream (Figure C-9a). Particulate generation also occurs in ball valves where a ball is rotated on a nonmetallic seat.

A related phenomenon, which may be described as “feathering,” occurs when valve stems are rotated against some nonmetallic seats such as Kel-F®. Because of the mechanical properties of some nonmetallic materials, a thin, feather-like projection of material is extruded from the seat. The feathered feature is more ignitable than the seat itself.

Instead of rotating, the sealed part can be designed as a push-in plug locked in place by a second part that is threaded but not sealed, as shown in Figure C-9b. Alternately, the sealed threads can be replaced with a flanged and bolted connection. Kel-F® and other nonmetallic materials subject to feathering should not be used for seals and seats in rotating configurations. Ball valves are not recommended for oxygen systems because of their tendency to generate particulate and their quick opening times. The quick opening times lead to rapid pressurization of downstream cavities, creating rapid heating of soft goods and increasing the risk of polymer ignition and combustion.

k. Eliminate 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. Because geometries both inside and outside can be complex, it may not be obvious from drawings or even from 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. Figure C-10 illustrates a thin-wall condition.

The thin wall in Figure C-10 is primarily the result of an overdrill caused by careless design or an overtolerance. The dimensions of a drilled intersection should be planned more carefully or the tolerances set more tightly. It may even be possible to eliminate the intersection altogether (the most desirable solution) as shown in Figure C-6b or C-6c, although analysis must still be performed to ensure that all sharp edges and thin walls are avoided. All intersections should be examined by X-ray or borescope to ensure that the drilling was acceptable.

A solution to this problem is to perform dimensional tolerance studies and to create CAD models of the component in question. An indication of thin walls should prompt a stress analysis of the local area to determine whether a problem actually exists. Dimensions and tolerances called out on the manufacturing drawing should then be tight enough to preclude stress concentrations.

l. Cold Flow and Extrusion of Seals.

This effect can often be minimized by using springs to provide an external shape memory for the seal, by reinforcing the materials with various types of fibers, and by supporting the seals with stiff back-up rings. Seal extrusion can be avoided by minimizing pressure and thermal reversal cycles.

C.4 RISK OPTIMIZATION

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

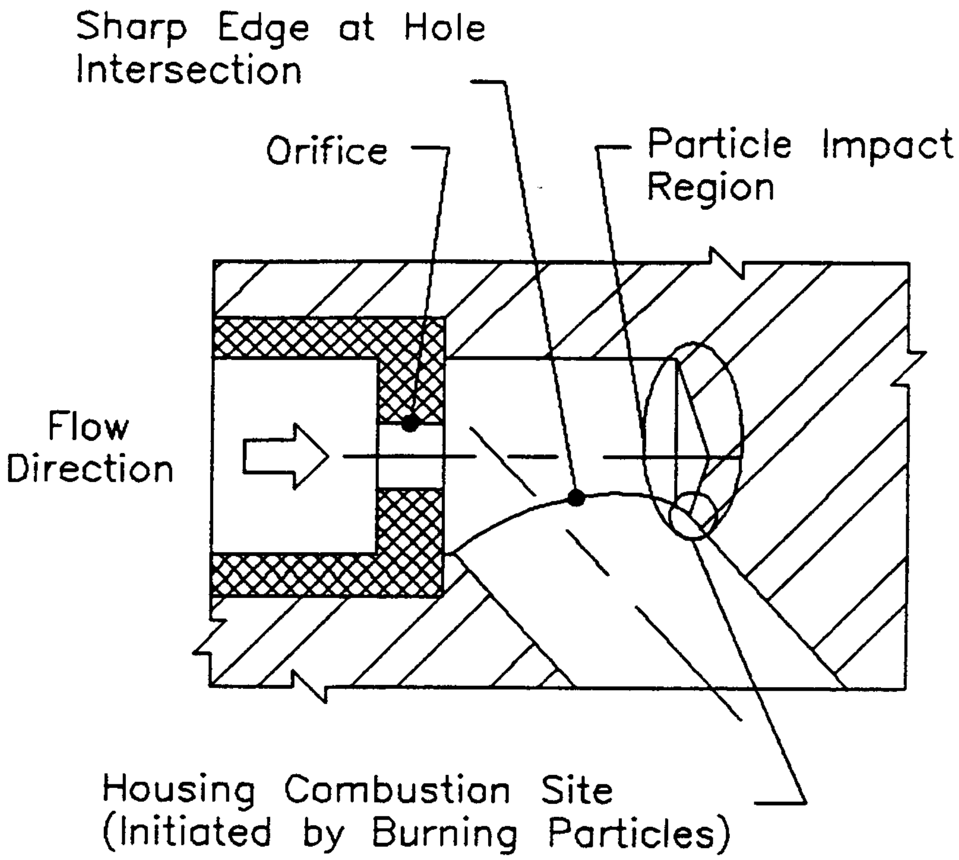


Figure C-1
Design Highly Susceptible to Particle Impact Ignition

Particles entrained in the flow stream are accelerated through the orifice and impact a blunt surface downstream. On impact, the particles are at near-sonic velocity and the kinetic energy is efficiently converted to heat. The drill point exaggerates the problem by concentrating the heat from multiple burning particles, and the sharp edge from the intersection of drilled holes allows kindling chain promoted combustion.

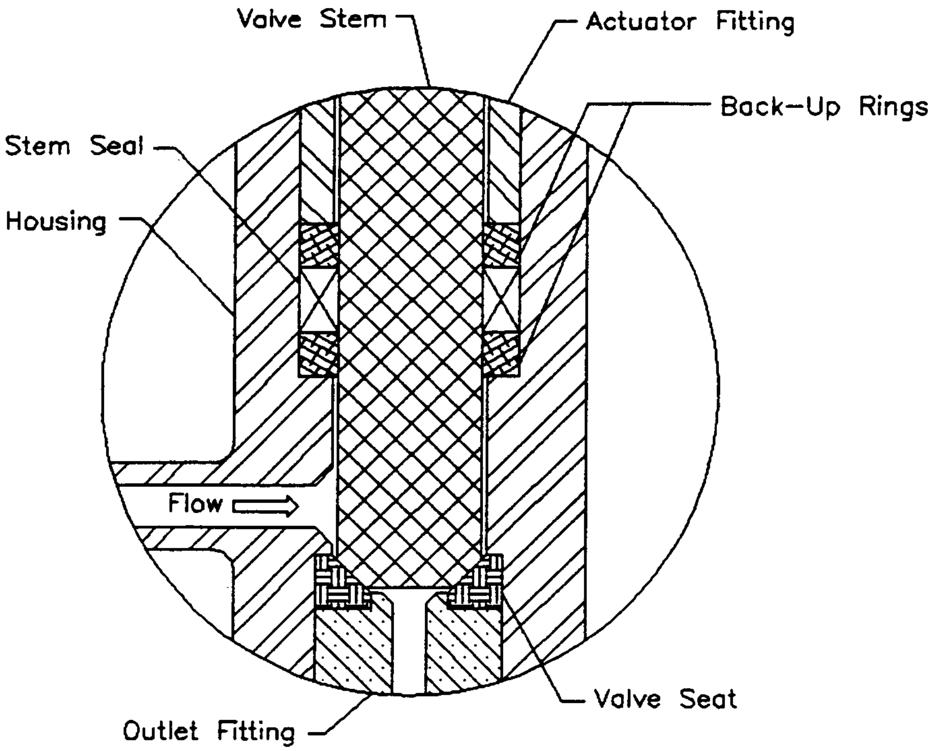


Figure C-2
Design Showing Minimization of Soft Good Exposure to
Pneumatic Impact Ignition

This configuration shows the soft goods removed from the region of maximum pneumatic impact heating where the fluid momentum is stopped. All soft goods have restricted flow paths from this region, greatly reducing fluid heating of soft goods.

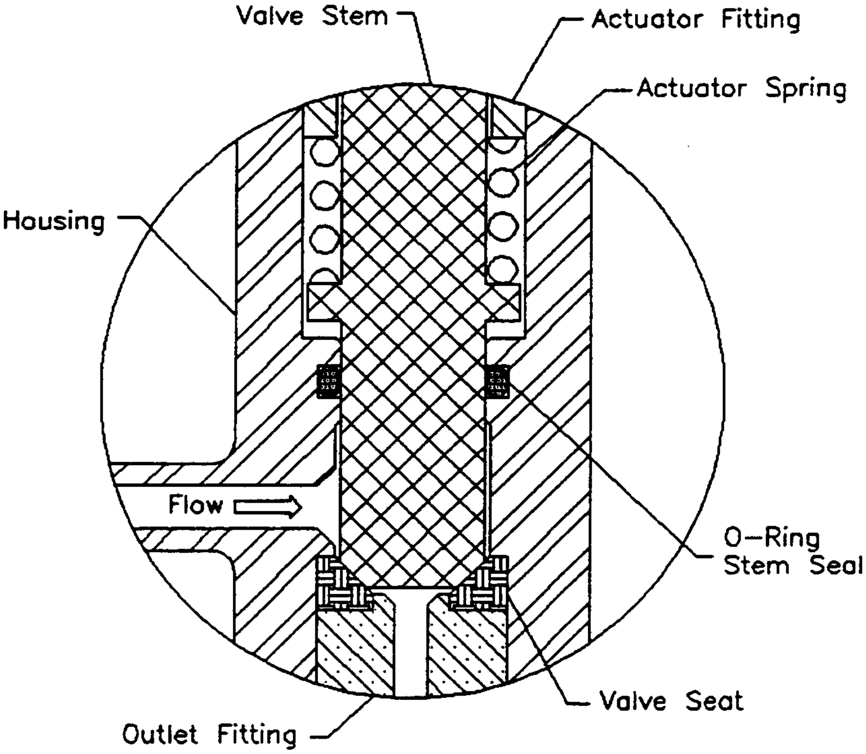


Figure C-3
Design Susceptible to Mechanical Impact Ignition

Spring-loaded valve seals can be exposed to transient flow conditions that cause rapid valve stem throttling as fluid dynamic pressures and mechanical forces vary. Valve stem throttling can, through single or multiple impacts, provide sufficient heating for ignition.

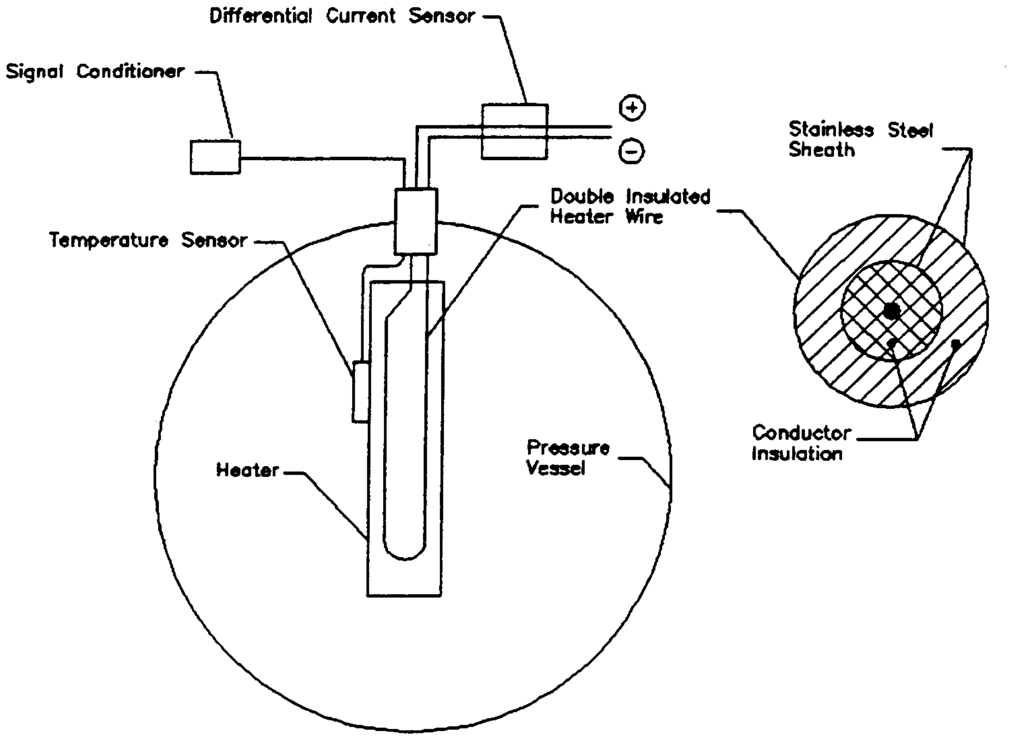


Figure C-4
Design Minimizing Electrical Arcing

Ignitions caused by electrical malfunction can be prevented by using double-insulated heater wire with a differential current sensor and a temperature sensor to monitor off-limit operating conditions.

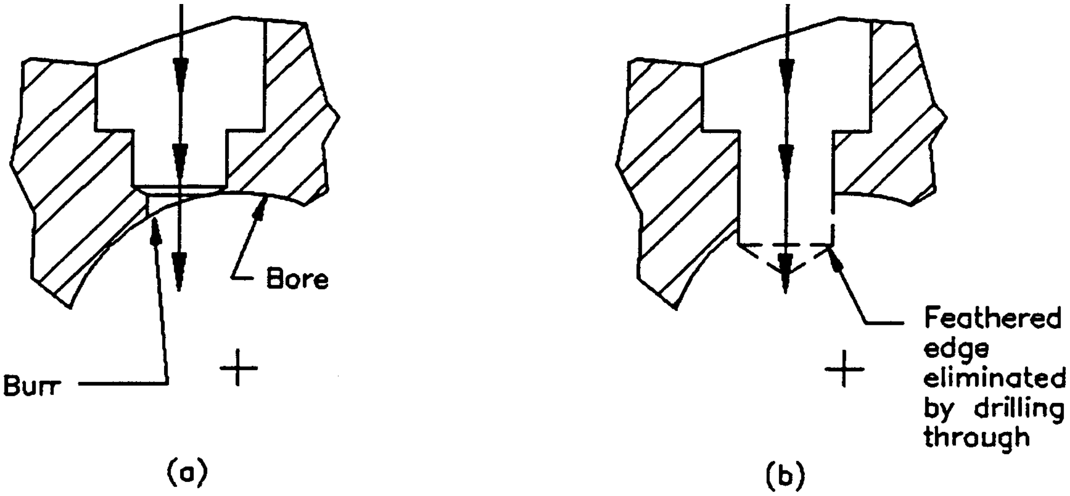


Figure C-5
Design With Sharp Edges

Insufficient drill-point penetration in the drilled hole creates a sharp edge at the intersection of the bore and drilled hole in Figure C-5a. As shown in Figure C-5b, this situation can easily be eliminated by extending the drill-point penetration. This configuration will be much less susceptible to several ignition mechanisms.

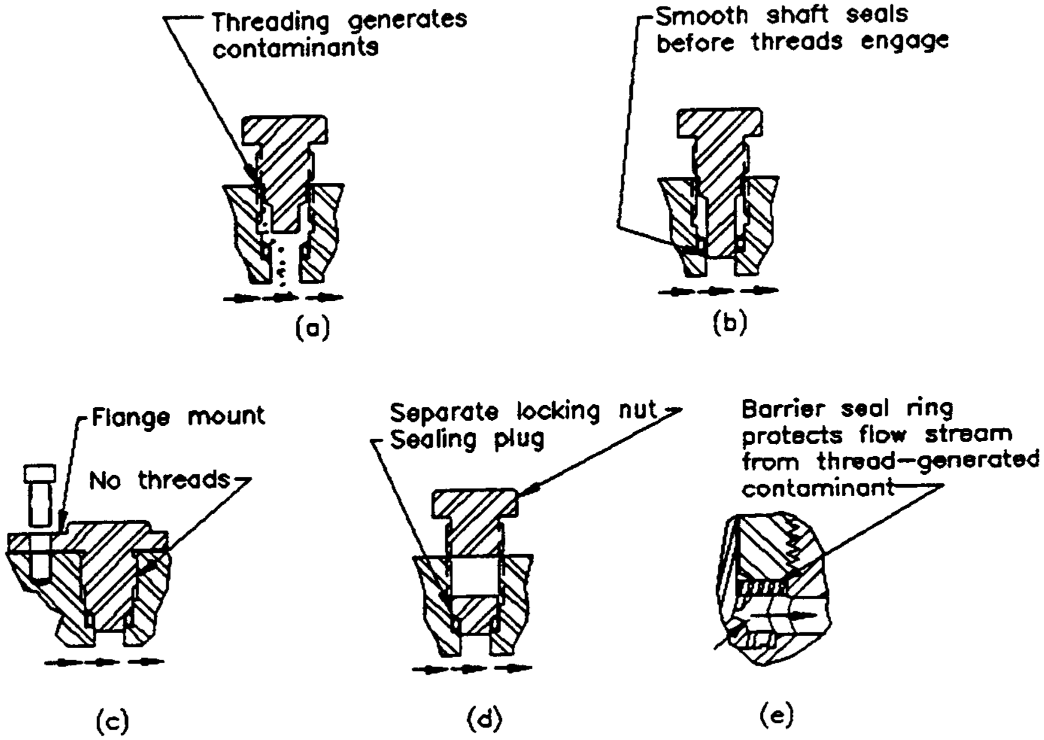
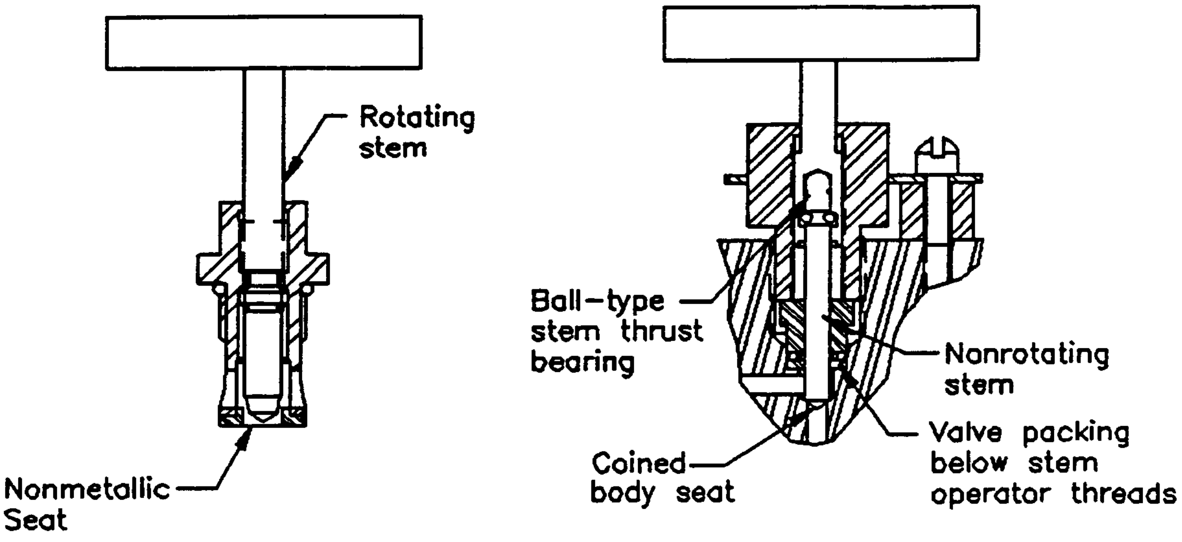


Figure C-6
Designs Showing Various Fitting and Particulate Generation Configurations

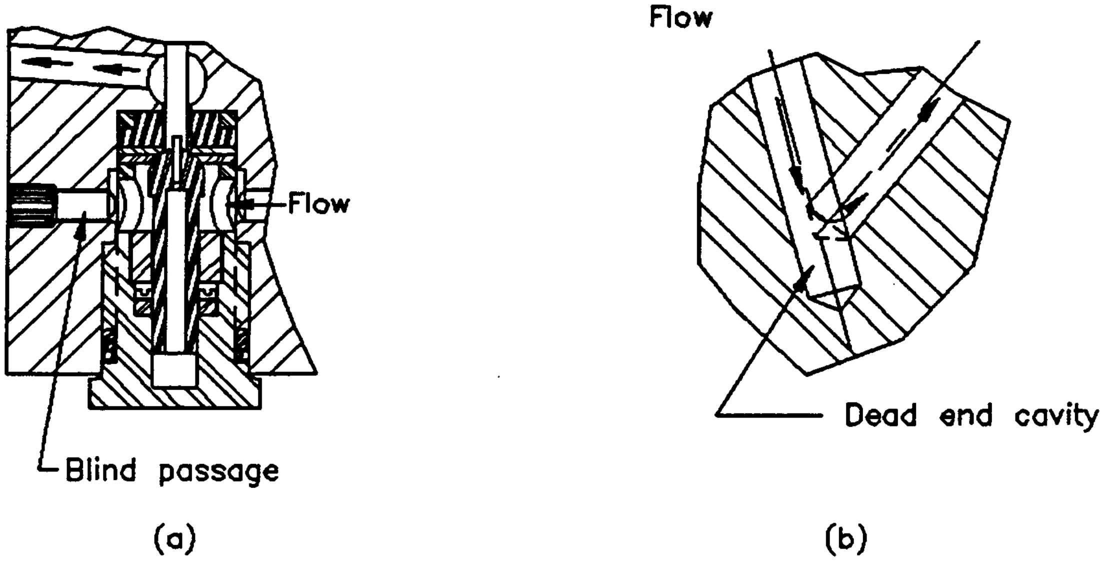
Figure C-6a shows how particulate can easily be generated during fitting assembly. The configuration will allow particles to be created while threading parts together to be released into oxygen-wetted regions. A build-up of particles can cause particle impact ignitions. Figures C-6 (b) through (e) show configurations that isolate assembly-generated contaminants from the oxygen.



(a) (b)

Figure C-7
Designs Illustrating Rotating Stem Valve and Particle Generation Configurations

Figure C7a shows a common valve configuration with a rotating valve stem. Manual valve actuation creates particulate in the threads and at the point of contract with the seat. Particle contamination can be minimized as shown in Figure C-7b by placing stem seals below the valve stem packing to isolate them from oxygen and by making the stem a nonrotation configuration. Axial stem movement without rotation will minimize particulate generation, and the hazard of particle impact ignition is reduced.



(a)

(b)

Figure C-8
Contaminant-Entrapping Configurations

Figure C-8a shows a configuration where flow passages are formed by intersecting drill holes and plugging part of the flow passage. Figure C-8b shows intersecting drilled holes with an oblique intersection angle and a large dead-end cavity. Both configurations are hard to clean and readily accumulate contaminants. The minimal benefits from ease of manufacture are more than offset by ignition hazards.

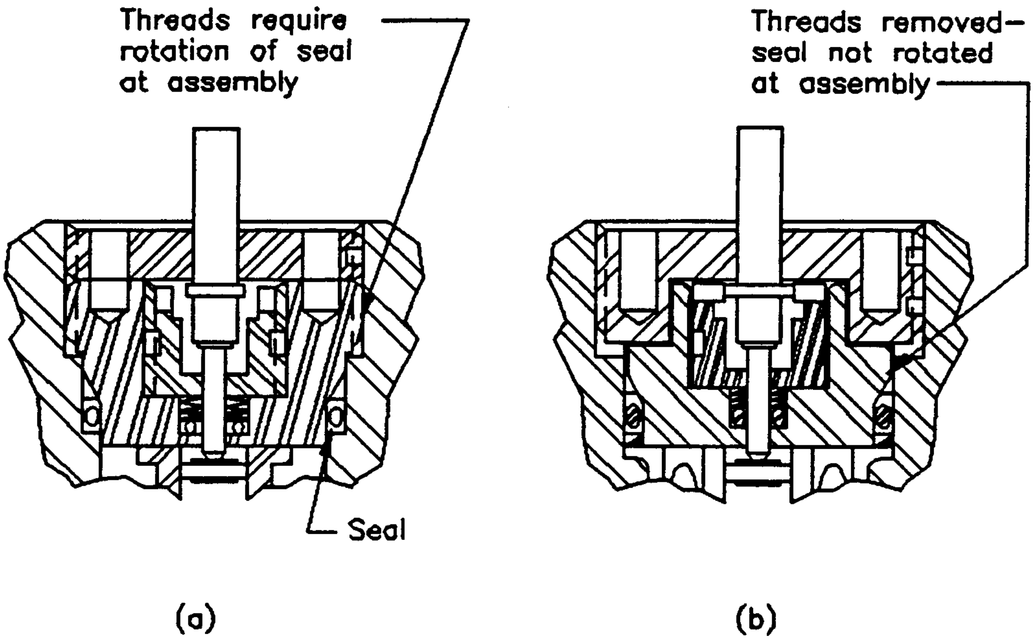


Figure C-9
Seal Configuration Reducing Assembly-Generated Contaminants

Figure C-9a shows a configuration where particulate generated by the threads at assembly can enter the oxygen-wetted valve regions, because the seal is not engaged during the threading operation. Figure C-9b shows one of many configurations that can be used to isolate assembly-generated particles from the contained oxygen and reduce wear and feathering of the seal or assembly.

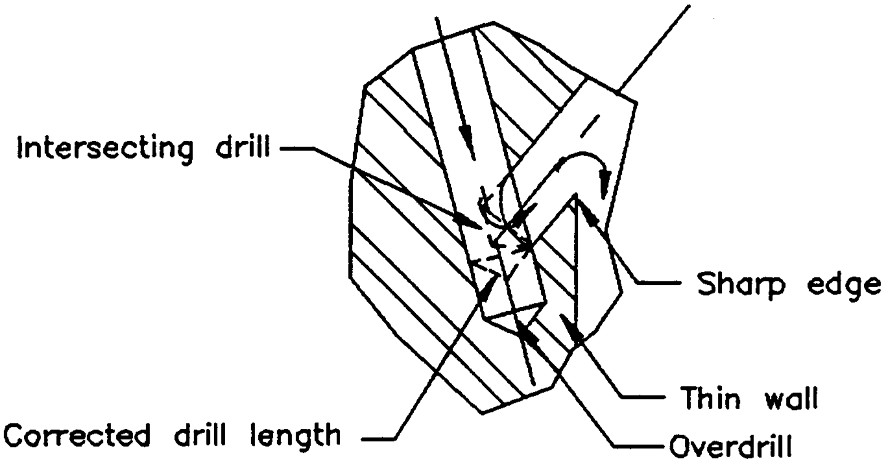


Figure C-10
Design Resulting in Thin Walls

This configuration should not be used because it combines the worst aspects of an overdrill for particle impact and accumulation with thin material sections, increasing the risks of kindling chain ignition of bulk materials. Manufacturing forethought can eliminate this situation.

C5. REFERENCES

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APPENDIX D.

PRESSURE VESSELS-TESTING, INSPECTION, AND RECERTIFICATION

APPENDIX D

PRESSURE VESSELS-TESTING, INSPECTION, AND RECERTIFICATION

D. 1 GENERAL

a. Pressure vessels will require testing, inspection, and qualification when installed and periodic recertification while in service. Refer to Chapter 4 for details on pressure vessel design for oxygen service.

b. Several accepted definitions of pressure vessels are:

   (1) ASME Code pressure vessels

   (2) NASA flight-weight pressure vessels. These do not meet ASME code. They typically have safety factors between 1.10 and 1.35.

   (3) NASA medium-weight pressure vessels. These do not meet ASME code, are nonflight, and have safety factors between 1.35 and 4.00.

   (4) DOT, API vessels, etc. These typically have safety factors between 1.5 and 4.0.

   (5) Compressed gas cylinders meeting the requirements of 49 CFR (1986)

c. Compliance with NMI 1710.3C (1991) is required. Inspection and testing methods for establishing the suitability and safety of oxygen vessels, pressure vessels, piping, and equipment are also included in industrial guidelines and federal codes (CGA 341 1970; ASME Section VIII (1986a) and Section IX (1986b); ANSI/ASME B31.10 1986; NHB 1700.6 1976).

d. The performance and design requirements of the system and its components should be verified by testing and analysis. Testing within off-limit ranges should be considered for evaluating limited design margins, single-point failures, and any uncertainties in the design criteria. Such testing should be performed per applicable codes. Before installation in a system, pressure vessels, piping, valves, flexible hoses, and pumping equipment should be pressure-qualification (proof)-tested to ensure they can withstand internal test pressures higher than design operating pressures.

e. If repairs or additions are made after the tests, the affected piping or equipment must be retested. Equipment not to be subjected to the pressure test should be either disconnected from the piping or isolated by blinds or other means during the test.

f. Cleanliness should be verified at system and component operating levels. Initial testing may be performed with clean inert fluids, and acceptance tests may be done with nitrogen. Life tests, however, should be conducted with oxygen.

D.2 TESTING

a. Qualification and Acceptance Testing.

Initial qualification tests to verify system integrity should not exceed the system's Maximum Allowable Working Pressure (MAWP). While the MAWP is held in the system, the test should be monitored from a remote location. After testing is completed, the components that have not previously been qualified for oxygen service should be reevaluated for flow and functional capabilities. They should be disassembled and inspected after testing.

b. Pressure Testing.

(1) All oxygen containers and systems must be pressure-tested according to the requirements in NHB 1700.6 (1976). Hydrostatic testing is recommended as a relatively safer and more reliable method of system testing than pneumatic pressure testing. However, because of the energy stored, hydrostatic testing should still be considered hazardous (Roth 1964). Construction materials for the LOX container and its attachments and the finish tank should be inspected as required by applicable codes. The liquid container should be subjected to either a hydrostatic or a proof test.

Note: Hydrostatic testing should be completed before cleaning (see Chapter 5).

(2) Hydrostatic and pneumatic tests should be performed per the requirements of applicable codes for pressure vessels and ANSI/ASME B31.l0 (1986) and B31.3 (1993) for piping and tubing. Pneumatic tests should be approved by the NASA center safety authority.

c. Performance Testing.

(1) Heat Leak Tests. The boiloff rate and heat leak establish the maximum allowable hauling distance of a liquid-oxygen transportation system. For calculation of one-way travel time, see 49 CFR (1986). The boiloff tests should be repeated after driving the trailer for a minimum of 1600 km (1000 miles).

(2) Leak Testing (NHB 1700.6 1976)

(a) Leak detection methods include soap tests (bubble tests), which have a sensitivity of approximately 10^{-3} cm^3/s (6 x 10^{-5} in^3/sec); and helium tests, which have a sensitivity of $10^{-9}cm^3/s$ (6 x 10^{-11} in^3/sec) or better. For vacuum-jacketed systems, chemical analysis of a vacuum pump discharge will indicate leakage. The helium mass spectrometer is the most sensitive leak detection instrument available for industrial use. The presence of a leak is shown on a meter that indicates how much helium is passing through the spectrometer tube. Helium leak testing should be performed before filling systems with oxygen.

(b) The systems must be checked for leaks, initially under atmospheric temperature conditions and then when loaded with fluids under the MAWP.

(c) Pressure-rise tests of vacuum-jacketed equipment will indicate if a leak is present.

(d) Before the oxygen vessel is completely assembled, the inner vessel should be helium leak-tested with a mass spectrometer. Leak tests should be conducted with the mass spectrometer set at 1 x 10^9-std cm^3/s (6 x 10^{-11} in^3/s) sensitivity. A no-leak indication for 15 minutes constitutes a successful test. Vacuum integrity and insulation stability tests should be performed by pumping the vacuum space to at least 30-mm Hg and sealing it. Pressure in the vacuum space should not rise more than 5-mm Hg during 48 hours. If the rise is more than 5-mm Hg it may be due to a leak or to H_2O saturated perlite outgassing in the annulus.

(e) Various leakage testing methods are described in Schmidt and Forney (1975) and KHB 1710.2A (1978).

(f) All vacuum leak detection and/or pumping must be done utilizing oxygen compatible vacuum pump oils in the event that backstreaming conditions occur. Pump shutdown solenoid valves should be in place to prevent oil migration during power outages or pump failure modes.

d. Weld Testing.

Unless the welded joints on the inner container of a LOX vessel are fully radiographed, all welds in or on the shell and heads, both inside and outside, should be tested by the magnetic particle method, the fluorescent dye penetrant method, or by the ultrasonic testing method (ASME 1986b, also see "Inspection" in this appendix). All cracks and other rejectable defects shall be repaired according to the repair procedures prescribed in the code under which the tank was built. The welder and the welding procedure should be qualified in accordance with ASME (1986b).

(1) NASA is responsible for the welding done by NASA personnel and shall conduct the required qualification tests of the welding procedures and the welders or welding operators. Contractors are responsible for welding done by their personnel. A supplier shall not accept a performance qualification made by a welder or a welding operator for another supplier without the authorized inspector's specific approval. If approval is given, acceptance is limited to performance qualification on piping and the same or equivalent procedures must be used, wherein the essential variables are within the limits set forth in ASME (1986b).

(2) A performance qualification must be renewed as required by ASME (1986b).

e. <u>Testing Aerospace (Flight-Weight) Pressure Vessels</u>.

NSS/HP-1740.1 (1974) includes standards for using fracture control techniques to design, fabricate, test, and operate aerospace pressure vessels. Where technically possible, each pressure vessel should be designed to accommodate pressure qualification and verification testing. Tests should be performed to confirm the design, manufacturing processes, and service life. Qualification tests must be conducted on flight-quality (Class III) hardware. All aerospace pressure vessels must be subjected to an acceptance pressure qualification test, such as described in NASA JSCM 1710 (1977) or MIL-STD-1522 (1986).

D.3 INSPECTION

a. Comprehensive inspection and control are required of all materials and components to be used in LOX and GOX piping installations. A quality control program should be established that will satisfy all NASA and construction code requirements for all piping, components, materials, and test equipment. Material identification and certification is required for all piping and components used in fabrication and assemblies subjected to LOX and GOX operating conditions. No substitutions for the materials and components specified are permitted, except where the substitution retains code compliance and has written approval.

b. Required inspections of the piping, storage, and system components should be made according to methods specified by NASA. Personnel performing inspections shall be qualified.

c. Before and during installation, piping and components should be examined for the integrity of seals and other means provided to maintain the special cleanliness requirements for LOX and GOX.

d. All controls and protective equipment used in the test procedure including pressure-limiting devices, regulators, controllers, relief valves, and other safety devices should be tested to determine that they are in good mechanical condition, have adequate capacity, and will not introduce contaminants.

e. The flexible hoses used for oxygen transfer should be hydrostatic-tested before initial use and recertified by visual inspection at least every 5 years. The hydrostatic test pressure and date to which the flexible hose can be used should be permanently imprinted on an attached tag. Flexible hoses should be secured per NASA specifications. Hoses that are determined to be unserviceable shall be turned in and destroyed to prevent further use.

f. Following are common inspection methods. Applicable codes will provide specific requirements.

  (1) Visual safety examination to verify dimensions, joint preparation, alignment, welding or joining, supports, assembly, and erection.

  (2) Magnetic particle examination to detect cracks and other surface defects in ferromagnetic materials. The examination should be performed according to applicable codes.

  (3) Liquid penetrant examination to detect cracks and other surface defects in all types of metals. The examination should be performed according to applicable codes.

  (4) Radiographic examination as required by NASA engineering design specifications:

    (a) Random radiography

    (b) 100-percent radiography according to the method outlined in applicable codes. High-pressure oxygen systems require 100-percent radiography.

    (c) Ultrasonic examination of the material (including welded joints) for internal discontinuities and thickness. The examination should be according to applicable codes and is recommended for use on highly stressed weld joints.

g. <u>In-Service Inspection and Recertification</u>

(1) Ground-based Pressure Vessels and Systems.

(a) Inspection and recertification of ground-based pressure vessels should be according to NHB 1700.6 (1976). The procedures are illustrated and the pressure systems and service parameters are defined. Each component within the system is identified and placed into one of the following categories: pressure vessels, tanks, vacuum vessels, piping and piping system components, and others (ANSI/ASME B31.10 1986; ANSI/ASME B31.3 1993; ASME 1986a; NHB 1700.1 1993; 49 CFR 1986; Schmidt and Forney 1975; NASA JSCM 1710 1977; KMI 1710.1C latest revision; NHB 8060.1B 1981; NMI 1710.3C 1991).

(b) Recertification periods and intervening periods of inspection have been established for the components, based on variations in energy level with modifications to consider cyclic duty, corrosion, and location.

(2) Aerospace (Flight-Weight) Vessels.

(a) Inspection and recertification of aerospace vessels should be according to NSS/HP-1740.1 (1974).

(b) Fracture mechanics theory and test data should be used to establish proof-test conditions. The proof-test conditions should account for significant factors that could influence service life. Post-proof-test inspection is mandatory where the proof test does not provide, by direct demonstration, assurance of satisfactory performance over the specified service life. The fracture control plan should include required inspection intervals, periodic verification tests, and environmental conditioning for physical and corrosion protection (McHenry 1975; Stuhrke and Carpenter 1975).

h. <u>Test Records</u>.

(1) Test records should be kept on file for each system and piping installation. These records should include:

(a) The test data and identification of the system, component, and piping tested

(b) The test method (for example, hydrostatic, pneumatic, sensitive leak test)

(c) The test fluid, the test pressure, the test temperature, and the hold time at maximum test pressure

(d) The locations, types, and causes of failures and leaks in components and welded joints; the types of repair; and data on retest

(e) Written approval by NASA-assigned safety/design engineer

(f) Nondestructive evaluation data

(2) Records should also be kept concerning the cleaning procedures used. <u>Record Keeping</u> in Chapter 5 gives a complete description of the required information.

D.4 REFERENCE

ANSI/ASME B31.3. "Chemical Plant and Petroleum Refinery Piping." *American National Standard Code for Pressure Piping*, American National Standards Institute/American Society of Mechanical Engineering, New York, NY (1993, or latest revision).

ANSI/ASME B31.10. "Cryogenic Piping Systems." *American National Standard Code for Pressure Piping*, American National Standards Institute/American Society of Mechanical Engineering, New York, NY (1986).

ASME. "Pressure Vessels." *ASME Boiler and Pressure Vessel Code*, Sect. VIII, Div. 1, American Society of Mechanical Engineering, New York, NY (1986a, or latest revision).

ASME. "Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators." *ASME Boiler and Pressure Vessel Code*, Sect. IX, American Society of Mechanical Engineering, New York, NY (1986b, or latest revision).

CFR Title 49. *Transportation*. Code of Federal Regulations (1986, or latest revision).

CGA 341. *Tentative Standard Insulated Tank Truck Specification*. Second Ed. (plus addenda), Compressed Gas Association, Inc., Arlington, VA (1970, or latest revision).

KHB 1710.2A. *KSC Safety Practices Handbook*. Vol. 2, No. 41, NASA Kennedy Space Center, FL, July (1978, or latest revision).

KMI 1710.1C. *KSC Safety Program and Reliability and Quality Assurance Program*, NASA Kennedy Space Center, FL (latest revision).

McHenry, H. I. "Advances in Cryogenic Engineering." *Fracture Mechanics and Its Application to Cryogenic Structures*, Vol. 22, K. D. Timmerhaus, R. P. Reed, and A. F. Clark, Eds., New York: Plenum Press (1975): pp. 9-26.

MIL-STD-1522. *Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems*. Military Standard, United States Air Force, Washington, DC (1986, or latest revision).

NASA JSCM 1710. *Certification and Recertification of Ground-Based Pressure Vessels and Pressurized Systems*. NASA Johnson Space Center, TX, May (1977, or latest revision).

NHB 1700.1. *Basic Safety Manual*. Vol. Vl-B, NASA TM-85234, NASA, June (1993, or latest revision).

NHB 1700.6. *Guide for Inservice Inspection of Ground-Based Pressure Vessels and Systems*. NASA (1976, or latest revision).

NHB 8060.lB. *Flammability, Odor, and Offgassing Requirements and Test Procedures for Materials in Environments That Support Combustion*. NASA TM-84066, NASA, Office of Safety and Mission Quality (1981, or latest revision).

NMI 1710.3C. *Safety Program for Pressure Vessels and Pressurized Systems*. NASA Management Instruction, NASA (1991, or latest revision).

NSS/HP-1740.1. *NASA Aerospace Pressure Vessel Safety Standard*. NASA Technical Memorandum, NASA TM-81074, NASA (1974, or latest revision).

Roth, E. M. *Space-Cabin Atmospheres*. Part I, NASA SP-47 (1964): p. 13.

Schmidt, H. W., and D. E. Forney. *ASRDI Oxygen Technology Survey,* Vol. 9, NASA SP-3090, NASA (1975).

Schutt, H. U., R. H. Knapp, and W. R. Schmeal. "Ignition of Some Common Engineering Alloys - The Critical Energy Input Concept and Effects of Oxygen Pressure." *Corrosion/76,* National Association of Corrosion Engineers, Paper No. 14 (1976).

Stuhrke, W. F., and J. L. Carpenter, Jr. *Fracture Toughness Testing Data - A Technology Survey*. OR-13432, Martin Marietta Aerospace; NASA Contract NAS3-17640, NASA CR-134752 (1975).

APPENDIX E.

CODES, REGULATIONS, AND GUIDELINES LISTING

APPENDIX E

CODES, REGULATIONS, AND GUIDELINES LISTING

E.1 Increased safety of personnel and facilities requires compliance with existing regulations as well as adherence to accepted standards and guidelines.

E.2 Regulations are directives by official bodies authorized to create safety requirements enforceable by political jurisdiction. On the federal level, these include the DOT and the Occupational Safety and Health Administration (OSHA). State and local officials may also issue regulations.

a. Most regulations originate with the federal government and are contained in the Code of Federal Regulations (CFR). They are introduced by DOT, OSHA, or the U.S. Coast Guard.

b. 49 CFR (1986) designates the rule-making and enforcement bodies of the DOT. Current federal regulations that pertain to interstate shipping of LOX (cryogenic fluids) and compressed gases are listed in Table E-1.

c. Recommendations of other Government agencies and of interested parties are also considered.

d. Proposed regulations are usually published along with a description of the issues. Comments are sought and reviewed and consideration is given to oral arguments made by interested parties.

e. When final regulations are published, provisions are made for interested parties to petition the officials to amend or repeal these regulations.

E.3 The regulations are mandatory.

E.4 Various industrial and governmental organizations have published standards and guidelines for the construction of facilities and for safe procedures to be followed in the various phases of production, handling, and use of LOX.

E.5 Many of these published guidelines have been adapted by regulatory bodies such as the Department of Transportation, the Federal Aviation Administration, the Coast Guard, and the Office of Hazardous Materials.

E.6 Rules and guidelines are the technical information and safe practices and procedures developed by organizations (or groups representing such organizations) for their own needs, such as NASA and the Los Alamos National Laboratory. These organizations assign technically qualified personnel (or committees) to evaluate hazards and to develop information, rules, and guidelines for minimizing operational risks.

E.7 Codes and standards are the consensus safety documents developed by nonprofit trade associations, professional societies, or standards-making and testing bodies that serve industrial, commercial, and public needs. Examples are the American National Standards Institute and the National Fire Protection Association. They are empowered to include advisory and mandatory provisions that may be adopted by authorized regulatory agencies.

E.8 Numerous groups, societies, and associations are responsible for monitoring oxygen safety standards. These groups and their applicable documents follow.

a. American National Standards Institute (ANSI).

- ANSI B31.3, *American National Standard Code for Pressure Piping. Chemical Plant and Petroleum Refinery Piping*
- ANSI B31.5, *American National Standard Code for Pressure Piping, Refrigeration Piping*
- ANSI B31.8, *American National Standard Code for Pressure Piping, Gas Transmission and Distribution Piping Systems*
- ANSI B31.10, *American National Standard Code for Pressure Piping, Cryogenic Piping Systems*
- ANSI Z292.2 and Z292.3, *Systems and Consumer Sites* (equivalent to NFPA 50)

b. American Petroleum Institute (API).

- API 620, *Recommended Rules for Design and Construction of Large, Welded, Low-Pressure Storage Tanks*
- API 2510A, *Design and Construction of LNG Installations at Marine and Pipeline Terminals, Natural Gas Processing Plants, Refineries, and Other Industrial Plants*

c. American Society of Mechanical Engineers (ASME).

- ASME Boiler and Pressure Vessel Code, Sect. VIII, Div. 1 and 2, *Pressure Vessels*
- PTC 25.3-1976, *Safety and Relief Valves*

d. Compressed Gas Association (CGA).

- *Handbook of Compressed Gases*, Chapter 2: "Regulatory Authorities for Compressed Gases in United States and Canada; and Appendix A, Summary of Selected State Regulations and Codes Concerning Compressed Gases"
- Pamphlet C-7, *Guide to Preparation of Precautionary Labeling and Marking of Compressed Gas Containers*
- Pamphlet G-4, *Oxygen*
- Pamphlet G-5.2, *Standard for Liquefied Hydrogen Systems at Consumer Sites*
- Pamphlet P-1, *Safe Handling of Compressed Gases in Containers*
- Pamphlet S-1.l, *Safety Relief Device Standards - Cylinders for Compressed Gases*
- Pamphlet S-1.2, *Safety Relief Device Standards - Cargo and Portable Tanks for Compressed Gases*
- Pamphlet S-l.3, *Safety Relief Device Standards - Compressed Gas Storage Containers*
- Technical Standard CGA-341, *Insulated Tank Truck Specification for Cold Liquefied Gases*

e. Federal Government.

- 14 CFR 60-199, *Aeronautics and Space*
- 29 CFR 1910, *Occupational Safety and Health*
- 46 CFR 140-149, *Shipping*
- 49 CFR 101-179, *Transportation*

- Federal Motor Carrier Safety Regulations, *Federal Highway Administration*, Chapter 3 and Parts 390-397
- The Association of American Railroads, *Specifications for Tank Cars*
- IATA, *Air Transport Restricted Articles*

f. Insuring Associations.

- American Insurance Association
- Factory Mutual Organization
- Industrial Risk Insurers

g. National Fire Protection Association (NFPA).

- NFPA 53*, Manual on Fire Hazards in Oxygen-Enriched Atmospheres*
- NFPA 59A-1975, *Standard for Storage and Handling of Liquefied Natural Gas at Utility Gas Plants*
- NFPA Pamphlet 50, *Standard for Bulk Oxygen Systems at Consumer Sites*
- NFPA Pamphlet 68, *Explosion Venting*
- NFPA Pamphlet 69, *Explosion Prevention System*
- NFPA Pamphlet 70, *National Electric Code*
- NFPA Pamphlet 78, *Lightning Protection Code*
- NFPA Pamphlet 496, *Purged and Pressurized Enclosures for Electrical Equipment in Hazardous Locations*
- NFPA Volumes 1 and 2, *National Fire Codes*

h. Other Organizations (including U.S. Government Agencies).

- Arthur D. Little, Inc. (ADL)
- Battelle Columbus Laboratories (BCL)
- Bureau of Mines (BM)

- Chemical Propulsion Information Agency (CPIA)
- Department of Transportation (DOT)
  - Federal Aviation Administration (FAA)
  - Federal Highway Administration
  - Federal Railroad Administration
  - Hazardous Materials Regulation Board (HMRB)
  - Office of Pipeline Safety
  - Office of Hazardous Materials (OHM)
  - US Coast Guard (USCG)
- Occupational Safety and Health Administration (OSHA)
- National Aeronautics and Space Administration (NASA)
- National Bureau of Standards (NBS) (this organization is now the National Institute of Standards and Technology (NIST))
- University of California, Los Alamos National Laboratory (LANL)

i. Professional Societies.

- American Industrial Hygiene Association (AIHA)
- American Institute of Chemical Engineers (AIChE)
- American Society of Heating, Refrigeration, and Air Conditioning Engineering (ASHRAE)
- American Society of Mechanical Engineers (ASME)
- Institute of Electrical and Electronic Engineering (IEEE)
- Instrument Society of America (ISA)

j. Technical and Trade Groups.

- American Association of Railroads (AAR)
- American Gas Association (AGA)
- American Petroleum Institute (API)
- Compressed Gas Association (CGA)
- Manufacturers' Chemists Association (MCA)
- Manufacturers' Standardization Society (MSS)
- Manufacturers' Standardization Society of Valve and Fittings Industry (MSS)
- National Electrical Manufacturer's Association (NEMA)

k. Testing Standards and Safety Groups.

- American National Standards Institute (ANSI)
- American Society for Testing and Materials (ASTM)
- National Fire Protection Association (NFPA)
- National Safety Council
- Underwriters' Laboratories, Inc.

E.9 Most of these guidelines and standards are not mandatory, except those from Government organizations. Within NASA, some controls are mandatory for NASA employees such as NHB 1700.1 (1993). In addition, each NASA center has its own safety manuals, management instructions, etc. NHS/IH 1845.2 (1983) establishes requirements necessary to ensure safe entry and work in confined spaces and reviews the physical effects of varying oxygen levels and partial pressures.

Table E-l
Federal Regulations for Shipping Oxidizers Interstate

(For changes in existing federal code for transportation of cryogenic fluids proposed by Hazardous Materials Regulations Board, see Federal Register Docket No. H.M. 115, Notice No. 74-3.)

General Information: R. M. Graziano's tariff 30	Summary of DOT Hazardous Materials Regulations
Highway and Railroad: CFR Title 49 172, 173, 174, 175, 176, 177	Hazardous materials regulations; labeling shipping classification; oxygen, nitrogen, neon, fluorine, argon, carbon monoxide
CFR Title 49 173.02	General information on charging cylinders, fluoride shipped in cylinders equipped with valve protection and without safety relief devices
CFR Title 49 177.840, 177.848, 177.860	Loading and unloading requirements: procedures in accidents (includes procedures for leakage of poisons, fluorine, and carbon monoxide)
CFR Title 49 178.337, 178.340	Specifications for MC331 cargo tanks: design, construction, testing, and certification
Portable tanks: 49 CFR 178.245, 178.246, 179.247, 173.315, 173.32	Information on design, loading of compressed gases, and safety relief requirements.
Tank cars: 49 CFR 173.304, 173.314, 174.500 176.703	Allowable filling densities, labeling for liquids and gases, relief unloading requirements.
49 CFR 177.337, 177.340, 177.824	Carbo tank specifications and general design requirements for transportation of compressed gases.
49 CFR 179	Requirements for transportation of hazardous materials: thermal protection requirements; restraint systems: materials, insulation, venting, and safety relief requirements detailed
49 CFR 179.104, 179.105	Special tank-car tank requirements;
49 CFR 179.200 to 179.400	Safety relief valve requirements: includes Appendix A of the AAR Specifications for Tank Cars (AAR 204W)

Table E-l

Federal Regulations for Shipping Oxidizers Interstate (continued)

General Information: R. M. Graziano's tariff 30	Summary of DOT Hazardous Materials Regulations
Cylinder design: 49 CFR 100 to 199	Information on transportation of cylinders containing gas or liquified gases; specifications for 4L pressure vessels
49 CFR 173.301 173.302, 173.337 173.36, 178.37 178.45	General information on cylinder specifications, manifolding, filling, pressure limits, and safety relief
Pipelines: 49 CFR 191 to 195	Minimum standards for inspection, testing, and maintenance of natural gas and other gas pipelines; new standards published in 1977
Air transport 14 CFR 103 Tariff 6D	Limitations of shipment by air; air-transport-restricted articles and regulations

E.10 REFERENCES

CFR Title 49. *Transportation*. Code of Federal Regulations (1986, or latest version).

NHB 1700.1. *Basic Safety Manual*. Volume V1-B, NASA TM-85234, NASA, June (1993, or latest revision).

NHS/IH 1845.2. *NASA Health Standard for Entry Into and Work in Confined Spaces*. NASA (1983, or latest revision).

APPENDIX F.

SCALING LAWS, EXPLOSIONS, BLASTS, AND FRAGMENTS

APPENDIX F

SCALING LAWS, EXPLOSIONS, BLASTS, AND FRAGMENTS

F.1 SCALING LAWS

A comprehensive review of accidental explosions has been published in Strehlow and Baker (1975). It characterizes explosions by type, discusses the various scaling laws and summarizes nonideal blast wave behavior and the mechanisms by which blast waves cause damage. (Also see Stull 1977, Hannum 1984, and DOD 6055.9 1992.)

The classical experimental work on blast waves has mainly used either high explosives or nuclear weapons to produce the waves. The intermediate and far-field waves usually resemble those predicted from point-source theory quite closely, so either high explosives or nuclear explosions can be considered ideal.

a. A point-source blast wave is a blast wave conceptually produced by the instantaneous deposition of a fixed quantity of energy at an infinitesimal point in a uniform atmosphere. Essentially, a point-source wave propagating away from its origin creates three regions of interest. The first is the near-field wave in which pressures are so large that external pressure (or counterpressure) can be neglected. This region is followed by an intermediate region of extreme practical importance because the overpressure and impulse are sufficiently high to do significant damage. The intermediate region is followed in turn by a “far-field” region that yields to an analytic approximation such that the positive overpressure portion of the curve for large distances can be easily constructed from the overpressure time curve at one far-field position.

b. Scaling the properties of point-source blast waves is common practice and is subject to cube-root scaling (Sach’s law, see Strehlow and Baker (1975) and Hannum (1984)). Theoretically, a given pressure will occur at a distance from an explosion that is proportional to the cube root of the energy yield. Full-scale tests have shown this relationship between distance and energy yield to hold over a wide range of explosive weights. According to this law, if d_1 is the distance from a reference explosion of W_1 (in pounds) at which a specified static overpressure or dynamic pressure is found, for any explosion of W (in pounds) these same pressures will occur at a distance d given by

$$\frac{d}{d_1} = \left[\frac{W}{W_1}\right]^{\frac{1}{3}} \qquad \textbf{(F-1)}$$

Consequently, plots of overpressures for various weight of explosives can be superimposed on the curve for 0.45 kg (1 lb) of explosive if, instead of distance, the distance divided by the cube root of the weight is plotted against overpressure. This correlating parameter, $d/(W^{1/3})$, called “scaled distance,” is used to simplify the presentation of the blast wave characteristics.

c. Cube-root scaling can also be applied to arrival time of the shock front, positive-phase duration, and impulse; the distances concerned also are scaled according to the cube-root law. The relationships can be expressed in the form

$$\frac{t}{t_1} = \frac{d}{d_1} = \left[\frac{W}{W_1}\right]^{\frac{1}{3}}$$

$$\frac{I}{I_1} = \frac{d}{d_1} = \left[\frac{W}{W_1}\right]^{\frac{1}{3}} \qquad \textbf{(F-2)}$$

where:

t = arrival time or positive time of duration

t_1 = arrival time or positive-phase duration for reference explosion

I = impulse

I_1 = impulse for the reference explosion W_1

d = distance from origin

d_1 = distance from origin for reference explosion W_1

If W_1 is taken as 1 lb (0.45 kg), the various quantities are related as

$t = t_1W^{1/3}$ at a distance $d = d_1W^{1/3}$

$I = I_1W^{1/3}$ at a distance $d = d_1W^{1/3}$.

d. However, no general laws exist for scaling blast waves from nonideal explosions because not all the physical parameters affecting such explosions are known. The general concept of equivalence for a nonideal explosion is not well understood. Usually the near-field overpressures are much lower than those of a point-source explosion that produces the equivalent far-field overpressure, but it is not obvious exactly what the relationship between near-field and far-field behavior should be or how this relationship differs with the type of accidental explosion. It is also not obvious how to evaluate the blast damage of any particular type of accidental explosion or how much the damage depends on the type of explosion.

F.2 EXPLOSIONS

a. Explosions in Buildings.

(1) Explosions in buildings are of three main types. The severity of damage increases from Type 1 to Type 3.

(a) Type 1. Some combustible material spills, resulting in a slow deflagration wave or flashback fire that causes a relatively slow pressure buildup in the building.

(b) Type 2. A piece of equipment explodes, producing a blast wave inside the building that either damages the structure or is relieved by venting.

(c) Type 3. A leak occurs and the combustible mixture that forms detonates.

(2) In a detonation, the blast wave behavior and the damage patterns are determined primarily by the behavior of the detonation and are only modified by the confinement. For the previously discussed explosions, the degree of confinement or the bursting pressure of the vessel or building determines the nature of the blast wave and the damage patterns generated.

b. Tank Ruptures.

(1) A rupture followed by combustion is a very special type of explosion. It occurs when a tank of liquefied fuel under pressure is heated by an external fire until it vents and torches. For an explosion to occur, the heating of the venting tank must be sufficiently intense to cause the internal pressure to rise above the tank's bursting pressure, even with venting. This type of explosion has three distinct damage-producing effects:

(a) A blast wave caused by internal pressure relief

(b) A fireball caused by subsequent massive burning of the tank's contents in the air

(c) Large fragments scattered for long distances because of the ductile nature of the tank's rupture and the rocketing of pieces by the pressure of the tank contents

(2) Because propellant explosions are not considered as point sources, the comparison between ideal and accidental explosions is inexact; the

concept of TNT equivalence, which is widely used in safety studies, is also very inexact and may be quite misleading.

Recent studies show that no single TNT equivalent can be used to describe the blast generated by a rupturing pressure vessel. However, the blast pressures combined with the positive shock-wave durations yielded positive shock wave impulse values, whose impulse-distance relationship was similar in slope to that for TNT. For large, high-pressure vessels, the impulses from tank rupture and those for TNT equivalent are not significantly different quantitatively. A general comparison of blast and fragment parameters generated by tank rupture and an equivalent TNT charge showed that static (side-on) pressures were higher for TNT above 41 to 69 kPa (6 to 10 psi) and lower for TNT at pressures below these values. Peak reflected (face-on) tank pressures showed a similar relationship to face-on TNT pressures. Positive shock wave durations were longer for tank rupture than for TNT. Impulse values, both face-on and side-on, were similar for TNT and tank rupture. Damage, depending on distance, may be greater for tank rupture. Tank-rupture fragments were larger than would be expected from a cased TNT charge (all above information from Baker et al. 1975).

Fragment velocities would be higher for a cased TNT charge than for tank rupture (Baker et al. 1974, 1978). The term “strength” refers to several characteristics of a blast wave that relate to the wave’s potential for causing damage. These characteristics are (Kinney and Graham 1985):

(a) Side-on overpressure. The overpressure in the blast wave, which would be observed were there no interaction between the blast and the structure.

(b) Duration. After the wave front passes, the static pressure falls and actually drops slightly below atmospheric pressure. However, it is the duration of the positive phase (the time required to drop the peak overpressure to atmospheric pressure) that is of greatest significance in causing damage.

(c) Blast-wind velocity. Behind the wave front the air moves at considerable speed in the same direction as the wave. For example, a peak overpressure of 34.5 kPa (5 psi) will be accompanied by a 72-m/s (236-ft/s) wind (Kinney and Graham 1985).

(d) Stagnation overpressure. The combined effects of side-on overpressure and the blast wind describe the load on the front face after the reflected shock has died out.

(e) Reflected overpressure. If a blast wave strikes a surface (such as a wall) at normal incidence, the airflow will stop, and a shock wave will reflect backward from the surface. Behind the reflected shock, the surface will briefly be subjected to the peak reflected overpressure (sometimes called the face-on overpressure), which the instantaneous dynamic loads impose on the front face of the structure.

(f) Positive phase impulse. The area under the positive phase of the side-on overpressure curve. Impulse has dimensions of force-time product and is obtained graphically given the side-on overpressure curve as a function of time.

c. Ground-Handling System Explosions.

(1) The hazards from accidental explosions in propellant ground-handling systems are similar in many respects to the hazards from such explosions in flight vehicles. These accidents cause damage by air-blast loading, fragment or appurtenance impact, radiation from fireballs, or fire from the ignition of combustible materials (Strehlow and Baker 1975*;* DOD 6055.9 1992; Hannum 1984; AMCP-706-180 1972; Strehlow, Savage, and Vance 1972).

(2) Both flight and ground systems can fail by material fatigue caused by overstressing. However, many of the possible causes of flight vehicle explosions such as loss of thrust during launch, guidance system failure, or rupture of a bulkhead separating a fuel from an oxidizer, are inapplicable for ground-handling systems. Conversely, transportation accidents followed by explosions are not likely to occur in flight.

(3) Because ground-handling systems have fewer weight constraints and therefore higher safety factors than do flight vehicles, the nature of the hazards is different. Also, the total energy stored in compressed gases or the total chemical energy stored in fuels and oxidants can be much greater than for many flight systems.

(4) Many more accidental explosions involving fuels and compressed fluids have occurred in ground-handling systems than in flight vehicles. These include

(a) Simple pressure-vessel failure because of fatigue or flaw growth

    - (b) Vessel failure induced by impact during a transportation accident
    - (c) Vessel failure by overpressure because of overheating
    - (d) Vessel and pipeline failure by overpressure, corrosion, or erosion
    - (e) Fuel leakage followed by a vapor cloud explosion

  - (5) The workbooks and handbooks included in the references (Baker et al. 1974; AMCP-706-180 1972) provide methods for predicting blast and fragment characteristics and effects for a wide range of possible explosion accidents in ground and flight systems. The material in the workbooks allows estimation of

    - (a) Explosive energy yield or energy release
    - (b) Characteristics of blast pressure waves generated by spherical and nonspherical explosions
    - (c) Effects of pressure waves on certain classes of targets
    - (d) Characteristics of fragments generated by ground equipment explosions, including massive vessel parts that rocket
    - (e) Effects of fragment impact, including effects of fragment revetments on blast waves

    Various safety factors are included in the prediction methods.

F.3 BLASTS

The primary source of blasts from accidental explosions in propellant ground handling and transportation systems is the rupture of compressed fuel or oxidizer cylinders, vessels, or lines.

- a. The various formulas for total energy release for compressed gas bursts are reviewed in Baker et al. (1978). These include:

  - (1) The explosive yield from compressed gas pressure burst

$$E = \left[\frac{p_1 - p_a}{g_1 - 1}\right] V_1 \qquad \textbf{(F-3)}$$

where:

E = blast yield (energy)
P_1 = initial absolute pressure in the vessel
P_a = absolute pressure of the outside atmosphere
g_1 = ratio of specific heats for the gas in the vessel
V_1 = initial volume of the vessel

(2) An estimate based on isentropic expansion from initial burst pressure to atmospheric pressure

$$E = \frac{p_1 V_1}{g_1 - 1}\left[1 - \left[\frac{p_a}{p_1}\right]^{\frac{(g_1 - 1)}{g}}\right] \qquad \textbf{(F-4)}$$

(3) A lower limit on the energy released, for example by constant-pressure addition of energy to the explosion source region at a release rate so slow that it does not produce a blast wave

$$E = p_a (V_f - V_1) \qquad \textbf{(F-5)}$$

where:

V_f = the final volume occupied by the gas that was originally in the vessel

b. The three equations are given in descending order of total blast energy. The blast yield is considered to lie between Equations F-4 and F-5. Equation F-3 gives slightly higher values than does Equation F-4, but both are considered very conservative (Baker et al. 1978).

c. The equations given for blast yields are based on the assumption that all the energy that can drive a blast wave does so, depending only on the energy release rate. For real vessels, some energy must be absorbed by the vessel as it fractures, both in the fracturing process itself and in accelerating the vessel fragments to their maximum velocity.

d. Baker et al. (1978) provide methods for estimating the velocity and kinetic energy of the vessel fragments. Also, the workbooks review the characteristics of blast waves from liquid propellant explosions and spherical gas vessel bursts and their similarities to and differences from waves from condensed high explosives such as TNT.

e. To estimate blast wave properties, dimensionless parameters are used (Baker et al. 1978). Prediction curves for scaled values of these parameters are given as functions of $\overline{R}$, a dimensionless distance. The properties of interest are p_s, side-on overpressure, t_a, time-of-arrival of side-on overpressure peak, T_s, time-of-duration of the positive phase of the side-on overpressure, and I, the positive phase impulse. The dimensionless parameters, designated with a bar on top, are defined as:

$$\overline{R} = \frac{R p_a^{\frac{1}{3}}}{E^{\frac{1}{3}}}$$

$$\overline{P} = \frac{p_s}{p_a}$$

$$\overline{t_a} = t_a A_a \frac{p_a^{\frac{1}{3}}}{E^{\frac{1}{3}}}$$

$$\overline{T_s} = \frac{T_s A_a p_a^{\frac{1}{3}}}{E^{\frac{1}{3}}}$$

$$\overline{I} = \frac{I_s A_a p_a^{\frac{2}{3}}}{E^{\frac{1}{3}}}$$

where:

p_a and E are as defined for Equation F-3
R = radius of the blast wave (standoff distance)
p_s = side-on overpressure
t_a = arrival time of side-on overpressure peak
A_a = ambient sound velocity
T_s = duration time of positive phase of side-on overpressure
I_s = positive-phase impulse of side-on overpressure

f. Scaling laws for nonideal explosions are not known exactly now, but they can be easily developed once the physics of such explosions are well known. They will likely be variants on Sach's law (Strehlow and Baker 1975; Hannum 1984). Theoretical work and some test results suggest that at distances at which the pressure levels are over approximately 103.4 kPa (15 psi) for LOX-liquid hydrogen explosions, the TNT equivalence in terms of peak pressure is approximately 0.07; for pressure levels from 101.4 to 0.69 kPa (14.7 to 0.1 psi), the TNT equivalence is approximately 1; and below 0.69 kPa (0.1 psi) it is approximately 2.0. Interpreting these numbers means that at 101.4 kPa (14.7 psi) and above, it takes approximately 6.5 kg (14.3 lb) of LOX and liquid hydrogen to generate the same pressure-distance relationship as does 0.45 kg (1 lb) of TNT; approximately 0.45 kg (1 lb) of LOX and liquid hydrogen between 101.4 to 0.69 kPa (14.7 psi to 0.1 psi); and only 0.23 kg (0.5 lb) of LOX and liquid hydrogen at less than 0.69 kPa (0.1 psi). If blast wave characteristics can be defined for accidental explosions, correlation with damage effects on buildings, vehicles, humans, etc., can be made from existing methods and data in the literature (Hannum 1984; Baker et al. 1978; AMCP-706-180 1972).

g. Fragmentation patterns from accidental explosions and the damaging effects of these fragments are difficult to predict. The blast waves produced by the explosion of liquid propellants that are accidentally mixed are usually unreproducible and difficult to model adequately. Extensive studies show that liquid-propellant explosions differ from TNT explosions in a number of ways, so the concept of TNT equivalence is far from exact.

F.4 FRAGMENTS

a. The fragments generated by bursting oxygen high-pressure gas or liquid vessels can vary widely in size and shape, depending on the total energy released, the release rate, and the pressure vessel design. A vessel that bursts because of a seam failure or crack propagation may generate only one fragment. This fragment can be propelled by the release of the contents. At the other extreme, a vessel whose contents explode can produce many small fragments.

b. In similar explosions, fewer fragments are generated in ground systems than in flight systems, primarily because of differences in pressure vessel materials and construction. Analytical predictions of fragment velocity distributions, fragmentation patterns, and free-flight ranges for lifting and rocketing fragments are given in Moore (1967).

c. Results of fragmentation studies providing fragment characteristics, mass, shape, and range as they relate to estimated blast yields of exploding liquid-propellant flight system tanks are included in Strehlow and Baker (1975); Baker et al. (1974, 1978); Hannum (1984); AMCP-706-180 1972; Strehlow, Savage, and Vance (1972); Moore (1967); Kuchta (1973); and Farber (1973). Methods of determining yields of blast behavior are described in Hannum (1984); Baker et al. (1978); Kuchta (1973); and Farber (1973).

d. Methods for predicting velocities and ranges of fragments from bursting vessels are available. The fragment range information is based on data from various explosion sources. Data are included in Strehlow and Baker (1975); KHB 1710.2A (1978); Hannum (1984); AMCP-706-180 1972; and Strehlow, Savage, and Vance (1972).

e. The fragment range and mass distributions for various explosion sources are also included in Strehlow and Baker (1975); KHB-1710.2A (1978); Hannum (1984); AMCP-706-180 (1972); and Strehlow, Savage, and Vance (1972).

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APPENDIX G.

ABBREVIATIONS AND ACRONYMS

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AAR	American Association of Railroads
AGA	American Gas Association
AIChE	American Institute of Chemical Engineers
AIHA	American Industrial Hygiene Association
AIT	Autoignition Temperature
Al	Aluminum
$A1_2O_3$	Aluminum oxide
ANSI	American National Standards Institute
API	American Petroleum Institute
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning
ASME	American Society of Mechanical Engineers
ASRDI	Aerospace Safety Research and Data Institute
ASTM	American Society for Testing and Materials
BCL	Battelle Columbus Laboratories
BM	Bureau of Mines
CDR	Critical Design Review
CFC	Chlorofluorocarbons
CFR	Code of Federal Regulations
CGA	Compressed Gas Association
CHEMTREC	Chemical Transportation Emergency Center
CPIA	Chemical Propulsion Information Agency
CTFE	chlorotrifluoroethylene
Cr	Chromium
Cr_2O_3	Chromium Oxide
DI	Deionized
DOD	Department of Defense
DODESB	Department of Defense Explosives Safety Board
DOE	Department of Energy
DOT	Department of Transportation
EMU	Extravehicular Mobility Unit
EPR	Emergency Procedures Review
FAA	Federal Aviation Administration
FeO	Iron Oxide
FEP	Fluorinated Ethylene Propylene

FMEA	Failure Modes and Effects Analysis
FMIEA/CIL	Failure Modes and Effects Analysis/Critical Item List
GOX	Gaseous Oxygen
GN_2	Gaseous Nitrogen
HCFC	Hydrochlorofluorocarbon
HMRB	Hazardous Materials Regulation Board
IEEE	Institute of Electrical and Electronic Engineering
IPA	Isopropyl alcohol
JSC	Johnson Space Center
KSC	Kennedy Space Center
LANL	Los Alamos National Laboratory
LeRC	Lewis Research Center
LOI	Limiting Oxygen Index
LOX	Liquid Oxygen
MAPTIS	Materials and Processes Test Information System
MAWP	Maximum Allowable Working Pressure
MCA	Manufacturers' Chemists Association
M&P	Materials and Processes
MSDS	Material Safety Data Sheet
MSFC	Marshall Space Flight Center
MSS	Manufacturers' Standardization Society
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Standards (this organization is now the National Institute of Standards and Technology (NIST))
NEMA	National Electrical Manufacturer's Association
NFPA	National Fire Protection Association
NHB	NASA Handbook
NHS	NASA Health Standard
NiO	Nickel Oxide
NMI	NASA Management Instruction
NSS	NASA Safety Standard
NSTS	National Space Transportation System
NTP	Normal Temperature and Pressure
NTSB	National Transportation Safety Board
OHM	Office of Hazardous Materials
ORI	Operational Readiness Inspection
OSHA	Occupational Safety and Health Administration

PDR	Preliminary Design Review
PTFE	Polytetrafluoroethylene (Teflon®)
QA	Quality Assurance
RP-1	Kerosene
S&A	Safe and Arm
SiO_2	Silicone Oxide
SOP	Standard Operating Procedure
SR	Safety Review
SRM	Solid Rocket Motor
SRM&QA	Safety, Reliability, Maintainability & Quality Assurance
SSA	System Safety Analysis
SSA/SR	System Safety Analysis/Safety Review
TNT	Trinitrotoluene
TRR	Test Readiness Review
USCG	US Coast Guard
WSTF	White Sands Test Facility

APPENDIX H.

GLOSSARY

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GLOSSARY

ACCEPTANCE TEST. A standard test that leads to certification of a component or system.

ADIABATIC. A process by which the system changes state without thermal energy exchange between the system and the surroundings.

ADIABATIC COMPRESSION. Mechanical work transferred to a system, where the energy goes into increasing the internal energy of the material for a static system or increasing the enthalpy for a dynamic system. If the process is also reversible (in the thermodynamic definition), this change is also isentropic.

AUTOIGNITION. The phenomenon in which a mixture of gases, vapors, mists, dusts, or sprays ignites spontaneously with no external ignition source. It is frequently called “autogenous ignition” or “spontaneous ignition.”

AUTOIGNITION TEMPERATURE (AIT). The lowest temperature at which material will spontaneously ignite (autogenous ignition).

BLAST WAVE. A shock wave in air, which has degenerated as the shock front becomes less dense.

BLAST YIELD. Energy released in an explosion, inferred from measurements of the characteristics of the blast waves generated by the explosion.

BUDDY SYSTEM. A system used in hazardous operations where one person performs the necessary task while another person standing nearby is fully prepared (clothing, training, etc.) to remove the primary person from the area in case of incapacitation.

BURN VELOCITY. The velocity of propagation of a flame through a flammable material. Burn velocities are absolute velocities measured relative to the velocity of the unburned material; flame speeds are measured in laboratory coordinates and are not absolute.

BURST PRESSURE. The pressure at which a gas storage vessel or burst disk bursts or fails.

CARGO TANK. Any container designed to be permanently attached to any motor vehicle or other highway vehicle and in which any compressed gas is to be transported. The term “cargo tank” does not include any tank used solely to supply fuel for the vehicle or containers fabricated for cylinders.

CATASTROPHIC FAILURE. One that causes complete and irreparable loss of function of a component or system. Structural failure of a pressure vessel is a catastrophic failure.

CERTIFICATION. The documentation that qualifies a vessel or system to operate in the intended service.

CLEANLINESS LEVEL. An established maximum of allowable contaminants based on sized distribution, or quantity on a given area or in a specific volume. Also, an absence of particulate and nonparticulate matter visible under visible light and/or UV illumination.

COLD INJURY. An injury caused by freezing of skin tissue caused by exposure to a very cold atmosphere, surface, or cryogenic. Also referred to as a “cryogenic burn.”

COMBUSTIBLE LIQUID. A liquid with a flash point at or above 333 K (140 °F).

COMBUSTIBLE SOLID. A solid that can burn in the presence of an oxidizer.

CONFINED SPACES. A confined space is not normally occupied by personnel. It has limited or restricted openings for entry and exit, may lack adequate ventilation, and may contain or produce “dangerous air contamination;” therefore, it may not be safe for entry.

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

CRITICAL SURFACE. A surface that requires precision cleaning.

CRYOGEN. Substances which boil at extremely low temperatures, usually at or below -150°C.

CRYOGENIC PROPELLANTS. Propellants that are gases at ambient temperature and pressure, but have been liquified by chilling to or below -150°C and pressurization.

EARTH-STORABLE PROPELLANTS. Propellants that are in the liquid or solid state at ambient temperature and pressure.

ELECTRICAL ARC/SPARK TEST. In this test, an electrical arc or spark is used to determine the susceptibility of materials to ignition in oxygen. Arc energy input and oxygen pressure are the major variables.

EXPLOSION. The rapid equilibration of pressure between the system and the surroundings. The pressure of the gas is dissipated as a shock wave. Explosions may occur through mechanical failure of vessels containing high-pressure fluids or through rapid chemical reactions producing large volumes of hot gases.

EXPLOSIVE. Any chemical compound or mechanical mixture that when ignited, undergoes a very rapid combustion or decomposition releasing large volumes of heated gases that exert pressure on the surrounding medium.

EXPLOSIVE YIELD. Energy released in an explosion. It is often expressed as a percent or fraction of the energy that would be released by the same mass of a standard high explosive such as TNT.

FAILURE MODE AND EFFECTS ANALYSIS (FMEA). A systematic, methodical analysis performed to identify and document all identifiable failure modes at a prescribed level and to specify the resultant effect of the modes of failure.

FIRE RESISTANT. Materials that will resist burning when contacted by fuels or oxidizers, but will eventually burn after continuous contact and exposure to an ignition source.

FLAMMABLE LIQUID. Any liquid with a flash point below 300 K (80 °F) as determined by standard methods (ASTM D 56 1985; ASTM D 92 1985).

FLASH POINT. The lowest temperature, corrected to 101.3 kPa (1.00 atm), at which an ignition source under specified conditions, causes the material vapor to ignite momentarily.

FAILURE RATE. The number of failures of an item per unit measure of use (cycles, time, miles, events, etc., as applicable for the item).

FLOW CAPACITY. The flow capacity of a pressure-relief device is determined at the flow rating pressure, expressed in cubic feet per minute of free air discharge.

FRAGMENTATION. The breaking up of the confining material when an explosion takes place. Fragments may be complete items, subassemblies, pieces of material, or pieces of equipment or buildings containing the flame.

GEYSERING. Geysering occurs in vertical systems with a tank and a long feedline from the tank filled with cryogenic oxygen. Heat transfer into the line causes gas bubbles to form and begin rising in the line. As the bubbles rise, they coalesce to form larger bubbles. In a line long with respect to its diameter, the result is an expanding vapor bubble of sufficient size to expel the liquid above it into the tank with a force large enough at times to rupture the tank or to damage internal tank components such as baffles, screens, or level sensors. When the liquid subsequently reenters the line, it can cause large water hammer forces with accompanying system damage.

HAZARD. A situation (or potential event) that may result in death or injury to personnel, or damage to equipment. It includes the effects of fire, flash, explosion, shock, concussion, fragmentation corrosion or toxicity.

HAZARDS ANALYSIS. A process that analyzes all possible ignition sources and the flammability of all materials present.

HAZARDOUS CHEMICAL. Any chemical hazardous by nature (corrosive, flammable, radioactive, toxic, etc.)

HEAT OF COMBUSTION/HEAT OF REACTION. The difference in the enthalpy of the products and the enthalpy of reactants for a given temperature and pressure.

HIGH PRESSURE. NMI 1710.3C (1991) indirectly defines high-pressure systems as those with pressures greater than or equal to 1 MPa (150 psi).

HYDROSTATIC TEST. A test performed on a pressure vessel or system in which the vessel or system is filled with a liquid (usually water) and pressurized to a designated level as prescribed in the applicable code.

IGNITION ENERGY. The energy required to initiate flame propagation through a flammable mixture. The minimum ignition energy is the minimum energy required to ignite a particular flammable mixture at a specified temperature and pressure.

IGNITION TEMPERATURE. The temperature required to ignite a substance.

MAXIMUM ALLOWABLE STRESS VALUE. The maximum unit stress permissible for a specific material, used in the design formulas.

MAXIMUM ALLOWABLE WORKING PRESSURE (MAWP). The maximum allowable operating pressure rating of pressure vessels manufactured and operated in accordance with ASME VIII (ASME 1986).

MAXIMUM USE PRESSURE. The maximum pressure to which a material or system can be subjected, based on reasonably foreseeable malfunctions, operation errors, or process upsets.

NONCOMBUSTIBLE MATERIAL. A material (as defined in NFPA 220 1985), which, in the form and under the conditions anticipated, will not ignite, burn, support combustion, or release flammable vapors when subjected to fire or heat. Materials reported as noncombustible, when tested in accordance with ASTM E 136-79 (1985), shall be considered noncombustible materials.

NET POSITIVE SUCTION PRESSURE (NPSP). That pressure (above atmospheric) that must be supplied to the suction side of a turbopump to prevent cavitation.

NONMETAL. Any material not containing metal, such as polymers. However, for the purposes of this document, “nonmetal” does not include ceramics, although they are classified as nonmetals.

OPERATING or WORKING TEMPERATURE. The temperature maintained in the part under consideration during normal operation.

OPERATING PRESSURE. The pressure of a vessel at which it normally operates. This pressure must not exceed the maximum allowable working pressure.

OVERPRESSURE. A blast wave above atmospheric pressure, resulting from an explosion. Overpressures are expressed as absolute pressures (kPa or psia), or as the increase in pressure above ambient (kPa or psig).

OXYGEN DEFICIENCY. An atmosphere containing oxygen at a concentration of less than 19.5 volume percent as measured by an oxygen-measuring device.

OXYGEN-ENRICHED. Several definitions of oxygen-enrichment are found in the literature. Oxygen-enriched atmospheres have been specified for oxygen concentrations greater than 21 volume percent (NFPA 53 1994), 23.5 volume percent (29 CFR 1910.146 1986), and 25 volume percent or a partial pressure of oxygen (PO_2) equal to or greater than 190 mm Hg under ambient pressure (ASTM G 63-92 1992). Oxygen-rich atmospheres expand the range of flammability, lower the ignition energy, and cause combustible materials to burn violently when ignited.

OXYGEN INDEX. Minimum concentration of oxygen in an ascending flow of oxygen and nitrogen at one atmosphere pressure that will just sustain combustion of a top-ignited, vertical test specimen (ASTM D 2863 1991).

OXYGEN MANIFOLD, HIGH-PRESSURE. A manifold connecting oxygen containers, having a DOT service pressure exceeding 250 psig (1.7 MPa).

OXYGEN MANIFOLD, LOW-PRESSURE. A manifold connecting oxygen containers, having a DOT service pressure not exceeding 250 psig (1.7 MPa).

PARTICULATE. A finely divided solid of organic or inorganic matter, including metals. These solids are usually reported as the amount of contaminant, by the number of a specific micrometer size present.

PNEUMATIC TEST. A test performed on a pressure vessel or system in which air or gas is introduced and pressurized to a designated level as prescribed in the applicable code.

PORTABLE TANKS/CONTAINERS. Any tank or container as defined by the DOT, designed primarily to be temporarily attached to a motor vehicle, other vehicle, railroad car other than tank car, or marine vessel, and equipped with skids, mountings, or accessories to facilitate mechanical handling of the container, in which any compressed gas is to be transported in.

PRECISION CLEANING. Final or fine cleaning accomplished in a controlled environment to achieve some cleanliness level.

PRECISION CLEANLINESS. A degree of cleanliness that requires special equipment and techniques for determination. Precision cleanliness levels normally include limits for particulate size and quantities.

PRECLEANING. All cleaning activities and procedures required to prepare items for precision cleaning.

PRESSURE VESSEL. Any certified vessel used for the storage or handling of gas or liquid under positive pressure.

PROMOTERS. Devices such as igniters, which by burning are intended to cause ignition of an adjacent surface.

PROOF TEST. A pressure test performed to establish the maximum allowable working pressure of a vessel, system, or component thereof: (1) when the strength cannot be computed with satisfactory accuracy; (2) when the thickness cannot be determined by means of the design rule of the applicable code or standard; or (3) when the critical flaw size to cause failure at the certified pressure cannot be identified by other nondestructive test methods.

PROPELLANT. Fuels and oxidizers used in jet and rocket engines. When ignited in a combustion chamber, the propellants change into gases with a large increase in pressure, thus providing the energy for thrust.

PV PRODUCT. The product required for ignition (where ***P*** is the normal load divided by the rubbing area and *v* is the relative linear velocity between the samples). Determined by a frictional heating test.

PYROLYSIS. The chemical decomposition of a material by thermal energy.

RADIANT HEAT. Heat that requires no medium to travel through, unlike conduction (direct and contact) or convection (transport of heat by fluid movement).

RECERTIFICATION. The procedure by which a previously certified vessel or system, by appropriate tests, inspections, examinations, and documentation, is qualified to continue or be returned to operations at the designed pressure.

RISK. The likelihood of occurrence of a specific consequence or loss, caused by faults or failures, or external events. For example, the number of fatalities deriving from possible failures in a given hazardous activity is the risk. When qualified, risk is often also used to mean the product of the likelihood, expressed as a probability, and the magnitude of a given loss, or the sum of such products over all possible losses, in other words, the expected loss. Individual risk is the probability of a given consequence (such as a fatality) occurring to any member of the exposed population. Group or social risk is the probability that a given number of individuals will suffer a given consequence.

RISK ASSESSMENT. Estimation of the potential severity of a hazard, and a determination of probability of that hazard contributing to a mishap (similar to the OSHA classification system).

RISK MANAGEMENT. The management of risks by identifying their sources, evaluating the magnitudes and likelihoods of their potential consequences and possible losses, and making decisions on their acceptability or need for mitigation. If mitigation needs to be made, the process includes defining and evaluating alternative mitigating measures, selecting the measures for implementation, and assuring that the selected measures provide the results intended.

SAFETY FACTOR. The ratio, allowed for in design, between the ultimate breaking strength of a member, material, structure, or equipment and the actual working stress or safe permissible load placed on it during ordinary use.

SET PRESSURE. The pressure marked on a safety relief valve at which system relief pressure begins.

SHOCK SENSITIVITY. The ease with which a material may be ignited by a mechanical impact, producing a deflagration and/or detonation.

SINGLE-POINT FAILURE. A single item or component that will cause an undesired event by failing.

SITUATIONALLY FLAMMABLE. A material that is flammable in oxygen in the use configuration and conditions (for example, temperature and pressure).

STORAGE CONTAINER. Any container designed to be permanently mounted on a stationary foundation and used to store any compressed gas.

SYSTEM SAFETY PROGRAM PLAN (SSPP). A description of the methods to be used by the contractor to implement the tailored requirements of a standard, including organizational responsibilities, resources, methods of accomplishment, milestones, depth of effort, and integration with other program engineering and management activities and related systems.

TANK. Any vessel used for the storage or handling of liquids where the internal pressure depends only on liquid head or a combination of liquid head and vapor pressure.

VAPOR EXPLOSION. The sudden vaporization of a superheated liquid, which can produce a shock wave.

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