Designation: G88 − 13

Standard Guide for Designing Systems for Oxygen Service[1]

1. Scope

1.1 This guide applies to the design of systems for oxygen or oxygen-enriched service but is not a comprehensive document. Specifically, this guide addresses system factors that affect the avoidance of ignition and fire. It does not thoroughly address the selection of materials of construction for which Guides G63 and G94 are available, nor does it cover mechanical, economic or other design considerations for which well-known practices are available. This guide also does not address issues concerning the toxicity of nonmetals in breathing gas or medical gas systems.

NOTE 1—The American Society for Testing and Materials takes no position respecting the validity of any evaluation methods asserted in connection with any item mentioned in this guide. Users of this guide are expressly advised that determination of the validity of any such evaluation methods and data and the risk of use of such evaluation methods and data are entirely their own responsibility.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory requirements prior to use.*

1.3 This standard guide is organized as follows:

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[1] This guide is under the jurisdiction of ASTM Committee G04 on Compatibility and Sensitivity of Materials in Oxygen Enriched Atmospheres and is the direct responsibility of Subcommittee G04.02 on Recommended Practices.

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2. Referenced Documents

2.1 *ASTM Standards:*[2]

G63 Guide for Evaluating Nonmetallic Materials for Oxygen Service
G72 Test Method for Autogenous Ignition Temperature of Liquids and Solids in a High-Pressure Oxygen-Enriched Environment
G74 Test Method for Ignition Sensitivity of Nonmetallic Materials and Components by Gaseous Fluid Impact
G93 Practice for Cleaning Methods and Cleanliness Levels for Material and Equipment Used in Oxygen-Enriched Environments
G94 Guide for Evaluating Metals for Oxygen Service
G128 Guide for Control of Hazards and Risks in Oxygen Enriched Systems
G175 Test Method for Evaluating the Ignition Sensitivity and Fault Tolerance of Oxygen Pressure Regulators Used for Medical and Emergency Applications

NOTE 2—The latest versions of these referenced documents should be consulted.

2.2 *ASTM Adjuncts:*[3]

ADJG0088 Oxygen Safety Videotape and Separate

2.3 *ASTM Manual:*

Manual 36 Safe Use of Oxygen and Oxygen Systems: Guidelines for Oxygen System Design, Materials Selection, Operations, Storage, and Transportation

2.4 *NFPA Standards*[4]

NFPA 50 Standard for Bulk Oxygen Systems at Consumer Sites
NFPA 53 Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres

2.5 *Compressed Gas Association Documents:*

CGA E-4 Standard for Gas Pressure Regulators
CGA G-4.1 Cleaning Equipment for Oxygen Service
CGA G-4.4 Oxygen Pipeline and Piping Systems
CGA G-4.6 Oxygen Compressor Installation and Operation Guide
CGA G-4.7 Installation Guide for Stationary Electric Motor Driven Centrifugal Liquid Oxygen Pumps
CGA G-4.8 Safe Use of Aluminum Structured Packing for Oxygen Distillation
CGA G-4.9 Safe Use of Brazed Aluminum Heat Exchangers for Producing Pressurized Oxygen
CGA G-4.11 Reciprocating Oxygen Compressor Code of Practice
CGA G-4.13 Centrifugal Compressors for Oxygen Service
CGA P-8.4 Safe Operation of Reboilers/Condensers in Air Separation Units
CGA P-8 Safe Practices Guide for Air Separation Plants
CGA P-25 Guide for Flat Bottomed LOX/LIN/LAR Storage Tank Systems
CGA PS-15 Toxicity Considerations of Nonmetallic Materials in Medical Oxygen Cylinder Valves
CGA SB-2 Definition of Oxygen Enrichment/Deficiency Safety Criteria

2.6 *European Industrial Gases Association Documents:*

EIGA/IGC 4 Fire Hazards of Oxygen and Oxygen Enriched Atmospheres
EIGA/IGC 10 Reciprocating Oxygen Compressors For Oxygen Service
EIGA/IGC 13 Oxygen Pipeline and Piping Systems
EIGA/IGC 27/12 Centrifugal Compressors For Oxygen Service
EIGA/IGC 33 Cleaning of Equipment for Oxygen Service Guideline
EIGA/IGC 65 Safe Operation of Reboilers/Condensers in Air Separation Units
EIGA/IGC 73/08 Design Considerations to Mitigate the Potential Risks of Toxicity when using Non-metallic Materials in High Pressure Oxygen Breathing Systems
EIGA/IGC 115 Storage of Cryogenic Air Gases at Users Premises
EIGA/IGC 127 Bulk Liquid Oxygen, Nitrogen and Argon Storage Systems at Production Sites
EIGA/IGC 144 Safe Use of Aluminum-Structured Packing for Oxygen Distillation
EIGA/IGC 145 Safe Use of Brazed Aluminum Heat Exchangers for Producing Pressurized Oxygen
EIGA/IGC 147 Safe Practices Guide for Air Separation Plants
EIGA/IGC 148 Installation Guide for Stationary Electric-Motor-Driven Centrifugal Liquid Oxygen Pumps
EIGA/IGC 154 Safe Location of Oxygen, Nitrogen and Inert Gas Vents
EIGA/IGC 159 Reciprocating Cryogenic Pump and Pump Installation

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[2] For referenced ASTM adjuncts and standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from ASTM Headquarters, Order ADJG0088.

[4] Available from National Fire Protection Association (NFPA), 1 Batterymarch Park, Quincy, MA 02169-7471, http://www.nfpa.org.

EIGA/IGC 179 Liquid Oxygen, Nitrogen, and Argon Cryogenic Tanker Loading Systems

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *characteristic elements*—those factors that must be present for an ignition mechanism to be active in an oxygen-enriched atmosphere.

3.1.2 *direct oxygen service*—service in contact with oxygen during normal operations. Examples: oxygen compressor piston rings, control valve seats.

3.1.3 *galling*—a condition whereby excessive friction between high spots results in localized welding with subsequent splitting and a further roughening of rubbing surfaces of one or both of two mating parts.

3.1.4 *indirect oxygen service*—service in which oxygen is not normally contacted but in which it might be as a result of a reasonably foreseeable malfunction (single fault), operator error, or process disturbance. Examples: liquid oxygen tank insulation, liquid oxygen pump motor bearings.

3.1.5 *oxygen-enriched atmosphere*—a fluid (gas or liquid) mixture that contains more than 25 mol % oxygen.

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

4. Significance and Use

4.1 *Purpose of Guide G88*—The purpose of this guide is to furnish qualified technical personnel with pertinent information for use in designing oxygen systems or assessing the safety of oxygen systems. It emphasizes factors that cause ignition and enhance propagation throughout a system's service life so that the occurrence of these conditions may be avoided or minimized. It is not intended as a specification for the design of oxygen systems.

4.2 *Role of Guide G88*—ASTM Committee G04's abstract standard is Guide G128, and it introduces the overall subject of oxygen compatibility and the body of related work and related resources including standards, research reports and a video[3] G04 has developed and adopted for use in coping with oxygen hazards. The interrelationships among the standards are shown in Table 1. Guide G88 deals with oxygen system and hardware design principles, and it is supported by a regulator ignition test (see G175).Other standards cover: *(1)* the selection of materials (both metals and nonmetals) which are supported by a series of standards for testing materials of interest and for preparing materials for test; *(2)* the cleaning of oxygen hardware which is supported by a series of standards on cleaning procedures, cleanliness testing methods, and cleaning agent selection and evaluation; *(3)* the study of fire incidents in oxygen systems; and *(4)* related terminology.

TABLE 1 Role of Guide G88 with Respect to Other ASTM G04 Standard Guides and Practices and their Supporting Test Methods[A],[B]

- G128 Guide to Control of Hazards and Risks in Oxygen-Enriched Systems
  - G88 Designing Systems for Oxygen Service
    - G175 Evaluating the Ignition Sensitivity and Fault Tolerance of Oxygen Regulators

  - G63 Evaluating Nonmetallic Materials
    - D2512 Compatibility of Materials With Liquid Oxygen (Mechanical Impact)
    - D2863 Measuring the Minimum Oxygen Concentration to Support Candle-Like Combustion (Oxygen Index)
    - D4809 Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)
    - G72 Autogenous Ignition Temperature of Liquids and Solids in High-Pressure Oxygen Enriched Atmospheres
    - G74 Ignition Sensitivity of Materials to Gaseous Fluid Impact
    - G86 Determining Ignition Sensitivity of Materials to Mechanical Impact in Pressurized Oxygen Environments
    - G114 Aging Oxygen-Service Materials Prior to Flammability Testing
    - G125 Measuring Liquid and Solid Material Fire Limits in Gaseous Oxidants

  - G94 Evaluating Metals
    - G124 Determining the Combustion Behavior of Metallic Materials in Oxygen Enriched Atmospheres

  - G93 Cleaning Methods for Material and Equipment
    - G120 Determination of Soluble Residual Contamination in Materials and Components by Soxhlet Extraction
    - G136 Determination of Soluble Residual Contaminants in Materials by Ultrasonic Extraction
    - G144 Determination of Residual Contamination of Materials and Components by Total Carbon Analysis Using a High Temperature Combustion Analyzer
    - G127 Guide to the Selection of Cleaning Agents for Oxygen Systems
      - G122 Test Method for Evaluating the Effectiveness of Cleaning Agents
        - G121 Preparation of Contaminated Test Coupons for the Evaluation of Cleaning Agents
    - G131 Cleaning of Materials and Components by Ultrasonic Techniques

  - G145 Studying Fire Incidents in Oxygen Systems

  - G126 Terminology Related to the Compatibility and Sensitivity of Materials in Oxygen-Enriched Atmospheres
- Manual 36 – Safe Use of Oxygen and Oxygen Systems: Guidelines for Oxygen System Design, Materials Selection, Operations, Storage, and Transportation

[A] ASTM D2863 is under the jurisdiction of Committee D20 on Plastics, and D4809 is under the jurisdiction of Committee D02 on Petroleum Products and Lubricants but both are used in the asessment of flammability and sensitivity of materials in oxygen-enriched atmospheres.

[B] ASTM Manual 36 – Safe Use of Oxygen and Oxygen Systems can be used as a handbook to furnish qualified technical personnel with pertinent information for use in designing oxygen systems or assessing the safety of oxygen systems. However, Manual 36 is not a balloted technical standard.

4.3 *Use of Guide G88*—Guide G88 can be used as an initial design guideline for oxygen systems and components, but can also be used as a tool to perform safety audits of existing oxygen systems and components. When used as an auditing tool for existing systems, Guide G88 can be applied in two stages: first examining system schematics/drawings, then by visually inspecting the system (that is, "walking the pipeline"). Guide G88 can be used in conjunction with the materials selection/hazards analysis approach outlined in Guides G63 and G94 to provide a comprehensive review of the fire hazards in an oxygen or oxygen-enriched system (**1**).[5]

5. Factors Affecting the Design for an Oxygen or Oxygen-Enriched System

5.1 *General*—An oxygen system designer should understand that oxygen, fuel, and heat (source of ignition) must be present to start and propagate a fire. Since materials of construction of the system are often flammable and oxygen is always present, the design of a system for oxygen or oxygen-enriched service requires identifying potential sources of ignition and the factors that aggravate propagation. The goal is to eliminate these factors or compensate for their presence. Preventing fires in oxygen and oxygen-enriched systems involves all of the following: minimizing system factors that cause fires and environments that enhance fire propagation; maximizing the use of system materials with properties that resist ignition and burning, especially where ignition mechanisms are active; and using good practices during system design, assembly, operations and maintenance.

5.2 *Factors Recognized as Causing Fires:*

5.2.1 *Temperature*—As the temperature of a material increases, the amount of energy that must be added to produce ignition decreases (**2**). Operating a system at unnecessarily elevated temperatures, whether locally or generally elevated, reduces the safety margin. The ignition temperature of the most easily ignited material in a system is related to the temperature measured by Test Method G72, but is also a function of system pressure, configuration and operation, and thermal history of the material. Elevated temperature also facilitates sustained burning of materials that might otherwise be self-extinguishing.

5.2.1.1 *Thermal Ignition*—Thermal ignition consists of heating a material (either by external or self-heating means, see also section 5.2.2) in an oxidizing atmosphere to a temperature sufficient to cause ignition. In thermal ignition testing, the spontaneous ignition temperature is normally used to rate material compatibility with oxygen as well as evaluate a material's ease of ignition. The ignition temperature of a given material is generally dependent on its thermal properties, including thermal conductivity, heat of oxidation, and thermal diffusivity, as well as other parameters such as geometry and environmental conditions (**3**). The characteristic elements of forced thermal ignition in oxygen include the following:

(1) An external heat source capable of heating a given material to its spontaneous ignition temperature in a given environment.

(2) A material with a spontaneous ignition temperature below the temperature created by the heat source in the given configuration and environment.

(3) Example: A resistive element heater in a thermal runaway fault condition causing oxygen-wetted materials in near proximity to spontaneously ignite.

5.2.2 *Spontaneous Ignition*—Some materials, notably certain accumulations of fines, porous materials, or liquids may undergo reactions that generate heat. If the heat balance (the rate of heating compared to the rate of dissipation) is unfavorable, the temperature of the material will increase. In some cases, a thermal runaway temperature (a critical condition) may be attained and some time later the material may spontaneously ignite. Ignition and fire may occur after short (seconds or minutes) or over long (hours, days or months) periods of time. In the most extreme cases, the thermal runaway temperature may be near or below normal room temperature. The characteristic elements of spontaneous ignition in oxidants include the following:

5.2.2.1 A material that reacts (for example, oxidizes, decomposes) at temperatures significantly below its ignition temperature. If the rate of reaction is low, the effect of reaction can still be large if the material has a high surface-area-to-volume ratio (such as dusts, particles, foams, chars, etc.). Likewise, materials that will not spontaneously combust in bulk forms may become prone to do so when subdivided. In some cases, reaction products may instead serve to passivate the material surface producing a protective coating that prevents ignition so long as it is not compromised (by melting, cracking, flaking, spalling, evaporating. etc.). Reaction products may also stratify or otherwise form an ignition-resistant barrier.

5.2.2.2 An environment that does not dissipate the transferred heat (such as an insulated or large volume vessel or an accumulation of fines).

5.2.2.3 Examples: an accumulation of wear dust in an oxygen compressor that has been proof-tested with nitrogen gas, then exposed to oxygen. Contaminated adsorbent or absorbent materials such as molecular sieves (zeolites), alumina, and activated carbon may become highly reactive in oxygen-enriched atmospheres.

5.2.3 *Pressure*—As the pressure of a system increases, the ignition temperatures of the materials of construction typically decrease (**2, 4**), and the rates of fire propagation increase (**2, 5**). Therefore, operating a system at unnecessarily elevated pressures increases the probability and consequences of a fire. It should be noted that pure oxygen, even at lower–than-atmospheric pressure, may still pose a significant fire hazard since increased oxygen concentration has a greater effect than total pressure on the flammability of materials (**6, 7**).

5.2.4 *Concentration*—As oxygen concentration decreases from 100 % with the balance being inert gases, there is a progressive decrease in the likelihood and intensity of a reaction (**2**). Though the principles in this standard still apply, greater latitude may be exercised in the design of a system for dilute oxygen service.

5.2.5 *Contamination*—Contamination can be present in a system because of inadequate initial cleaning, introduction during assembly or service life, or generation within the system by abrasion, flaking, etc. Contaminants may be liquids, solids, or gases. Such contamination may be highly flammable and readily ignitable (for example, hydrocarbon oils). Accordingly, it is likely to ignite and promote consequential system fires through a kindling chain reaction (see 5.2.14). Even normally inert contaminants such as rust may produce ignition through particle impact (see 5.2.6), friction (see 5.2.8), or through

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[5] The boldface numbers in parentheses refer to the list of references at the end of this standard.

augmentation of resonance heating effects (see 5.2.9). A properly designed system, if properly cleaned and maintained, can be assumed to be free of unacceptable levels of hydrocarbon contamination, but may still contain some particulate contamination. System design and operation must accommodate this contamination, as discussed in the following paragraphs.

5.2.6 *Particle Impact*—Collisions of inert or ignitable solid particles entrained in an oxidant stream are a potential ignition source. Such ignition may result from the particle being flammable and igniting upon impact and, in turn, igniting other system materials (**8**). Ignition may also result from heating of the particle and subsequent contact with system plastics and elastomers, from flammable particles produced during the collision, or from the direct transfer of kinetic energy during the collision. Particle impact is considered by many to be the most commonly experienced mechanism that directly ignites metals in oxygen systems. The characteristic elements of particle impact ignition include the following:

5.2.6.1 *Presence of Particles*—Absolute removal of particles is not possible, and systems can generate their own particles during operation. The quantity of particles in a system will tend to increase with the age of the system. Hence, a system must be designed to tolerate the presence of at least some particles. The hazard associated with particles increases with both the particles' heat of combustion and their kinetic energies.

5.2.6.2 *High Fluid (Gas) Velocities*—High fluid velocities increase the kinetic energies of particles entrained in flowing oxygen systems so that they have a higher risk of igniting upon impact. High velocities can occur as a result of reducing pressure across a system component or during a system start-up transient where pressure is being established through a component or in a pipeline. Components with inherently high internal fluid velocities include pressure regulators, control valves, and flow-limiting orifices. Depending on system configuration, some components can generate high fluid velocities that can be sustained for extended distances downstream. System start-ups or shut-downs can create transient gas velocities that are often orders of magnitude higher than those experienced during steady-state operation.

NOTE 3—The pressure differential that can be tolerated to control high gas velocities is significantly smaller than for control of downstream heat of compression (**9**) (see 5.2.7 for discussion of heat of compression). Even small pressure differentials across components can generate gas velocities in excess of those recommended for various metals in oxygen service (**10, 11**). Eq 1 can be used to estimate the downstream gas pressure for a given upstream pressure and maximum downstream gas velocity, assuming an ideal gas and isentropic flow (**9**):

$$P_D = \frac{P_T}{\left[\left(\frac{V_D^{\,2}}{2g_c KRT_D}\right)+1\right]^K} \qquad (1)$$

where:

P_D = downstream pressure (absolute),
P_T = source pressure (absolute),
V_D = maximum gas velocity downstream,
g_c = dimensional constant (1 kg/N s^2 or 4636 lb in.^{2}/lb$_f$s^2 ft),
K = $\gamma/(\gamma-1)$ where γ is the ratio of specific heats C_p/C_v (γ = 1.4 for O_2),
R = individual gas constant for O_2 (260 N-m/kg °K or 0.333 ft^3 lb$_f$/in.^{2} lb$_m$ °R),[6] and
T_D = temperature downstream (absolute).

NOTE 4—Fig. 1 shows the maximum gas velocity versus pressure differential considering isentropic flow for gaseous oxygen, based on the

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[6] Reference (**9**) provides Eq 1 with the given list of variables as defined here. However, the value for the Individual Gas Constant, R, was incorrectly stated as the Universal Gas Constant, and its metric value was incorrectly listed as 26 N-m/kg K instead of 260 N-m/kg K.

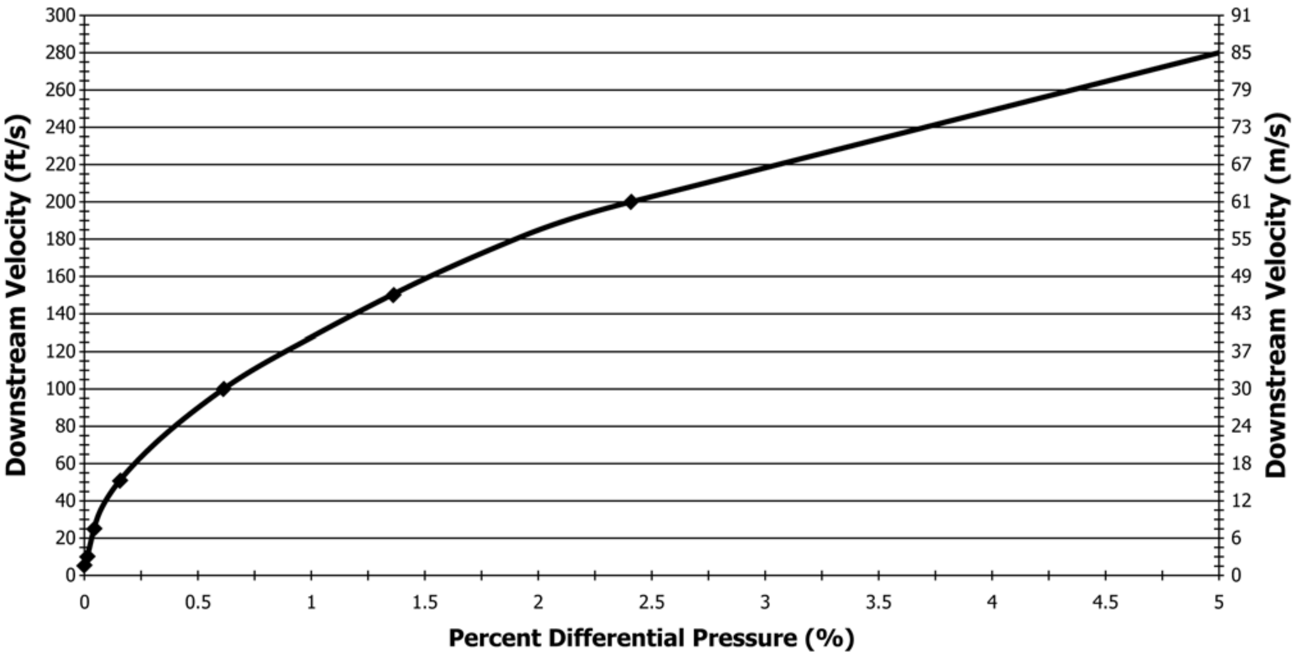


FIG. 1 Maximum Oxygen Gas Velocity Produced by Pressure Differentials, Assuming Isentropic Flow

equation shown above. Even with only a 1.5-percent differential pressure, gas velocity exceeds the 45 m/s (150 ft/s) minimum velocity required to ignite particles in particle impact experiments (**12**).

5.2.6.3 *Impingement Sites*—A particle entrained in a high-velocity fluid must impinge upon a surface, or impact point, to transfer its kinetic energy to heat and ignite. Impingement sites can be internal to components (for example in the body of an in-line globe valve just downstream of its seat), or downstream of high fluid velocity components (for example inside an elbow or Tee placed close to the outlet of a component with a high fluid velocity). Generally, impacts normal (perpendicular) to the impact surface are considered most severe.

5.2.6.4 *Flammable Materials*—Generally, both the particle(s) and the target (impact point) materials must be flammable in the given environment for ignition and sustained burning to occur. However, particle impact ignition studies have shown that some highly flammable metals, such as aluminum alloys, may ignite even when impacted by inert particles (**8**). Additionally, common nonmetal particles have been shown to be ineffective igniters of metals by particle impact (**13**), and softer nonmetal targets, though more prone to ignition by other means, are generally less susceptible to direct ignition by particle impact because they tend to cushion the impact (**14**). This cushioning effect of nonmetals can act to increase the time-to-zero velocity of a particle, lower its peak deceleration, and generally create a less destructive collision. However, harder nonmetal targets, such as those used in some valve seat applications, have been shown to ignite in particle impact studies (**14**).

5.2.7 *Heat of Compression*—Heat is generated from the conversion of mechanical energy when a gas is compressed from a lower to a higher pressure. High gas temperatures can result if this compression occurs quickly enough to simulate adiabatic (no heat transfer) conditions. Heat of compression has also been referred to as compression heating, pneumatic impact, rapid pressurization, adiabatic compression, and gaseous impact. This can occur when high-pressure oxygen is released into a dead-ended tube or pipe, quickly compressing the residual oxygen initially in the tube or pipe. The elevated gas temperatures produced can ignite contaminants or materials in system components. The hazard of heat of compression increases with system pressure and with pressurization rate. Heat of compression is considered by many to be the most commonly experienced mechanism that directly ignites nonmetals in oxygen systems. In general, metal alloys are not vulnerable to direct ignition by this mechanism. Fig. 2 shows an example of a compression heating sequence leading to ignition of a nonmetal valve seat. Sequence A shows high-pressure oxygen upstream of a fast-opening valve in the closed position. Downstream of the valve is oxygen at initial pressure, volume, and temperature (P_i, V_i, T_i, respectively). P_i and T_i are assumed to be at ambient conditions in this example). A second valve with a nonmetallic seat is shown downstream in the closed position, representing a “dead-end,” or closed volume. Sequence B shows the opening of the fast-opening valve, rapidly pressurizing the downstream volume with high-pressure oxygen (final pressure shown as P_f), compressing and heating the original gas volume. The final temperature generated at the “dead-end” from such an event (shown as T_f) can exceed the ignition temperature of the exposed nonmetal valve seat and cause it to ignite. The presence of lubricant, debris, or other contaminants proximate to the valve seat may increase the hazard since they may be easier to ignite. Once ignited, the lubricant, debris, or other contaminants may begin a kindling chain (see 5.2.14). In order for ignition to occur, pressurization of the downstream volume must be rapid enough to create

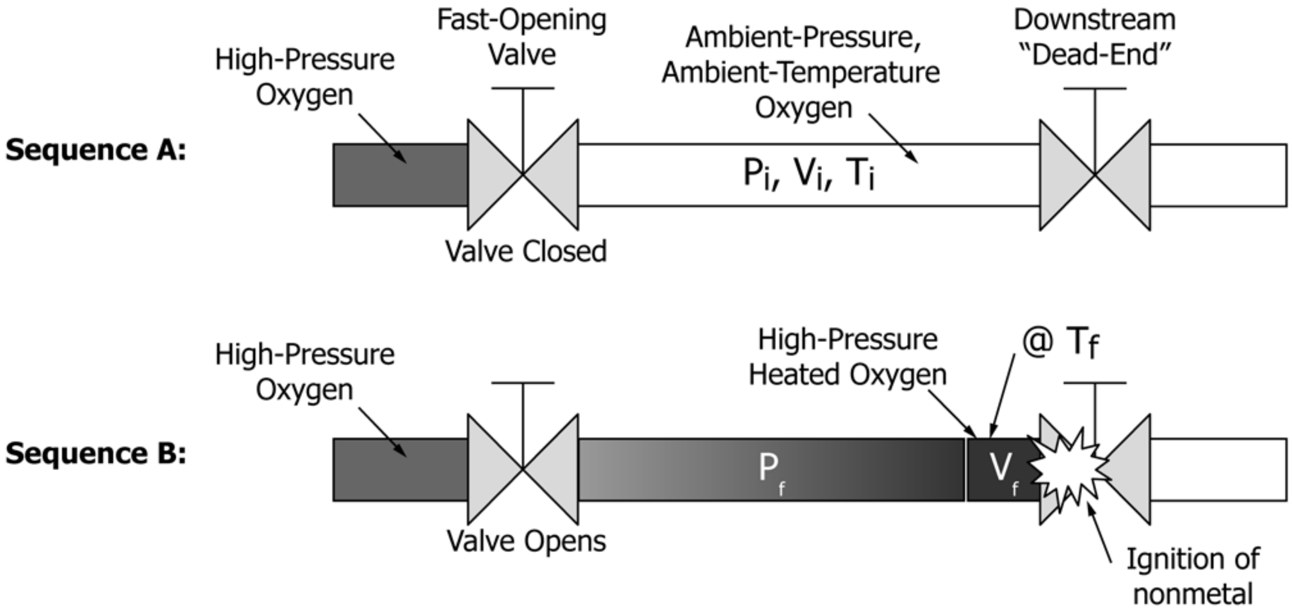


FIG. 2 Example of a Compression Heating Sequence Leading to Ignition of a Nonmetal Valve Seat

near-adiabatic heating, as discussed below. The characteristic elements for heat of compression include the following:

5.2.7.1 *Compression Pressure Ratio*—In order to produce temperatures capable of igniting most materials in oxygen environments, a significant compression pressure ratio (P_f/P_i) is required, where the final pressure is significantly higher than the starting pressure.

NOTE 5—Eq 2 shows a formula for the theoretical maximum temperature (T_f) that can be developed when pressurizing a gas rapidly from one pressure and temperature to an elevated pressure without heat transfer:

$$\frac{T_f}{T_i} = \left[\frac{P_f}{P_i}\right]^{(n-1)/n} \tag{2}$$

where:

T_f = final temperature, abs,
T_i = initial temperature, abs,
P_f = final pressure, abs,
P_i = initial pressure, abs, and

$$n = \frac{C_p}{C_v} = 1.40 \text{ for oxygen} \tag{3}$$

where:

C_p = specific heat at constant pressure, and
C_v = specific heat at constant volume.

NOTE 6—Table 2 gives the theoretical temperatures (T_f) that could be obtained by compressing oxygen adiabatically from an initial temperature (T_i) of 20°C and initial pressure (P_i) of one standard atmosphere to the pressures shown. Figs. 3 and 4 show these final temperatures graphically as a function of Pressure Ratio (P_f/P_i) and Final Pressure (P_f), respectively. Table 2 and Fig. 3 show that pressure ratios as low as 10 (for example rapidly pressurizing a system from ambient to 1 MPa (145 psia)) can theoretically produce temperatures that exceed the autogenous ignition temperatures (AIT) of many nonmetals or contaminants in oxygen systems (based upon the AIT of various materials per Test Method G72). Fig. 4 shows how increasing the downstream pressure prior to the compression event lowers the final temperature.

5.2.7.2 *Rapid Pressurization*—The rate of compression, or time of pressurization, must be fast to minimize heat loss to the surroundings. Pressurization times on the order of fractions of a second as opposed to seconds or minutes are most severe. For example, Teflon-lined flexhoses can be ignited if pressurized in fractions of a second but not if pressurized in seconds **(15)**.

TABLE 2 Theoretical Maximum Temperature Obtained when Compressing Oxygen Adiabatically from 20°C and One Standard Atmosphere to Various Pressures

Final Pressure, P_f		Pressure Ratio, P_f/P_i	Final Temperature, T_f	
kPa	PSIA		°C	°F
345	50	3.4	143	289
690	100	6.8	234	453
1000	145	9.9	291	556
1379	200	13.6	344	653
2068	300	20.4	421	789
2758	400	27.2	480	896
3447	500	34.0	530	986
5170	750	51.0	628	1163
6895	1000	68.0	706	1303
10 000	1450	98.6	815	1499
13 790	2000	136.1	920	1688
27 579	4000	272.1	1181	2158
34 474	5000	340.1	1277	2330
100 000	14 500	986.4	1828	3322
1 000 000	145 000	9863.9	3785	6845

5.2.7.3 *Exposed Nonmetal Proximate to a Dead-end*—For ignition to occur by heat of compression, a nonmetal material must be exposed to the heated compressed gas slug proximate to a dead-end location (for example a nonmetal valve seat in a closed valve). Nonmetals typically have lower thermal diffusivities and lower autogenous ignition temperatures than metals and thus are more vulnerable to this mechanism.

5.2.8 *Friction and Galling*—The rubbing together of two surfaces can produce heat and can generate particles. An example is the rub of a centrifugal compressor rotor against its casing creating ignition from galling and friction at the metal-to-metal interface. Heat produced by friction and galling (see 3.1.3) may elevate component materials above their ignition temperatures. Particles can participate in ignition as contaminants (see 5.2.5) or in particle impacts (see 5.2.6). The characteristic elements of ignition by galling and friction include the following:

5.2.8.1 *Two or More Rubbing Surfaces*—Metal-to-metal contact is generally considered most severe as it produces a high-temperature oxidizing environment, and it destroys protective oxide surfaces or coatings, exposing fresh metal and generating fine particles. By comparison, limited test data for nonmetals suggests that nonmetals can deform or fragment under frictional loading and not necessarily ignite (though generally none of these results are desirable in an oxygen system).

5.2.8.2 *High Rubbing Speeds and/or High Loading*—These conditions are generally considered most severe as they create a high rate of heat transfer as reflected by the Pv Product, (the loading pressure normal to the surface multiplied by the velocity of the rubbing surfaces) **(16)**.

5.2.9 *Resonance*—Acoustic oscillations within resonant cavities can create rapid heating. The temperature rises more rapidly and achieves higher values when particles are present or when gas velocities are high. Resonance phenomena in oxygen systems are well documented **(17)** but limited design criteria are available to avoid its unintentional occurance. An example of resonance ignition has been demonstrated in aerospace applications with solid or liquid rocket fuel engines. Gaseous oxygen flows through a sonic nozzle and directly into a resonance cavity, heating the gas and solid or liquid fuel. When the gas reaches the auto-ignition temperature of the fuel, ignition occurs and a flame jet is emitted from the chamber **(18)**. The characteristic elements of ignition by resonance include the following:

5.2.9.1 *Resonance Cavity Geometry*—The requirements include a throttling device such as a nozzle, orifice, regulator, or valve directing a sonic gas jet into a cavity or closed-end tube. Fig. 5 shows an example of a system with a sonic nozzle/orifice directly upstream of a Tee with a closed end. The gas flows out the branch port of the Tee (making a 90° turn) but the closed end creates a cavity in which shock waves generated by the throttling device can resonate.

5.2.9.2 *Acoustic Resonance Phenomena*—The distance between the throttling device and the closed end affects the frequency of acoustic oscillations in the cavity, similar to a

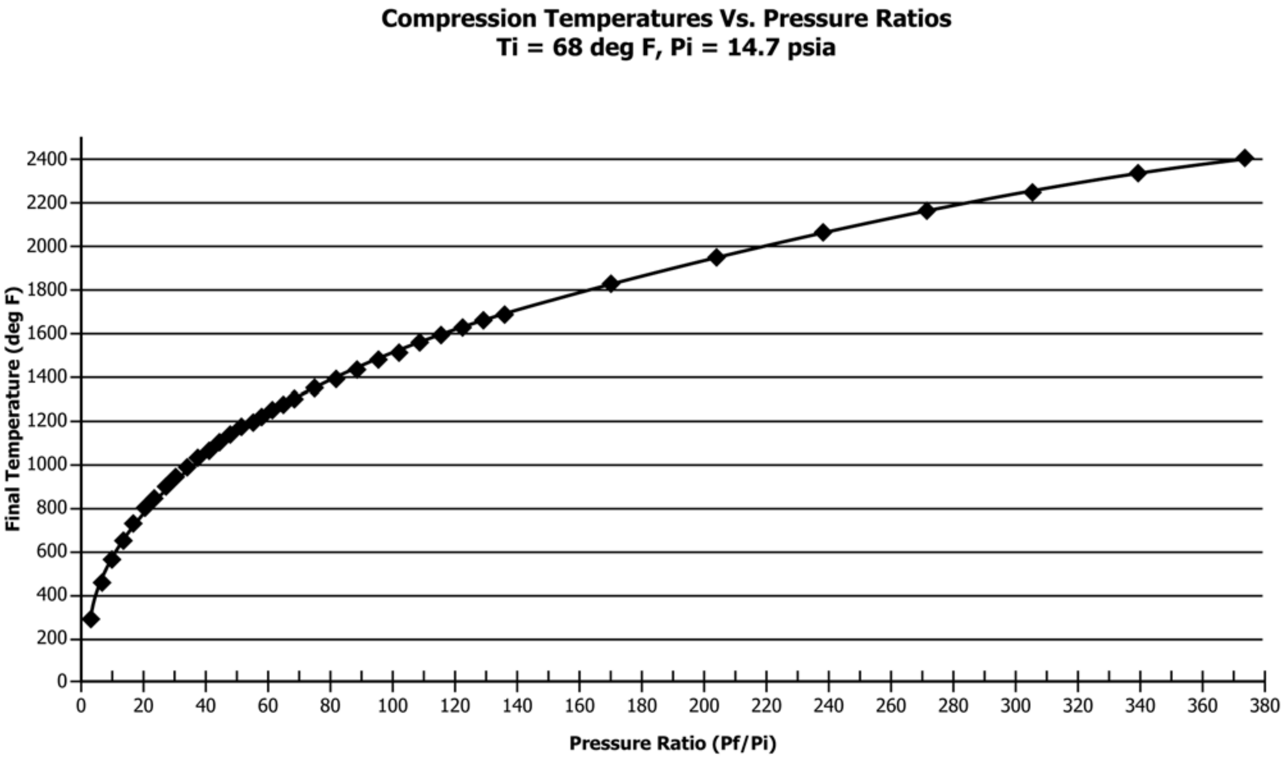


FIG. 3 Final Compression Temperatures for Pressure Ratios

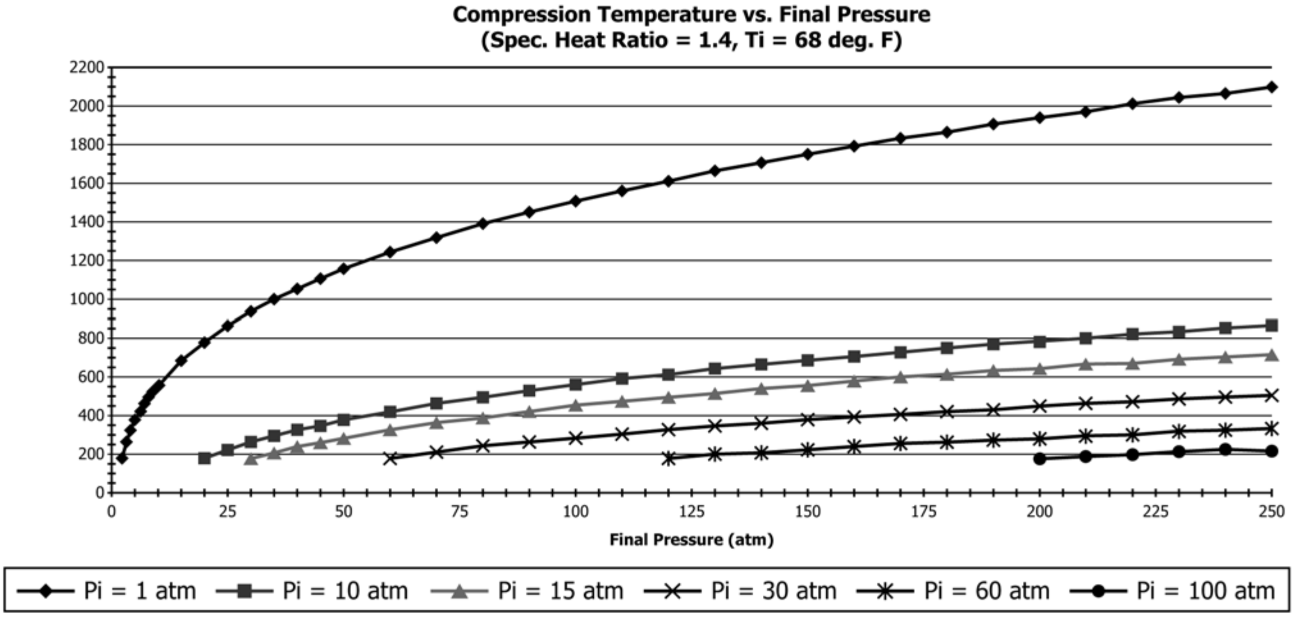


FIG. 4 Final Compression Temperatures for Final Pressures Given the Initial Presssures Shown

pipe organ with a closed end, due to the interference of incident and reflecting sound waves. This distance also affects the temperature produced in the cavity. Higher harmonic frequencies have been shown to produce higher temperatures. The resonant frequency has been shown to be a function of pipe diameter and pressure ratio (**17**).

5.2.9.3 *Flammable Particulate or Contaminant Debris at Closed End*—Particulate or debris residing at the closed end of

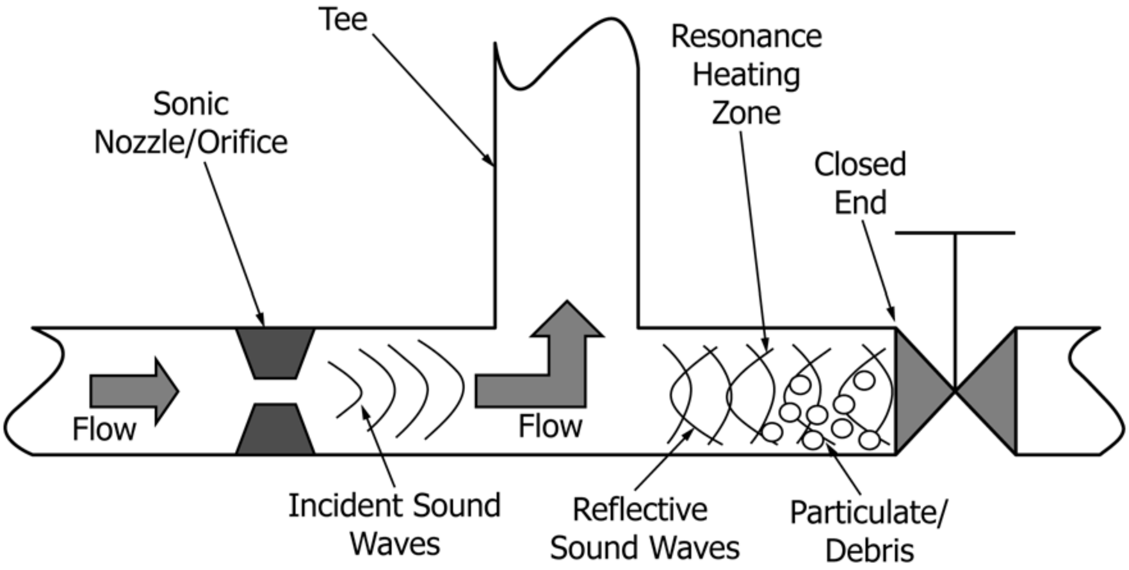


FIG. 5 Example of a System Configuration with Potential for Resonance Heating

the cavity (see Fig. 5) can self-ignite due to the high temperatures produced by resonance heating, or they can vibrate and their collisions generate sufficient heat to self-ignite.

5.2.10 *Static Electric Discharge*—Accumulated static charge on a nonconducting surface can discharge with enough energy to ignite the material receiving the discharge. Static electrical discharge may be generated by high fluid flow under certain conditions, especially where particulate matter is present. Examples of static electric discharge include arcing in poorly cleaned, inadequately grounded piping; two pieces of clothing or fabric creating a static discharge when quickly pulled apart; and large diameter ball valves with nonmetal upstream and downstream seats, where the ball/stem can become electrically isolated from the body and can develop a charge differential between the ball and body from the ball rubbing against the large surface area nonmetallic seat. The characteristic elements of static discharge include the following:

5.2.10.1 Static charge buildup from flow or rubbing accumulates on a nonconducting surface.

5.2.10.2 Discharge typically occurs at a point source between materials of differing electrical potentials.

5.2.10.3 Two charged surfaces are not likely to discharge unless one material is conductive.

5.2.10.4 Accumulation of charge is more likely in a dry gas or a dry environment as opposed to a moist or humid environment.

5.2.11 *Electrical Arc*—Sufficient electrical current arcing from a power source to a flammable material can cause ignition. Examples include a defective pressure switch or an insulated electrical heater element undergoing short circuit arcing through its sheath to a combustible material. The characteristic elements of electrical arc ignition include the following:

5.2.11.1 Ungrounded or short-circuited power source such as a motor brush (especially if dirty and/or high powered), electrical control equipment, instrumentation, lighting, etc.

5.2.11.2 Flammable materials capable of being ignited by the electrical arc or spark.

5.2.12 *Flow Friction*—It is theorized that oxygen and oxygen-enriched gas flowing across the surface of or impinging directly upon nonmetals can generate heat within the nonmetal, causing it to self-ignite. Though neither well understood, well documented in literature, nor well demonstrated in experimental efforts to date, several oxygen fires have been attributed to this mechanism when no other apparent mechanisms were active aside from a leaking, or scrubbing action of gas across a nonmetal surface (most commonly a polymer) (**19**). An example is ignition of a nonmetallic cylinder valve seat from a plug-style cylinder valve that has been cycled extensively and is used in a throttling manner. Flow friction ignition is supported by unverifiable anecdotes. The background for the flow friction hypothesis suggests the characteristic elements:

5.2.12.1 *Higher-pressure Systems*—Though there is currently no clearly defined lower pressure threshold where flow friction ignition becomes inactive, the current known fire history is in higher-pressure systems operating at approximately 3.5 MPa (500 psi) or higher.

5.2.12.2 Configurations including leaks past nonmetal component seats or pressure seals, or "weeping" or "scrubbing" flow configurations around nonmetals. These configurations can include external leaks past elastomeric pressure seals or internal flows on or close to plastic seats in components. Flow friction is not believed to be a credible ignition source for metals.

5.2.12.3 Surfaces of nonmetals that are highly fibrous from being chafed, abraded, or plastically deformed may render flow friction more severe. The smaller, more easily ignited fibers of the nonmetal may begin resonating, or vibrating/flexing, perhaps at high frequencies due to flow, and this "friction" of the material would generate heat.

5.2.13 *Mechanical Impact*—Heat can be generated from the transfer of kinetic energy when an object having a relatively large mass or momentum strikes a material. In an oxygen environment, the heat and mechanical interaction between the objects can cause ignition of the impacted material. The characteristic elements of mechanical impact ignition include the following:

5.2.13.1 *Single, Large Impact or Repeated Impacts*—Example: If a high-pressure relief valve "chatters," it can impart repeated impacts on a nonmetallic seat, in combination with other effects, and lead to ignition of the seat.

5.2.13.2 *Nonmetal at Point of Impact*—Generally, test data show this mechanism is only active with nonmetals, though aluminum, magnesium, and titanium alloys in thin cross-sections as well as some solders have been ignited experimentally (**20**, **21**). However, in these alloys, mechanical failure (which introduces additional ignition mechanisms) will likely precede, or at minimum coincide with, mechanical impact ignitions in liquid oxygen (LOX) (**22**).

5.2.13.3 Special caution is required for mechanical impact in LOX environments. Some cleaning solvents are known to become shock-sensitive in LOX. Porous hydrocarbons such as asphalt, wood, and leather can become shock-sensitive in LOX and react explosively when impacted even with relatively small amounts of energy (**23**). Testing has showed that the presence of contamination on hydrocarbon materials will increase the hazard (**24**). If LOX comes into contact with any porous hydrocarbon materials, care should be take to avoid mechanical impacts of any kind until the LOX has dissipated. This can take as long as 30 minutes depending on the material exposed. Examples of this include leather work gloves soaked in LOX and exposed to the impact of a wrench, and LOX overflow onto an asphalt driveway then driven over by a truck or walked on by personnel.

5.2.14 *Kindling Chain*—In a kindling chain (referred to as promoted ignition in Guide G94), an easily ignitable material, such as flammable contamination, ignites and the energy release from this combustion ignites a more ignition-resistant material such as a plastic, which in turn ignites an even more ignition-resistant material such as a metallic component. The fire eventually leads to a breach of the system. The primary intent is to prevent ignition of any material in the system, but secondarily, to break the kindling chain so if ignition does occur, it does not lead to a breach of the system. One method to accomplish this is to limit the mass of nonmetallic components so that if the nonmetal does ignite, it does not release sufficient energy to ignite the adjacent metal.

5.2.15 *Other Ignition Mechanisms*—There are numerous other potential ignition sources that may be considered in oxygen system design that are not elaborated upon here. These include environmental factors such as personnel smoking; open flames; shock waves and fragments from vessel ruptures; welding; mechanical vibration; intake of exhaust from an internal combustion engine; smoke from nearby fires or other environmental chemicals; and lightning.

6. Test Methods

6.1 The test methods used to support the design of oxygen systems are listed in Table 1.

7. System Design Method

7.1 *Overview*—The designer of a system for oxygen service should observe good mechanical design principles and incorporate the factors below to a degree consistent with the severity of the application. Mechanical failures are undesirable since these failures, for example rupture and friction, can produce heating, particulates, and other factors which can cause ignition as discussed in the following sections.

NOTE 7—Good mechanical design practice is a highly advanced and specialized technology addressed in general by a wealth of textbooks, college curricula and professional societies, standards and codes. Among the sources are the American Society of Mechanical Engineers Pressure Vessel and Piping Division, the American Petroleum Institute, the American National Standards Institute, and Deutsches Institut für Normung. Prevailing standards and codes cover many mechanical considerations, including adequate strength to contain pressure, avoidance of fatigue, corrosion allowances, etc.

7.2 *Final Design*—Oxygen system design involves a complex interplay of the various factors that promote ignition and of the ability of the materials of construction to resist such ignition and potential burning (**10**, **11**, **25**). There are many subjective judgements, external influences, and compromises involved. While each case must ultimately be decided on its own merits, the generalizations below apply. In applying these principles, the designer should consider the system's normal and worst-case operating conditions and, in addition, indirect oxygen exposure that may result from system upsets and failure modes. The system should be designed to fail safely. To this end, failure effect studies to identify components subject to indirect oxygen exposure or for which an oxygen exposure more severe than normal is possible are recommended. Not every principle can be applied in the design of every system. However, the fire resistance of a system will improve with the number of principles that are followed.

7.3 *Avoid Unnecessarily Elevated Temperatures.*

NOTE 8—Ignition requires at least two key conditions to be met: *(1)* the minimum in-situ ignition temperature must be exceeded, and *(2)* the minimum in-situ ignition energy must be exceeded. The optimum combination of temperature and energy required for ignition have not been studied for most oxygen system hardware.

7.3.1 Locate systems a safe distance from heat or radiation sources (such as furnaces).

7.3.1.1 Avoid large energy inputs. Large energy inputs from hot gases, friction, radiation, electrical sources, etc. have the effect of increasing the propensity of a material to burn extensively if ignited and, if the input is large and at a sufficient temperature, may actually produce ignition.

7.3.1.2 Example—An external electrical heater experiences a short circuit and arcs to the wall of a heat exchanger for oxygen. As the arcing progresses, a progressively larger region of the heat exchanger will become overheated and if the temperature rises sufficiently or if the arcing actually breaches the exchanger wall, ignition and fire may result. Even if the exchanger was initially operated under conditions where it was burn-resistant, the region that is preheated may achieve its fire limit and burn.

NOTE 9—Electrical heaters on oxygen equipment may require ground fault interrupters (GFIs) to prevent large energy inputs and fires due to heater failure. When a GFI is used, its trigger current should be significantly below any level that could sustain arcing or protracted heating during a failure.

7.3.2 Design for efficient dissipation of heat.

7.3.3 Provide monitoring equipment and automatic shutdown devices where practical (such as heaters and bearings).

7.3.3.1 Avoid temperature envelope drift. Temperature drift may occur from increasing ambient temperature, heater controller failure, etc.

NOTE 10—Whenever a temperature controller is used, an over-temperature alarm or shutdown should also be incorporated and it should not share common components, including the temperature sensor, with the controller.

7.3.4 Prefer a nonmetallic material whose autogenous ignition temperature in oxygen (per Test Method G72) exceeds the maximum use temperature by at least 100°C (per Guide G63). A larger temperature differential may be appropriate for high use pressures or other aggravating factors.

7.4 *Avoid Unnecessarily Elevated Pressures.*

7.4.1 Reduce pressure near the supply point rather than near the use point. This allows intermediate equipment to be at minimum pressure.

7.4.2 Ensure proper system relief protection.

7.4.2.1 Avoid pressure envelope drift. Pressure drift may result from creep in an oxygen pressure regulator, a sticking relief valve, increased system temperature, vent failure, etc.

7.5 *Design for System Cleanness:*

7.5.1 Design a system that is easy to clean and easy to maintain clean (see Practice G93 and Ref (**26**)). It should be possible to disassemble the system into components that can be thoroughly cleaned.

7.5.2 Avoid the presence of unnecessary sumps, dead-ends and cavities likely to accumulate debris.

NOTE 11—Any groove (including the corrugations of bellows-type flexible hoses), depression, ridge (including mismatched coaxial piping or weld-backup ring edges), projection or upwardly inclined section may retain and accumulate debris.

NOTE 12—Any upward flow, including vertical piping and inclined piping will act as a phase separator and leave debris that is not entrained at its lower end. With two-phase liquid and gas flow, any region that is not free-draining may allow fractional evaporation (see 7.17.3.1) of the liquid and production of a deposit.

7.5.2.1 Avoid sumps, dead-ends, or cavities in LOX and oxygen-enriched cryogenic systems where the liquid is stagnant and can vaporize, allowing dissolved low-boiling-point hydrocarbons to concentrate and eventually precipitate. Various names have been applied to this vaporization and precipitation process including fractional vaporization, LOX boil-off, dead-end boiling, boiling-to-dryness, and dry boiling (see 7.17.3) (**27-30**).

7.5.2.2 Design necessary sumps, cavities, dead-ends or remote chambers carefully to exclude or minimize the accumulation of contaminants.

NOTE 13—Sumps and cavities cannot always be avoided and sometimes they are desirable to safely accumulate small amounts of debris. In these cases, they should be of burn-resistant alloys capable of withstanding ignition of the debris that might be present and should not be prone to acoustic resonance (see 7.10.1). Heat sinks or diluents (see 7.18.2) can also help to reduce this hazard.

NOTE 14—Systems that are free-draining and smooth surfaced internally, and that have a general downward flow direction will tend to retain less debris and deposits. Some contaminants (oils in particular) migrate more easily across polished surfaces than across rough (for example, grit-blasted) surfaces (**31**). The amount of oil retained on a smooth surface texture is less, and the surface-area-to-volume ratio is less (see 7.17). Thus, smooth surface finishes may be used to reduce contamination and oil hazards at critical regions.

NOTE 15—"Seal welds" are sometimes used to isolate internal regions of oxygen systems that cannot be adequately finished or cleaned. Because this practice has been linked to known incidents within industry, if seal welds are to be used, they should be used with caution and always properly applied.

7.5.2.3 Design bypass lines to exclude or minimize the accumulation of contaminants.

NOTE 16—A compatible bypass valve is typically a small economical copper-base alloy or nickel-base alloy valve that can be installed directly across a rapid-opening valve for use in pressure equalization to minimize particle impact and heat of compression ignition (see 7.6.2.3 and 7.7.2.4). The associated piping upstream and downstream of the bypass valve should also be designed for these hazards (see 7.6.3 and 7.6.4).

NOTE 17—Bypass lines are often used for system start-up scenarios or to facilitate cleaning or maintenance. When used on horizontal piping, bypass lines should be added off the top of the piping (see Fig. 6). Related tactics may be used on vertical piping. Though bypass piping off the top is preferred, construction at or above the horizontal center line is acceptable (**10**).

7.5.3 Use filters to limit the introduction of particles and to capture particles generated during service.

7.5.3.1 Consider the use of filters at sites of oxygen entry into a system, downstream of points where particles are likely

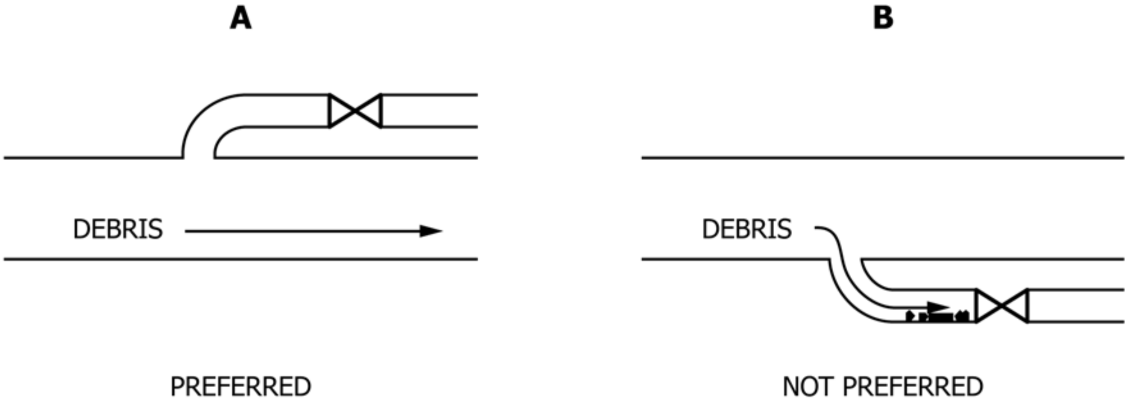


FIG. 6 Proper Orientation of Bypass Valves

to be generated, and at points where particle presence produces the greatest risk, such as at the suction side of compressors or upstream of throttling valves.

7.5.3.2 Use the finest (smallest mesh size) filtration for a system that meets system flow requirements.

NOTE 18—Common strainer mesh sizes for larger industrial gas applications range from 30 to 100 mesh (60 to 150 micron). For smaller, higher-pressure applications such as aerospace or welding, filters range from 2 to 50 micron.

7.5.3.3 Filter elements should not be fragile or prone to breakage. If complete blockage is possible, the elements should be able to withstand the full differential pressure that may be generated.

7.5.3.4 Design and maintain filters to limit local debris. Preventive maintenance of filters should be adequate to limit the hazard associated with flammable debris collected on the filter element.

7.5.3.5 Provide for preventive maintenance of filters.

NOTE 19—Such provision may include pressure gauges to indicate excessive pressure drop and a method of isolating the filter from the system to perform maintenance on it.

7.5.3.6 Use burn-resistant materials for filter elements since they typically have high surface-area/volume ratios (see 7.17 and Guides G63 and G94).

7.5.3.7 Consider parallel, redundant filter configurations with upstream and downstream shutoff valves (with pressure equalization if required) if the system cannot be shut down to change filter elements.

7.5.3.8 Avoid exposing filters or strainers to bi-directional flow. Exposing filters to backflow allows collected debris from the filter to flow back into the system and defeats the purpose of the filter. Furthermore, large debris dumps from backflow can increase the likelihood of ignition.

7.5.4 After assembly, purge systems with clean, dry, oil-free filtered inert gas, if possible, to remove assembly-generated contaminants.

NOTE 20—Unlike fuel gas systems, oxygen systems generally do not require inert gas purges after use, prior to "breaking into" the system for maintenance. The bulk materials of construction are often considered situationally nonflammable at ambient conditions (even with commercially-pure oxygen in the system), and the energies required to ignite these materials under these conditions are very high. If there exists a possibility of fuel gases or other ignitable contaminants being present, inert gas purges prior to maintenance are generally required.

7.5.5 Consider the locations and effects of operationally-generated contaminants in oxygen systems.

NOTE 21—Components that, simply by their function, generate particulates include compressors, pumps, check-valves, rotating-stem valves, and quick-disconnect fittings.

NOTE 22—Erosion in system piping caused by particle impingement can produce additional particulate debris and potentially contribute to ignition in an oxygen environment. Erosion has been shown to depend strongly on the angle of impact (angle between the direction of motion of the impinging particle and the tangent to the impacted surface at the point of impact) and the properties of the impacted material, among other factors **(32)**. For ductile materials, erosion is considered most severe at impact angles between 20 and 30 degrees, as material removal is implied to be predominantly by plastic flow. For brittle materials, erosion is considered most severe at a 90 degree impact angle, and material removal is implied to be predominantly by brittle fracture.

7.6 *Avoid Particle Impacts.*

NOTE 23—Particle impact can lead to ignition and fire in oxygen systems (see 5.2.6). Particle impacts tend to occur where oxygen streams are forced to stop or change direction near obstacles. Particles, which have greater inertia than gases, do not change direction as quickly and often impact the obstacle. The obstacle may be a large blunt surface or a raised edge.

7.6.1 Use filters to entrap particles (see 7.5.3).

7.6.2 Limit gas velocities to limit particle kinetic energy.

7.6.2.1 For steel pipelines, *Oxygen Pipeline Systems* **(10)** may be consulted for an industry approach to limiting oxygen gas velocities for given materials and pressures.

7.6.2.2 Use caution with choke points, nozzles or converging/diverging geometries that can produce Venturi effects and high local velocities (see Fig. 7).

NOTE 24—These geometries can produce local velocities far greater than the calculated average. They can even produce localized sonic and supersonic velocities in some cases where the overall pressure differential is less than required for critical (or choked) flow **(33)**.

(1) Use reducers with caution. Tapered "reducers" that downsize or "upsize" piping of differing diameter can produce extremely high local velocities and even form a rudimentary Venturi tube (see Fig. 7A) **(33)**.

(2) Do not neck tubing bent to form elbows or radii. Do not kink, compress or crush tubing (see Fig. 7B) **(33)**.

(3) Avoid configurations and operating conditions that would allow liquids to freeze and obstruct flow paths (see Fig. 7C) **(33)**.

(4) Recognize that tapered valve stems can form diverging geometries (see Fig. 7D) **(33)**.

7.6.2.3 Equalize pressure across valves prior to their operation (see 7.7.2.4).

(1) Consider that system start-ups or shut-downs can create high transient gas velocities. These velocities are often orders of magnitude higher than those experienced during steady-state operation.

(2) Consider that even small pressure differentials across components can generate gas velocites in excess of those recommended for various metals in oxygen service (see 5.2.6.2) **(10, 11)**.

7.6.3 Use burn-resistant materials where gas velocities cannot be minimized (such as internal to and immediately upstream and downstream of throttling valves).

NOTE 25—High-velocity and turbulent gas streams may be present in systems where the average cross-sectional velocity is calculated to be acceptable. For example, flow through a throttling valve or from small-bore piping into large-bore piping may create localized high-velocity jets, eddies and turbulence. These flow disturbances may cause high-velocity fluids to impinge against the interior of the larger piping. However at some point, the high-velocity fluid caused by these flow disturbances will settle and again resemble the calculated average velocity of the flowing fluid. Traditional practice **(10)** has been to assume that the flow velocities within the pipe will approach the average velocity within a distance of about eight to ten internal pipe diameters. Therefore, burn-resistant alloys are often used for a minimum of eight inside pipe diameters (based on the smallest diameter that would produce an acceptable average velocity) downstream of high-velocity flow disturbances. In some applications, the required length of burn-resistant alloy may also be determined using computational fluid dynamics to model areas of high velocity and impingement.

NOTE 26—If a high-velocity stream flows at right angles from a small

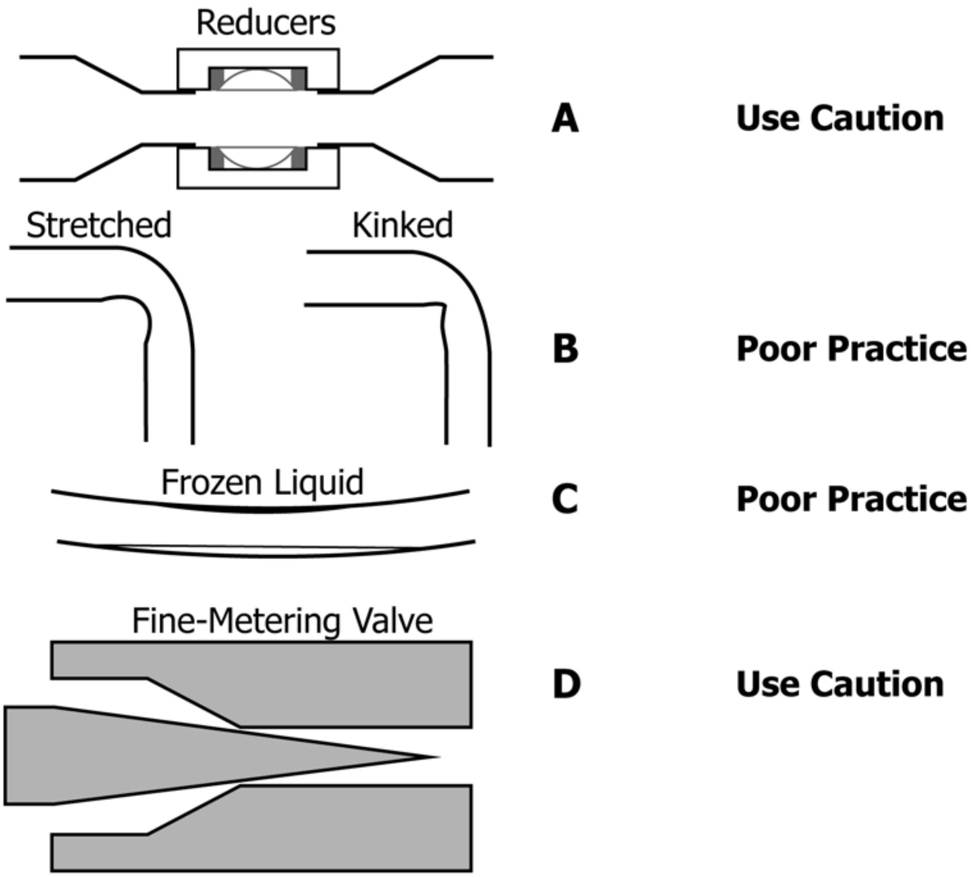


FIG. 7 Converging/Diverging Geometries that can Produce Venturi Effects and High Local Velocities

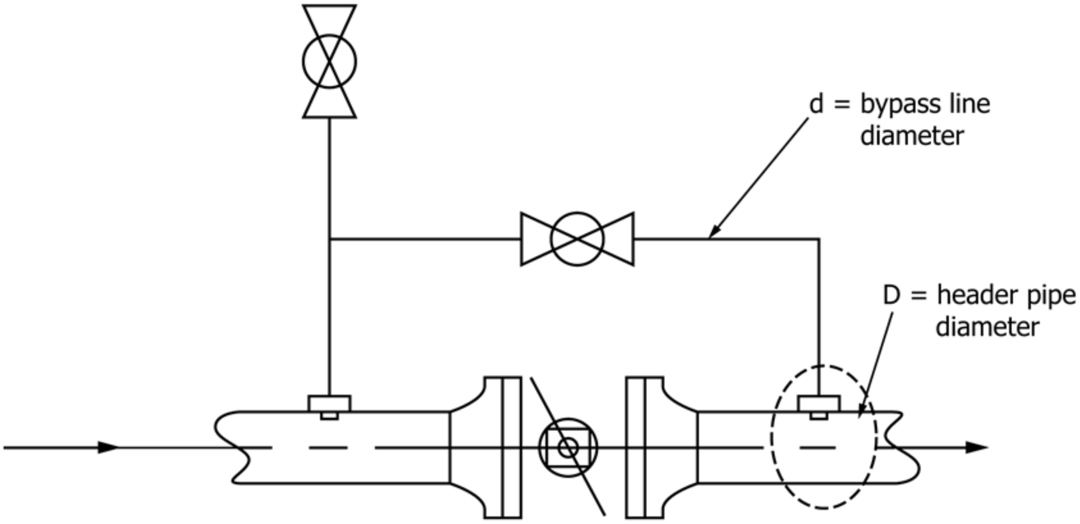


FIG. 8 Example of Bypass Line Configuration

diameter line, d, into a large diameter line, D, as shown in the bypass valve assembly in Fig. 8, then the design should ensure the flow is settled (that is, gas velocities should be low) before it reaches the opposite wall to avoid designing for impingement at this location (circled in Fig. 8). However, as in all oxygen system designs, the worst-case gas velocities at these impingement sites should be calculated and appropriate materials considered.

7.6.4 Use burn-resistant materials at particle impingement points (such as short-radius elbows, Tees, branch connections, orifices, and globe-style valves (**10**).

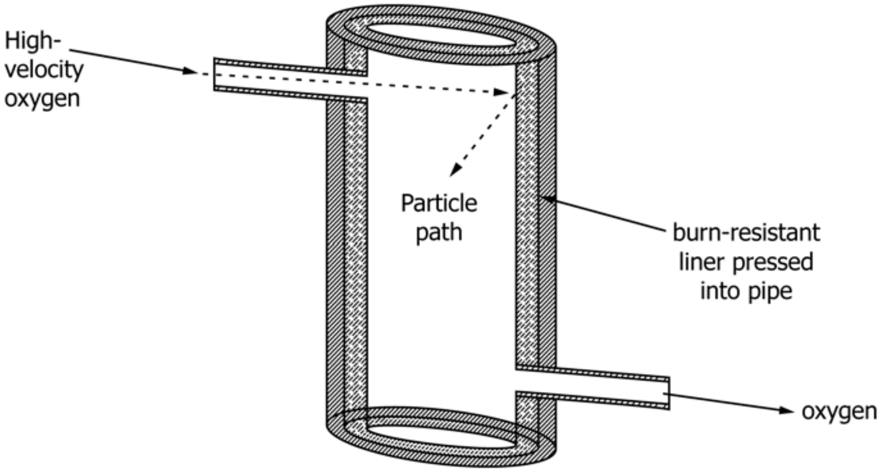


FIG. 9 Example of a Burn-Resistant Liner Applied Inside a Pipe

7.6.4.1 Burn-resistant alloys may be used as liners in applications where experience shows good reliability (Fig. 9). However, experience shows that welded impingement plates are generally not reliable and therefore not preferred.

NOTE 27—There is industrial experience with welded impingement plates in locations such as branch ports of Tees, and they have exhibited poor reliability, tending to break free in service if inadequately supported, and may flex and fatigue if inadequately supported or if insufficiently rigid. They may form a pressure-containing crevice (possibly containing unacceptable debris), or even a pressure-vessel-within-the-pressure-vessel if seal welded and the crevice may need to be vented externally. They are discouraged for general use. If used, they should be designed the same as for any pressure-containing component.

7.6.4.2 Weld overlay of burn-resistant metal alloy may be used to protect impingement sites (**34**).

NOTE 28—Overlay thickness must be sufficient to resist particle ignition (typically more than 1.0 to 3-mm, 0.039 to 0.125-in., thick). This precludes the use of electroplating to protect impingement sites, because it is too thin and may break free to produce unwanted debris. Platings are used only rarely in oxygen systems; typically only on precision surfaces such as valve balls and only if of the highest quality and adhesion.

7.6.5 Minimize pressurization rates which can create high transient gas velocities.

NOTE 29—System start-up dynamics can produce gas velocities and flow profiles that are more severe than those for steady-state flow conditions. Slow pressurization of a system can minimize these dynamics.

7.6.6 Do not impinge gas streams onto seats, seals, or other plastics or elastomers.

NOTE 30—Gas streams that impinge on nonmetals can cause premature deterioration of the nonmetal and lead to ignition by several mechanisms (for example, see flow friction, 5.2.12). Further, particulate entrained in gas streams can become embedded in the nonmetal and create surface impurities that may render the nonmetal more vulnerable to ignition.

7.6.7 Design for particle impacts to be at shallow oblique angles where practical.

7.6.7.1 Use the calculated normal (perpendicular) component of particle velocity as the effective gas velocity.

7.6.7.2 Streams interfacing at an angle of 20° or less are not considered hazardous for particle impingement (**10**) but may still be severe for erosion.

NOTE 31—Where gas streams are merged at an acute angle, the normal component of particle velocity (V sin theta) is often taken as a measure of the effective gas velocity (a 45-degree angle would be treated as 70 % of actual velocity). Further, the particle residence time (that is, time a burning particle resides against an impact target) is low. Thus, streams that impinge at an angle of 20° or less are not considered impingement sites (**10**).

NOTE 32—Streams containing particulates impacting at an angle of 20 to 30 degrees on a ductile material, or 90 degrees on a brittle material may cause debris generation through erosion (see 7.5.5).

7.6.8 Arrange for particles to move through a system without accumulation or sudden dispersal.

7.6.8.1 Orient high-flow (for example, ball, plug, butterfly, and gate) valves so that particles do not accumulate at the point of first opening, as shown in Fig. 10C. In horizontal piping configurations, orient high-flow valves vertically (with the stem directed up as shown in Fig. 10C) as opposed to horizontally (stem directed to the side as shown in Fig. 10A and B).

7.6.8.2 Implement strategic use of downward or upward flow piping where practical to accumulate fewer particles.

7.6.8.3 Use excess flow mechanisms, such as automatically resetting (**35**) or manually resetting excess flow valves, to reduce particle acceleration and to reduce both the consequences of ignition and the volume of oxygen that is available for reaction or release during a fire (see 7.12.1.1).

7.6.9 Relocate vulnerable impingement sites.

7.6.9.1 Locate vulnerable components out of both the normal- and upset-flow path.

NOTE 33—In Fig. 11, for pressure taps, location A is an impingement point for larger particles. Locations B and C are less vulnerable.

NOTE 34—Flow through elbows and curved piping can produce increased velocities through the establishment of twin-vortex secondary flow that may occur for some distance and may cause smaller particles to impact the wall or other obstacles, as shown in Fig. 11 (**36**).

NOTE 35—In assessing flow patterns in oxygen systems, modern computational fluid dynamics software can be helpful. These programs can calculate local gas velocities and gas directionality which can aid in evaluating the particle impact ignition hazard.

7.6.10 Eliminate impingement sites when possible.

7.6.10.1 Do not use weld-backup rings. The edge of back-up ring can be a blunt target for particles (see Fig. 12A)

7.6.10.2 Match piping joint bores carefully to prevent the edge from being a blunt target (see Fig. 12B).

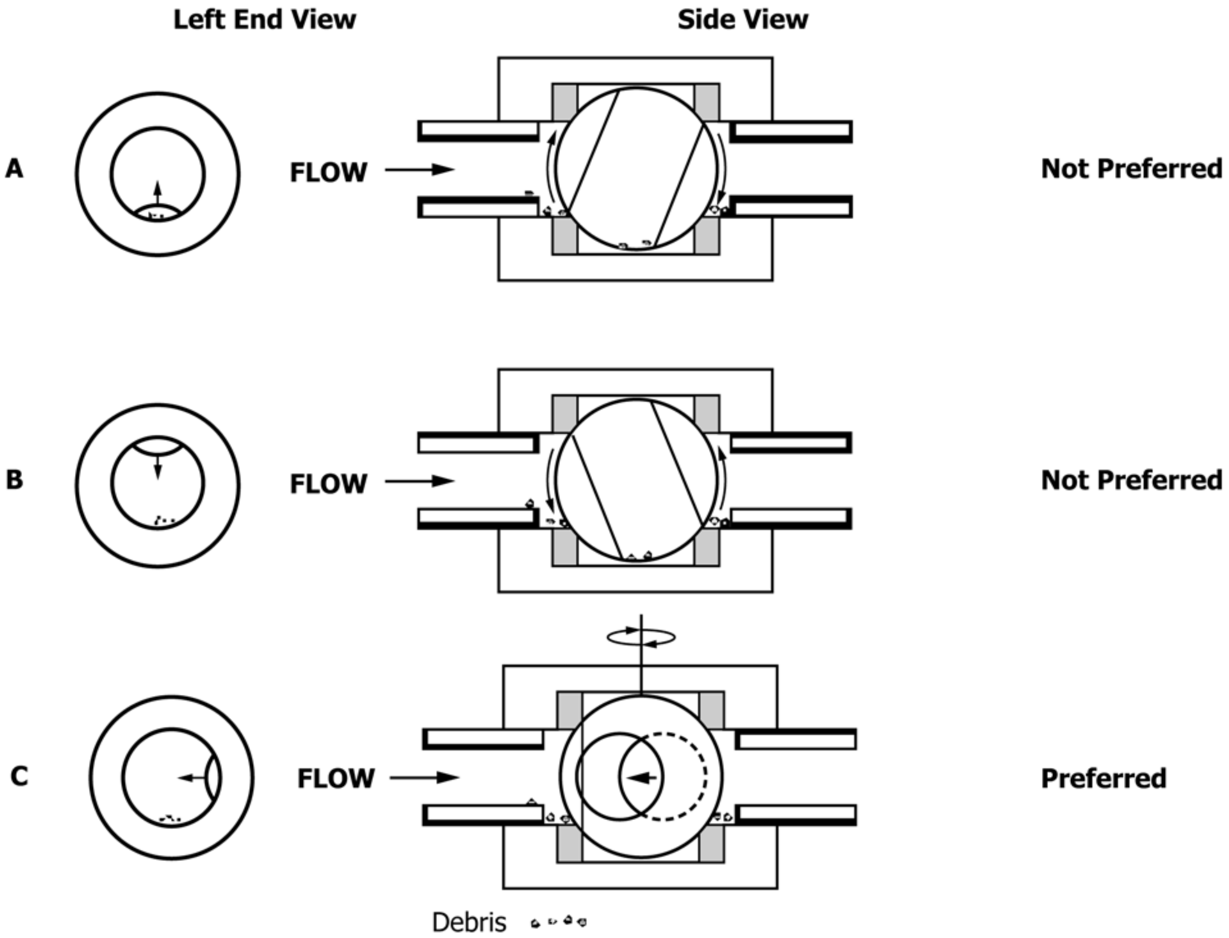


FIG. 10 Debris in Ball Valve Installations, Side and End Views

7.6.10.3 Match flange-gasket bores to piping inside diameter (see Fig. 12C).

7.6.10.4 Avoid large reduction ratios in pipe reducers (see Fig. 12D).

(1) Inlet:outlet diameter ratios > 3:1 are considered impingement sites **(10)**.

7.6.10.5 Use elbows and bent pipe with large ratios of curvature to diameter (L:d).

(1) Industry practice states that piping bends with a radius of curvature less than 1.5 times the pipe diameter (R < 1.5D) are considered impingement locations **(10)**. More "conservative" designs have historically considered R<5D as causing impingement **(37)**.

7.7 *Minimize Heat of Compression.*

NOTE 36—Heat of compression (also called adiabatic compression or pneumatic impact) is heat transferred when a gas is compressed (see 5.2.7). Ignition can occur if the temperature produced and the energy transferred to surrounding vulnerable materials (typically polymers) exceeds their autogenous ignition temperatures and minimum ignition energies.

7.7.1 Do not rapidly compress gas volumes against nonmetallic materials.

NOTE 37—Rapidly pressurizing nonmetallic materials to pressures greater than 3.4 MPa (500 psi) can generate theoretical maximum temperatures greater than the autogenous ignition temperature of all practical nonmetallic materials (see 5.2.7.1, Table 2).

7.7.2 Avoid rapid pressurization of components.

7.7.2.1 Avoid the use of fast-opening valves where downstream system volumes can be quickly pressurized.

NOTE 38—Fast-opening valves (such as standard ball valves) may be used if specifically designed to enable slow pressurization or used strategically for isolation only and are never opened with a differential pressure across the valve.

7.7.2.2 Select automatic valve operators that are slow opening.

7.7.2.3 Install flow restrictors where practical to limit pressurization rates.

NOTE 39—Orifice plates that are used for flow restriction typically experience high pressure differentials and choked flow. To reduce the risk of particle impact ignition, burn-resistant materials should be used for the orifice plastes and components/piping immediately downstream up to the point of flow settling (see 7.6.3). Orifice plates that are used for flow measurement typically experience relatively small pressure drops and only marginal gas velocity increases. They are much less severe in service and are often treated as impingement sites but not necessarily as causing hazards downstream.

7.7.2.4 Provide for pressure equalization across rapid-opening valves (see 7.6.2.3).

(1) Use slow-opening compatible bypass valves for pressure equalization where applicable (see 7.5.2.3).

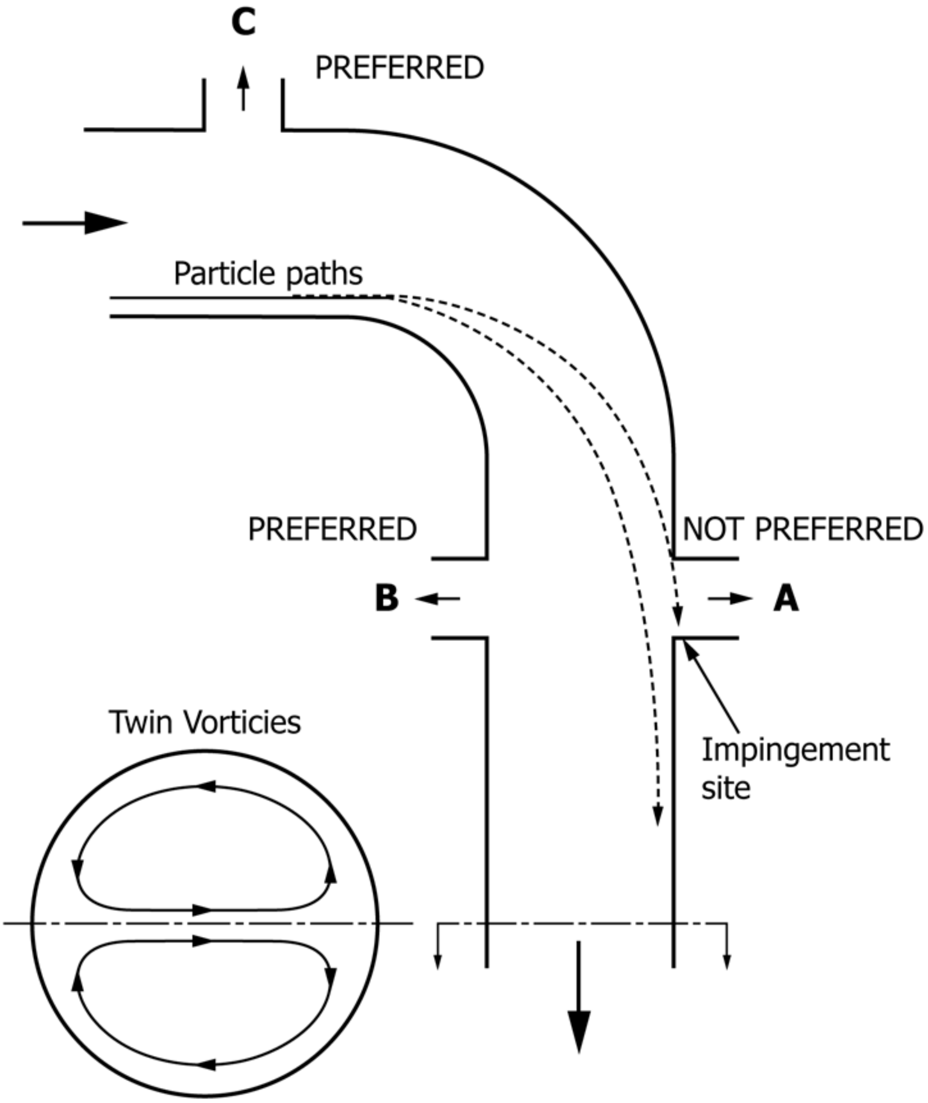


FIG. 11 Particle Paths and Twin Vortex Secondary Flows

(2) Equalize pressure from alternative (including temporary) sources where applicable prior to operating the fast-opening valve (**9**).

NOTE 40—When a valve is opened, the gas velocity through it is a maximum initially then decreases as the downstream system pressure increases. Particle impact is the primary concern and must be addressed at this time when gas velocities are greatest. As the downstream system approaches the upstream pressure, gas temperature downstream approaches a maximum and ignition of exposed polymers is the primary concern that must be addressed. Estimates can be made of the degree of pressure equalization needed to cope with each portion of the hazard (**9**). For example, if a downstream pressure is at least 90 % of the upstream absolute pressure, then its compression only increases the system temperature by 9°C (16°F), usually sufficient to defeat this ignition mechanism (**9**). If the downstream pressure is at least 50 % of the upstream absolute pressure (pressure ratio = 2), then its compression results in a final estimated temperature of less than 93°C (200°F) (starting from 20°C (68°F)), which is below the AIT of most nonmetals (see Figs. 3 and 4). Further, even a downstream pressure of only 15 % of the upstream absolute pressure (pressure ratio = 6.7), will probably not generate sufficient heat to ignite most highly-compatible nonmetals such as polytetrafluoroethylene (PTFE) (see Figs. 3 and 4) (**9**).

NOTE 41—Depending upon the sealing mechanism of some ball valves and how they are operated, they can isolate the ball bore when closed, potentially creating a low-pressure cavity within the bore that can be rapidly pressurized upon initial opening of the valve, subjecting the downstream seat to heat of compression (**38**). Ensure that ball valves are specified with features to prevent this.

7.7.2.5 Avoid pressurization times of less than 1 second where practical. Longer pressurization times are preferred and may be required for larger piping systems.

NOTE 42—Testing has shown that pressurization rates of less than 1 second can ignite polymer-lined flexible hoses, even at low pressures (**15**). Experience indicates that smaller, high-pressure systems, such as those with an oxygen cylinder source can be especially vulnerable to ignition by heat of compression.

7.7.2.6 Use "distance/volume pieces" to isolate polymers from end points that experience heat of compression (**39**).

NOTE 43—A distance/volume piece (DVP) is a section of metal, as shown in Fig. 13, that is used (typically at the end of a flexible polymer-lined hose) to contain the hot compressed-gas slug that can form during pressurization and to safely absorb its heat of compression. Fig. 13A and B show DVPs at the ends of hoses downstream from where they are pressurized. Fig. 14C shows DVPs on both ends of a hose that may be

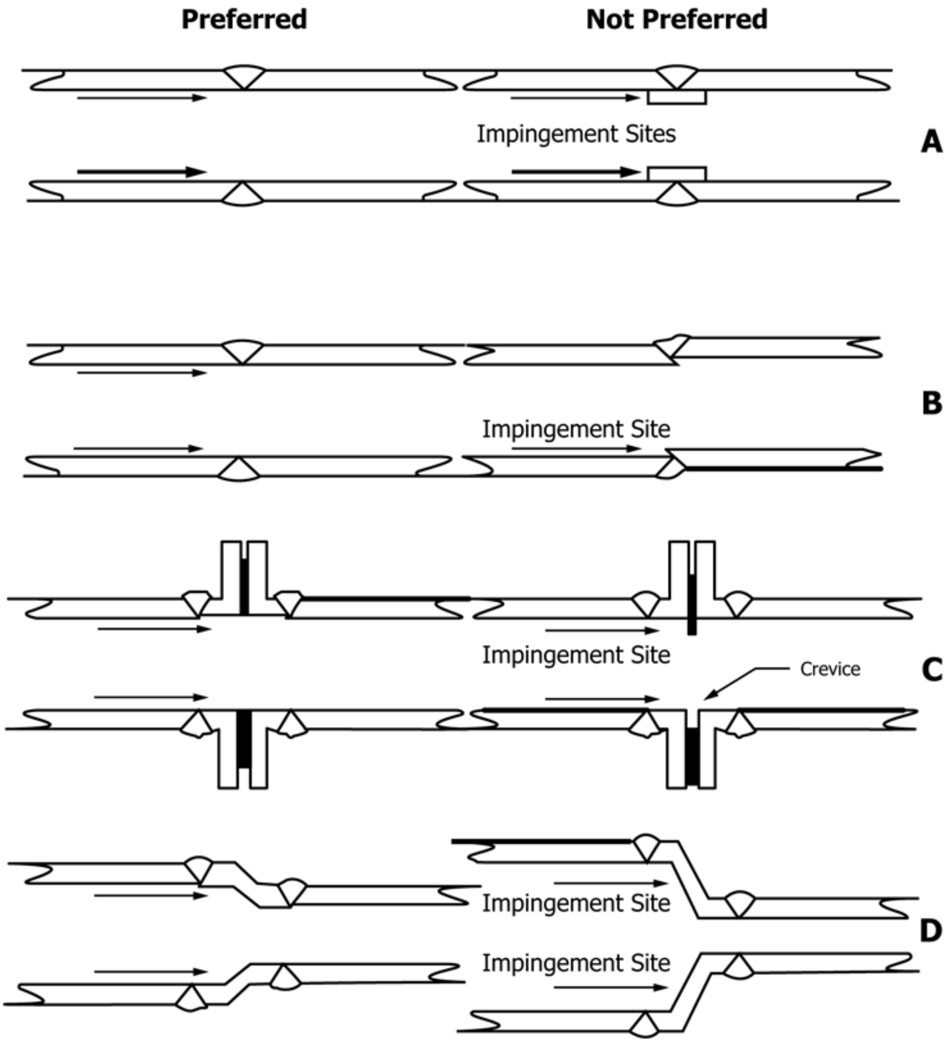


FIG. 12 Eliminating Impingement

pressurized from either direction. Several design criteria for these devices have been proposed (**15**, **39**, **40**). The required size of distance/volume piece can be calculated by ensuring the compressed volume of gas in the system downstream of the pressurization point is completely contained in the distance/volume piece. A complimentary computer algorithm[4] is available from ASTM G04 committee to assist in this calculation based on two of the strategies that have been proposed (**40**).

7.7.2.7 Use larger distance/volume pieces where applicable for increased protection from compression heating.

Note 44—When a system is rapidly pressurized, the initial gas volume (slug) is compressed and heated. For a constant final pressure, the lower the initial system pressure, the higher will be the final compressed-slug temperature, and the greater the prospect of exceeding polymer (or contaminant) autogenous ignition temperatures. However, up to a point (estimated at about 31 % of the final absolute pressure (**41**)), the higher the initial system pressure, the greater the heat available to transfer to system components, and therefore the greater the likelihood of exceeding the component's minimum ignition energy. The critical initial condition relative to these combined factors lies within these extremes and has not been well studied. Designs should ensure that the initial pressure does not vary greatly from the design pressure to prevent both of these effects.

7.8 *Avoid Friction and Galling.*

7.8.1 Avoid rubbing components. Components that commonly rub include some valve stem and seat assemblies, packing glands, etc. (**11**).

7.8.2 Design rotating or reciprocating machinery so that clearances are adequate and verifiable (**42-44**).

7.8.3 Use burn-resistant materials where friction cannot be limited.

7.8.4 Use sensors to detect rubs or instabilities in rotating or reciprocating equipment and, if applicable, to initiate shut down.

Note 45—Carefully assess whether to shut down or otherwise respond to anomalous conditions in the operation of high-speed machinery that is rotating above its critical speeds. The transition through the critical-speed points may worsen rubs and instabilities and be an additional ignition-inducing or fire-aggravating influence. If such anomalous conditions occur in rotating or recipricating equipment, sensors may also act to shut off the oxygen supply where appropriate.

7.8.5 Ensure periodic maintenance is performed on rubbing, rotating or reciprocating equipment at intervals specified by the manufacturer.

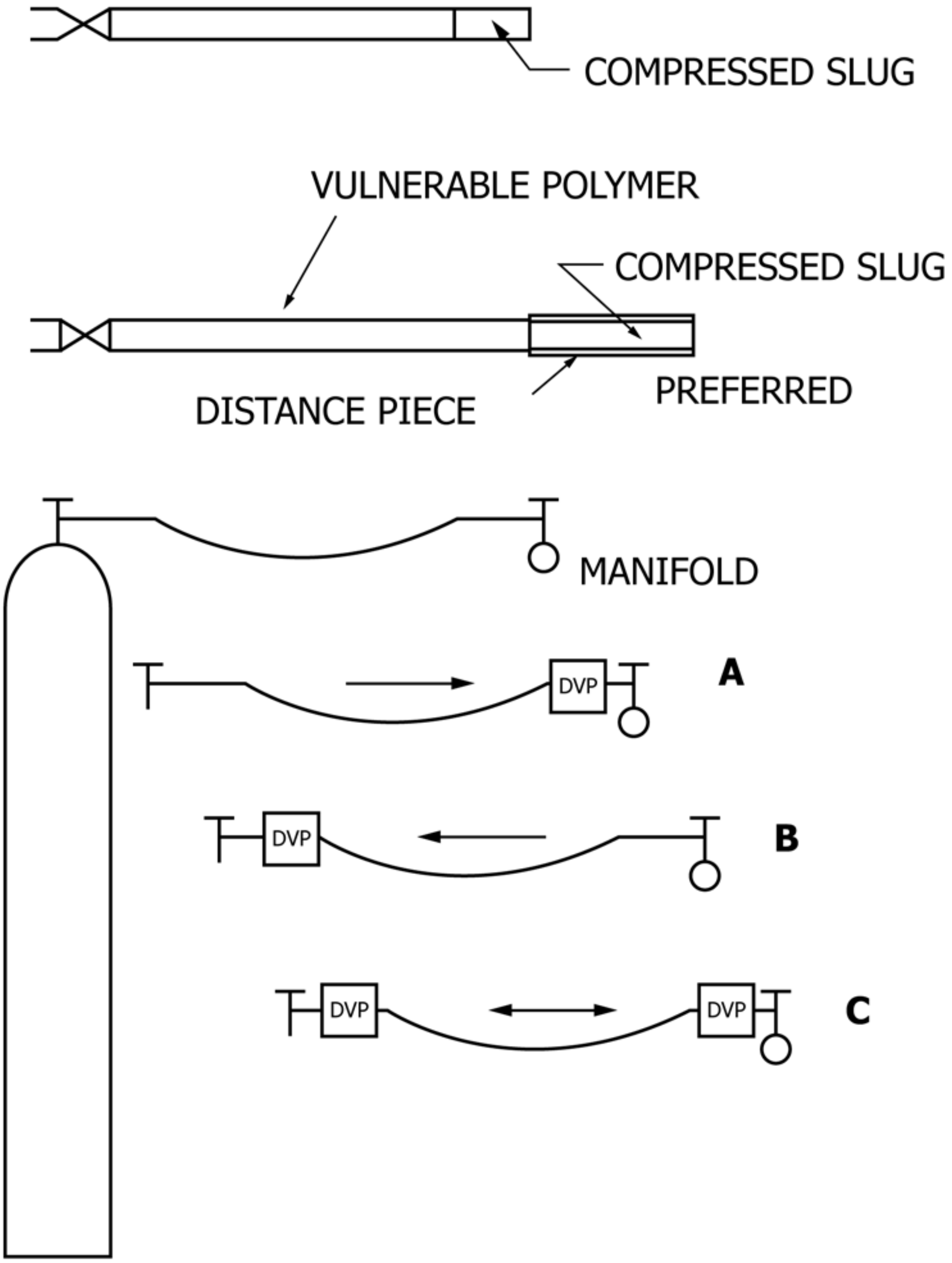


FIG. 13 Distance/Volume Pieces (DVPs) on Polymer-Lined Flexible Hoses

7.9 *Avoid Corrosion.*

NOTE 46—Corrosion prevention is a highly advanced and specialized technology addressed in general by a number of textbooks, college curricula and professional societies (**45, 46**). Within ASTM, Committee G01 on Corrosion of Metals publishes a body of standards and sponsors manuals and symposia on the subject. Important corrosion issues that are commonly dealt with by oxygen system designers include the following: *(1)* influence of internal moisture, *(2)* external corrosion prevention through material selection, coatings and both active and passive cathodic corrosion prevention, *(3)* stress corrosion cracking, *(4)* corrosive product species, and *(5)* corrosive degradation or combustion species.

NOTE 47—Moisture should be avoided in oxygen systems unless specifically designed for corrosion resistance (**46**). A dew point of -40°C (-40°F) or lower is preferred for oxygen systems.

7.10 *Avoid Resonance.*

NOTE 48—Resonance is a highly configuration-dependent phenomena in which standing (resonant) pressure waves form in relatively stagnant regions of a gas system. A detailed description of resonance ignition and an example illustration are provided in 5.2.9.

7.10.1 Avoid unnecessary blind, open, symmetrical, unswept passages (see Fig. 5).

7.10.2 Avoid unintentional sonic gas jets into closed-end cavities.

NOTE 49—Studies performed to date on resonance phenomenon indicate that acoustic resonance generally requires internal symmetry and open flow geometries. Baffles, mufflers, or other system configuration changes can prevent resonant conditions from developing. However, care must be taken not to introduce particle impingement sites with these design changes.

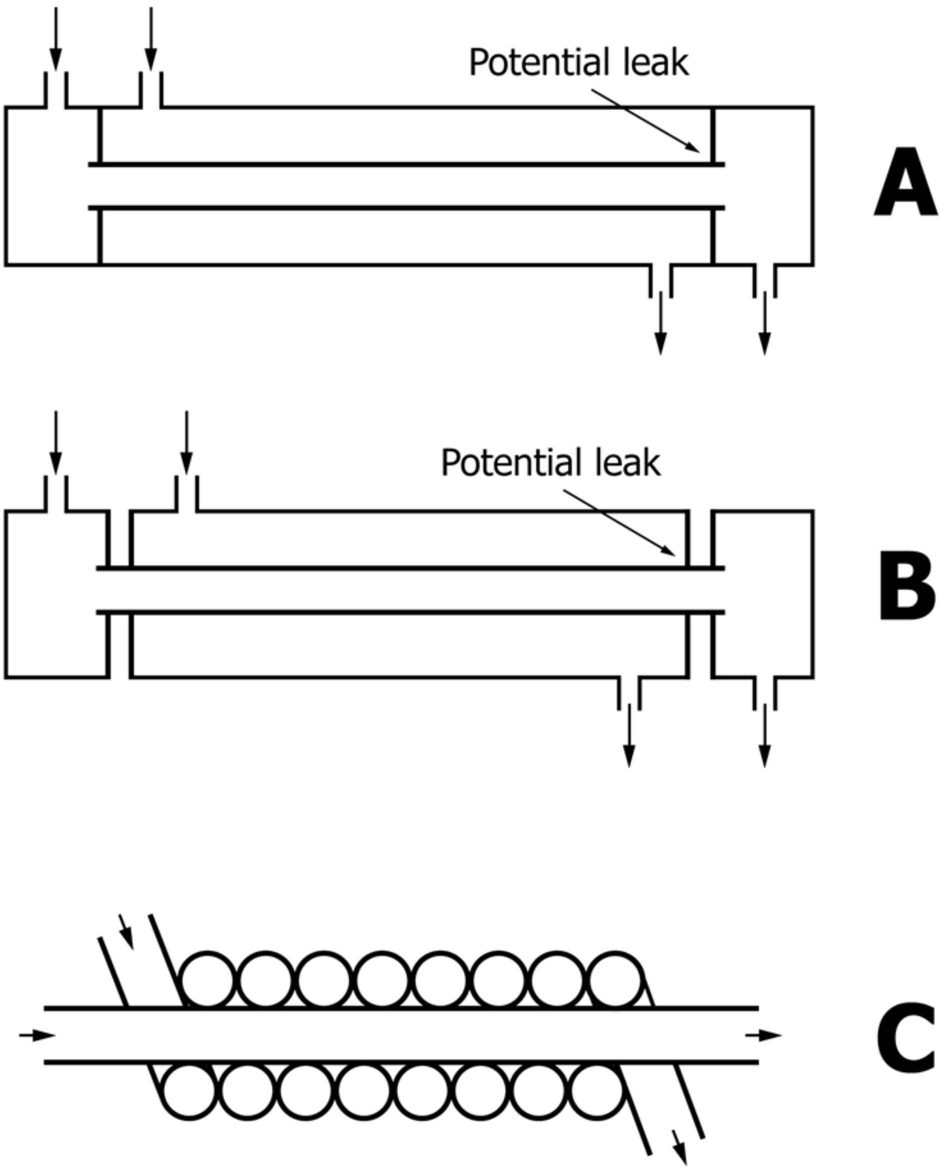


FIG. 14 Examples of Safeguard for a Heat Exchanger

7.11 *Use Proven Hardware.*

7.11.1 Use hardware that has a significant trouble-free history in oxygen service under similar operating conditions.

7.11.2 Pretest components or systems with oxygen in a controlled environment prior to use.

NOTE 50—"Techniques Employed by the NASA White Sands Test Facility to Ensure Oxygen System Component Safety" in STP 812 (**47**), discusses one procedure for stress-testing of components that has been used with the basic apparatus specified for gaseous impact testing in Test Method G74. An elaboration of one philosophy for this type of testing is given in ASTM , "Safe Use of Oxygen and Oxygen Systems" (**11**). In the case of oxygen regulators for medical applications, a recent standard, Test Method G175, provides a consensus validation procedure.

7.11.3 Ensure the conditions that establish the history of use or component testing (that is, pressure, temperature, flow rates, etc.) are as severe or more severe than the intended application. System severity is discussed in Guide G128.

7.12 *Design to Manage Fires* (**48**, **49**).

7.12.1 Provide an automatic remote means of gas shutoff to isolate critical components from all bulk oxygen supplies.

NOTE 51—The shutoff may be activated by a fire or other sensor and may, if advantageous, simultaneously vent the oxygen in the system (see 7.13.1). In some cases where shutoff valves may be at risk in an incident or where the consequence of failure is great, they should be protected (such as by barricades or fire-breaks)

7.12.1.1 Use excess flow valves where practical to shut off flow in the event of a line rupture. Ensure that the materials and design of excess flow valves are suitable for the oxygen application. (see 7.6.8.3).

7.12.2 Locate bulk oxygen supplies away from the system and flammable materials.

7.12.3 Use shields, barriers, or safety distance as required to isolate potentially hazardous apparatus (**10**).

7.12.4 Install fire extinguishment equipment where applicable, to extinguish secondary (and in some cases primary) fires caused by the initial fire in the oxygen system.

7.12.5 Install fire-break sections in pipelines, tubing runs, equipment, etc. Use burn-resistant materials or changes in flow direction, such as elbows, to enhance fire-break performance where practical.

7.13 *Anticipate Indirect Oxygen Exposure.*

7.13.1 Discharge vents to areas capable of dissipating the oxygen or resisting ignition, and direct vents above and away from personnel.

7.13.2 Evaluate the effects of leaks or releases on surrounding areas and equipment. For example, avoid cryogens on carbonaceous surfaces (see 5.2.12).

7.13.3 Anticipate that mechanical failures, such as leaks through control valve seats, may result in an oxygen exposure exceeding system design limits.

7.14 *Minimize Available Fuel/Oxygen* (**50**).

7.14.1 Shield and minimize the size of all system nonmetals, especially primary seals and seats (**11**).

NOTE 52—Most nonmetals will support burning in near-100 % oxygen concentrations at just slightly elevated oxygen pressures. They are also more easily ignited than metals and generally exhibit larger heats of combustion when they burn (see 7.21.3). Thus, nonmetals are generally considered the most vulnerable parts in oxygen system components and as such should be minimized and protected from potential ignition mechanisms.

7.14.2 Minimize the internal volume of components to reduce the oxygen they contain.

7.15 *Avoid Potentially Exothermic Material Combinations.*

NOTE 53—Exothermic material combinations are generally most severe as finely-divided geometries such as metal powders, dust or fine particulates, which may be generated by metal fabrication processes, wear, and corrosion processes. Poor cleaning practices may aggravate the potential hazard.

7.15.1 Avoid chlorine-containing lubricants on aluminum in high-stress load applications.

NOTE 54—Testing and experience has shown that aluminum and lubricants containing chlorine components (for example chlorotrifluoroethylene (CTFE)) can react violently under increased mechanical stress due to exothermic aluminum-chlorine reactions. Worst-case applications may include connection fittings where higher stress loads are common.

7.15.2 Avoid contact of corrosion products, especially oxides of iron, copper and nickel, with aluminum.

NOTE 55—Iron oxide (rust) in the presence of aluminum powder can, upon ignition, result in an exothermic reaction as the oxygen in the iron oxide is transferred to the aluminum with a net release of heat. This is in a class of reactions known as thermite, which can also occur with less common low-heat-of-formation metal oxides (zinc oxide, copper oxide, etc.) and other metals (magnesium, titanium, zirconium, etc. (**21, 51**)) that have high heat-of-formation oxides. Thermite igniters are sometimes used to ignite metals in experimental programs. It should be noted, however, that thermite reactions require large energy inputs for initiation (that is, the aluminum must reach its melting temperature) and are relatively uncommon in general oxygen applications. Theoretical heats of reaction for thermite reactions can be cited (**21, 51**).

7.15.3 Avoid conditions where molten or powdered aluminum may form in the presence of palladium or nickel. These combinations can form exothermic intermetallic compounds.

NOTE 56—Aluminum powders are very reactive and can readily self-ignite, becoming molten. Palladium in contact with aluminum powder can, upon ignition, result in an energetic exothermic reaction as the palladium alloys with the aluminum to produce an intermetallic compound (such as palladium aluminides) with a net release of heat. Nickel can also form intermetallic compounds with aluminum powder (such as nickel aluminides) (**21**). Bifilar palladium and aluminum wire with electrical stimulation is a frequently used ignition source for experimental materials flammability testing in oxygen.

7.15.4 Avoid conditions where metal hydrides contact oxygen without a sufficient heat sink.

NOTE 57—The hydrogen in metal hydrides can react with oxygen exothermically, sometimes spontaneously, upon first contact. Common practice is to use palladium oxide to getter hydrogen in the vacuum jackets of liquid oxygen vessels. Incidents have occurred where failure of the vacuum space produced spontaneous reactions of the gettered hydrogen when oxygen leaked into the vacuum space. Some of these incidents may have involved the formation of palladium hydrides at some stage of the getter lifetime. Subsequent testing has shown that wrapping the palladium oxide with a properly-designed heat sink that contains the palladium oxide can reduce the hazard. This approach is being successfully used throughout industry. Further, stable hydrides may not be as reactive in oxygen.

7.15.5 Avoid conditions where burning metals contact liquids.

NOTE 58—Contact of hot molten and/or burning metals with liquids can lead to "steam" explosions (**21**) or even more severe reactive explosions, either of which can be particularly destructive. Very reactive metals, such as aluminum, have produced severe reactions when burned under or spilled into liquid oxygen (LOX), and even when abruptly combined with water (**21**). In some cases, the reaction can be more destructive than TNT (**52**).

7.16 *Anticipate Common Failure-Mechanism Consequences.*

7.16.1 Avoid unintended exposure to oxygen. Materials not intended to be exposed to oxygen may not be compatible with oxygen and ignition mechanisms may be present.

7.16.1.1 Spillage of LOX onto porous materials (wood, asphalt, macadam, etc.) can produce an easily ignited explosion hazard (see 5.2.13.3).

7.16.2 Use redundant safeguards where secondary hazards are present.

NOTE 59—A safeguard can be a physical container wall, electronic system (interlock), or computer code, administrative procedure, etc. When the failure of a single safeguard can lead to a hazard (exposure of contamination, over-pressurization of components, excess velocities, etc.), it is referred to as a single-safeguard failure (**11**). In crucial systems, or systems prone to failure, corrosion, etc., two or more levels of safeguards may be required.

7.16.2.1 Example: Noncontact heat transfer fluid of ethylene glycol and water is often used in heat exchange with an oxygen system. The heat-exchanger wall between the fluids is one safeguard against their mixture. Fig. 14, Parts A-C exhibit three different multiple safeguard systems for this application.

(1) Fig. 14, Part A is the least conservative and exhibits a simple shell-and-tube. In this case, failure of the press fit on any tube or corrosion at the tube/header interface may allow contact of the coolant and gas. Water in any coolant that enters the oxygen circuit will quickly evaporate to leave ethylene glycol which has a very low ignition threshold in oxygen. Oxygen leaking into the coolant circuit presents less risk because of the large amount of water that is present. A second safeguard could be achieved by maintaining the oxygen pressure significantly above that of the coolant so that any

leakage is in the less risky direction. Methods to sense such leakage in the coolant circuit should be used.

(2) Fig. 14, Part B shows a more conservative system in which the oxygen and coolant circuits do not share a common header. In this case leakage of oxygen or coolant at the vulnerable press fits does not introduce either fluid into the other circuit. If both leak and contact, it is at the low risk atmospheric pressure condition.

(3) Fig. 14, Part C shows the most conservative system in which the vulnerable press-fits have been eliminated and leakage between the circuits must breach two contiguous physical walls. In this case, as well as Case B, a tertiary safeguard could be applied by maintaining the oxygen pressure above the coolant pressure to minimize the effect of the most hazardous leakage path.

7.17 *Avoid High Surface-Area-to-Volume (S/V) Conditions where Practical*—High S/V conditions include mesh screens, powders, granules, open-cell foams and sponges, thin fins, sharp edges, points, sintered filters, etc.

NOTE 60—The hazards of fires in oxygen increase with the amount of exposed surface area, and the speed and extent to which a material is heated increases as the mass of the material absorbing the heat is decreased. Therefore objects that expose a lot of surface area with minimal associated mass tend to be more flammable (more easily ignited, faster burning, etc.) than objects with small reaction surfaces and large masses (heat sinks) to absorb heat. Further, high S/V geometries can be difficult to clean sufficiently for oxygen service and often require special treatment. Table 3 **(53)** shows the wide range of S/V properties of many common shapes.

7.17.1 Use burn-resistant materials for high S/V configurations. The higher the surface-area-to-volume ratio, the more critical is the use of burn-resistant materials. In the most extreme cases, such as powders, even the most highly burn-resistant of common engineering metals may be too flammable for any practical use.

NOTE 61—Mesh screens of nickel and sintered element filters of brass or tin bronze have been shown to be burn-resistant and therefore preferred for their respective applications (see 7.5.3.5).

7.17.2 Avoid thin metallic sections where practical.

7.17.2.1 Metals are more flammable in thin sections than in thick sections. Also, thin metallic sections can ignite thicker adjacent sections through the kindling chain mechanism (see 5.2.14).

7.17.2.2 Thin sections of metals should be avoided where practical but if required (for example, metal filter) should be made from burn-resistant metals.

TABLE 3 S/V Ratio of Various Shapes

Shpae	S/V Ratio (m^2/m^3)
1 µ dust Spheres	6 000 000
0.3 mm Spheres	20 000
0.2 mm Rods^A	20 000
0.1 mm Sheets^B	20 000
0.6 mm Spheres	10 000
0.2 mm Sheets	10 000
3.2 mm (0.13-in.) Rods	1259
6.4 mm (0.25-in.) Rods	630

^{A} Wires, screens, and rods, for the same diameter, have identical S/V ratios.

^{B} Sheets, strips and structured packing, for the same thickness, have identical S/V ratios.

NOTE 62—Experimental data reveal that for most materials, ignitability and flammability decrease with increasing thickness of the specimen. In some cases, a component may be shifted from a flammable condition to a nonflammable condition by increasing its thickness. Practical criteria to exploit this effect with piping components in some situations have been proposed **(10)**. However, the flammability of materials also varies greatly with system conditions (pressure, temperature, gas velocity, etc.). Thus, increasing thickness to reduce flammability may not necessarily be reliable.

NOTE 63—Exterior corrosion creating thin sections on piping can reduce both the pressure rating and oxygen compatibility of the pipe. For example, an oxygen fire internal to piping is more likely to burn through a thin section of corroded pipe (especially at an elbow, Tee, or other impingement point).

7.17.2.3 Remove sharp edges and burrs exposed to oxygen because they are more easily ignited than bulkier base materials.

NOTE 64—Burrs are also easily broken off in systems and can become undesired contaminant or potential particle impact ignition hazards.

7.17.3 Avoid intimate contact configurations of oxygen with flammable materials.

NOTE 65—Many of the hazards of oxygen fires increase with the degree of intimacy of oxygen with flammable (that is, "reactive") materials. Intimate configurations are those where the quantity of oxygen in close proximity with flammable materials is large. This produces the ability for a large quantity of oxygen to rapidly combine with the fuels, even at explosive speed, as opposed to slower combustion in which vaporization, diffusion and other mass transport must occur for the oxygen to react. As a result, ignition is easier, rate of reaction is greater, and peak temperatures and pressure during a fire are increased.

NOTE 66—Solutions and some mixtures of oxygen do not exhibit a clearly defined surface area, but as with high S/V geometries, they have large numbers of oxygen molecules in close proximity with reactive material molecules and can yield rapid or even explosive reactions. Some of these configurations can be difficult to identify but include porous closed-cell materials into which oxygen may diffuse, materials with a high solubility for oxygen (including miscible gas/gas and liquid/liquid mixtures), molecular sieves containing both oxygen and hydrocarbon adsorbates (that is, activated charcoal), "char" products from incomplete combustion processes, etc. (see 7.5.2.1).

7.17.3.1 Example: Fractional evaporation of liquid oxygen. As the liquid vaporizes, low-boiling-point hydrocarbons concentrate and may ultimately produce an intimate mixture or slurry of fuel with oxygen.

NOTE 67—Where explosive reactions of intimate mixtures may occur, one can estimate the scale of damage possible and the zone of hazard using TNT equivalencies **(54-56)** which relate the available heat of combustion (as limited by the amount of fuel or oxidant, whichever is less, in the intimate configuration) plus any compressed-gas energy to a comparable energy release from TNT and its studied destructive potential. These estimates can help decide if a system will safely contain a reaction, or assist in the design of any needed barriers and the selection of safe distances **(11)**.

7.18 *Avoid Unnecessarily Elevated Oxygen Concentrations.*

7.18.1 Reduce the oxygen concentration (that is, perform any mixing operations) near the oxygen supply point rather than near the mixture use point so that intermediate equipment is exposed to lower oxygen concentrations.

7.18.2 Use diluents where practical to minimize ignition and increase the burn-resistance of the materials **(57-59)**.

NOTE 68—A diluent is most commonly taken to be a material that is nonreactive with oxidants or fuels in the system of interest **(59)**. Diluents may be inherent (nonreactive under all conditions) or situational (nonreactive at system conditions). Examples commonly include the noble gases and stable oxides such as carbon dioxide. Diluents may be solids, liquids or gases. In rare cases, diluents can enable or accelerate a fire. More often, diluents slow or swamp a reaction, often preventing it. They are often used as extinguishers. Their effect depends on their mass, heat capacity and specific chemistry among other factors. In most cases, the effectiveness of a diluent increases as the size and mass of the diluent molecule increases (monatomic neon is more effective than monatomic argon, triatomic carbon dioxide is more effective than diatomic nitrogen) because heavier and larger diluents absorb more heat and diffuse more slowly. However, diluents may be situational. Nitrogen is a diluent that does not react during iron or hydrocarbon combustion, but may be a slight oxidant during aluminum or titanium combustion. In some cases, tiny amounts of diluents may have dramatic effects on the hazard of oxygen.

NOTE 69—Common diluent impurity gases in commercial oxygen include argon, nitrogen, and water vapor. Even as minor constituents, these diluent gases can be crucial to the oxidation hazard of a system, especially if the system contains specific metals (aluminum, magnesium, titanium, etc.). Oxygen specifications may vary in purity from 99.5 % oxygen to 99.9999 % oxygen (balance largely argon) and the flammability hazard can vary widely (**7**).

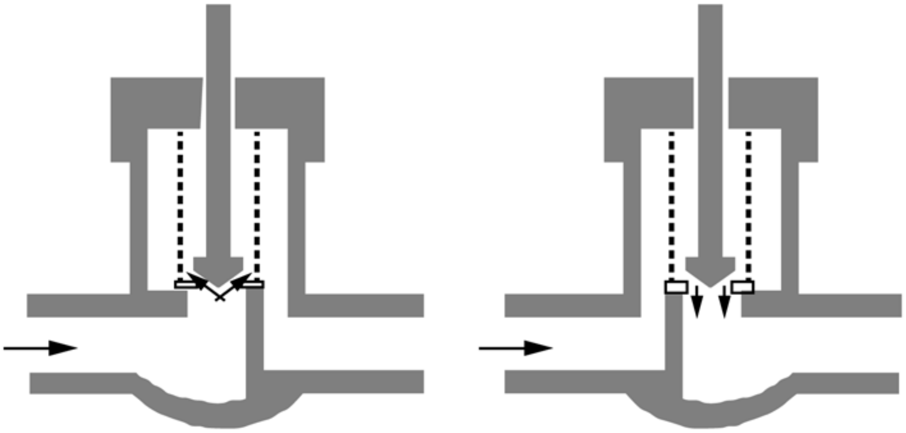
7.18.3 Avoid unintentional oxygen concentration drift in oxygen-enriched air systems.

NOTE 70—Oxygen concentration drift may result from depletion of diluent sources, software bugs in programmable logic controllers (PLCs) or other computerized controllers, creep in the oxygen pressure, etc. NFPA 86 on ovens and furnaces (**59**) is concerned with the use of PLCs on critical systems. Similar safety concerns apply to use of these devices with critical oxygen systems.

7.19 *Anticipate Permutations from Intended System Design.*

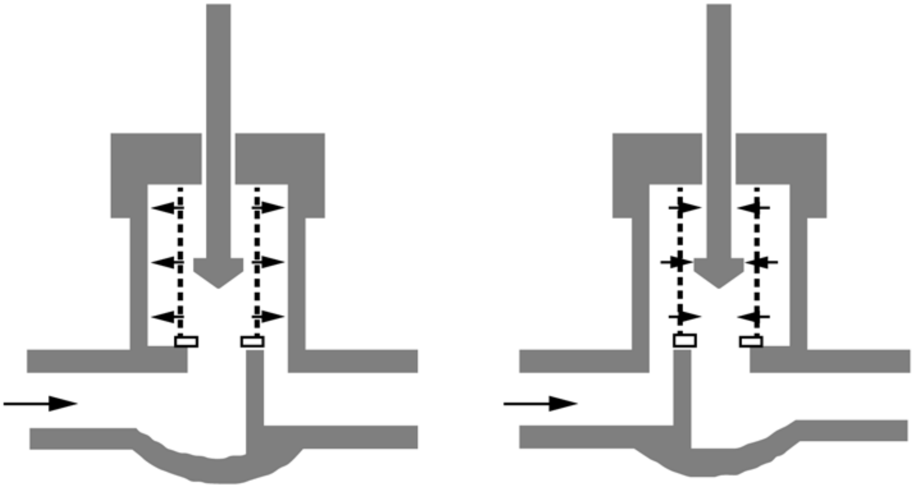
7.19.1 Perform failure effects and reliability studies to identify predictable system failures. These include Failure Modes and Effects Analyses (FMEAs), Hazards and Operability Studies (HAZOPSs), and fault-tree analyses (**58**) in addition to Oxygen Hazards and Fire Risk Assessments (OHFRAs) (**1, 60**).

NOTE 71—In general, administrative controls (procedures that rely on human actions) are significantly less reliable than well-designed automatic



A Normal Flow
Pressure Drop at Seat

B Reverse Flow
Pressure Drop at Seat



C Normal Flow
Pressure Drop at Cage

D Reverse Flow
Pressure Drop at Cage

FIG. 15 Reversing Flow through a Common Cage-Type Valve systems. However, automated systems (especially software-driven systems) can be unreliable and many are cited as "fault-intolerant." In crucial circumstances, redundant systems may be needed to achieve the degree of reliability on critical factors a system requires.

7.19.2 Design for component directionality and verify flow direction after installation.

NOTE 72—Many components can be used in assorted orientations that may seem similar in function, but can be widely different in oxygen compatibility. As discussed above, Fig. 10 illustrates how the angular orientation of valves may affect compatibility. Fig. 15 illustrates how the flow direction used with valves can also affect compatibility by altering the components that experience the most severe impingement. For globe-style valves such as that shown in Fig. 15, the generally preferred flow direction to minimize oxygen hazards is from under to over the seat, shown in Examples A and C. This configuration is generally considered less severe for high-velocity particle impingement and also may provide some level of flow control during opening (depending on the valve stem/plug characteristics). An over-to-under-the-seat flow direction exposes the stem seals to the high-pressure side even when the valve is closed. For the valve shown in Fig. 15, if the pressure drop (that is, highest gas velocity) is taken at the seat (Examples A and B), changing flow direction changes the most severe impingement sites from the stem tip and inside cage surface in Example A, to the downstream body of the valve in Example B. Similarly, if the pressure drop is taken through the cage (Examples C and D), the most severe impingement site changes from the bonnet wall in Example C, to the stem and stem tip in Example D. Other compatibility factors may be altered in similar or differing ways.

NOTE 73—Though many components have the intended flow direction stamped on the component body to ensure proper installation, many do not have this feature. Component directionality should always be verified after system installation. When in doubt, the component manufacturer should always be consulted regarding intended flow direction.

7.19.3 Control system configurations and custom modifications, including materials.

NOTE 74—Once an oxygen system is designed, reviewed, and approved, its configuration should be controlled to ensure inappropriate substitutions are not made. In many cases, components may be customized to adjust a specific property and to achieve adequate oxygen compatibility. When these components fail, wear out, are upgraded or undergo preventive maintenance, it is critical that components are replaced in-kind or that a formal management of change process is employed to ensure new configurations are properly reviewed for oxygen hazards.

NOTE 75—Whenever a component is customized (a material change, a geometry change, an installation change) it should be given a unique part number that distinguishes it from off-the-shelf hardware, and the new part number should be placed on the component and on all parts lists and flow sheets. In some cases components can be manufactured so that they can only be installed correctly.

7.19.4 Avoid overly-complicated procedures.

NOTE 76—Complex and repetitive procedures are more prone to discrepancy than simple, straightforward procedures. Equipment should be designed for simple verifiable operation.

7.19.5 Ensure that oxygen is not substituted for other gases. A common error is to substitute oxygen for compressed air.

7.19.5.1 Do not use oxygen to purge or proof-test incompatible equipment.

7.19.5.2 Prevent misconnections. To prevent misconnections, the designer can employ unique fittings (such as the CGA cylinder-valve fitting scheme), different line sizes for different chemical streams, color coding of piping, labeling, etc.

7.19.5.3 Prevent cross-piping. Interlocks, flow logic, ganged valves, automated systems, and double-block-and-bleed piping can all be used to prevent cross-piping.

7.19.5.4 Use caution with check valves intended to prevent cross-contamination by oxygen.

NOTE 77—The use of check valves to exclude oxygen from selected regions of systems must be done with extra care if a reliable block is crucial. Most check valves are not designed as absolute shut off valves. As such, many check-valve designs do not provide reliable or complete blockage against reverse flows. Others will not seal against small reverse differential pressures. Where exposed to contamination or process liquids, deposits may prevent their closure. Thus, other methods, such as automatic or manual block valves, or redundant or double check valves, are used to provide a more reliable block than single check valves, especially in applications where preventing cross-contamination is critical.

7.20 *Avoid Designs and Failure Scenarios that can Introduce Potential Flow Friction Ignition Hazards.*

7.20.1 Avoid leaks past nonmetallic component seats or pressure seals, or "weeping" or "scrubbing" flow configurations around nonmetals. These configurations can include external leaks past elastomeric pressure seals or internal flows on or close to plastic seats in components.

NOTE 78—Flow friction has not been shown to be a credible ignition source for metals (see 5.2.12).

7.20.1.1 Ensure that redundant O-ring seals can contain reverse pressure between them. O-ring seals are sometimes redundant, creating a chamber between the seals that can retain pressure when the system is vented. O-rings not designed to contain reverse pressure may be forced out of their grooves or become damaged, producing loose slivers of elastomer.

7.20.1.2 Ensure that polymers that can absorb oxygen do not expand and "push out" from their grooves. Porous polymers, especially some fluorocarbon rubbers, when exposed to oxygen under pressure for long periods, can become permeated with oxygen, potentially increasing their flammability. Upon venting they may expand to sizes significantly larger than normal. Polymers exposed to other gases (especially carbon dioxide, which dissolves into many polymers) may experience similar "inflations." This can result in damage as the polymer expands and pushes itself from its groove.

7.20.2 Avoid oxygen flow over nonmetal surfaces that are highly fibrous, as from being chafed, abraded, or plastically deformed.

NOTE 79—These scenarios may render flow friction more severe as smaller, more easily ignited fibers of the nonmetal may actually begin resonating, or vibrating/flexing, perhaps at high frequencies induced by flow, and this "friction" would generate heat (see 5.2.12).

7.21 *Use Only the Most Compatible of Practical Materials and Designs.*

NOTE 80—In most oxygen systems the cost of using only the most compatible materials and designs is justified by the additional safety that is achieved. However, there are many instances in which cost, complexity, reliability, and performance cannot accommodate the most compatible materials. For example, compressors must seek the maximum efficiency, and are often barricaded to achieve safety and allow design flexibility. Industrial gas pipelines often can only be realistically fabricated of steel, and a large body (**10**) of practices has evolved to achieve safety, etc. In these cases where system materials are potential fuels, identifying and minimizing ignition mechanisms is critical to avoiding fires. Guides G63 and G94 provide guides for selecting nonmetals and metals, respectively, for oxygen service.

7.21.1 Use the most ignition- and burn-resistant materials in component and system designs wherever practical.

7.21.2 Choose fully-oxidized materials such as minerals in preference to metals or polymers where practical. Most minerals are effectively nonflammable in oxygen. However, their mechanical properties render them practical in only a small number of applications.

7.21.3 Use metals in preference to polymers. In general, metals are far more difficult to ignite than polymers, but applications that require elasticity or plasticity (gaskets, valve seats, packings, etc.) often preclude the use of metals. For these applications, use the minimum size and quantity of nonmetals and embed them within or otherwise protect them with metals (see 7.14.1).

7.21.3.1 Use copper/copper-base and nickel/nickel-base alloys as opposed to other metals where practical.

7.21.4 Use fluorinated/halogenated polymers (PTFE, PFPE, CTFE, FPM, FKM) as opposed to polymers containing carbon-hydrogen bonds (hydrocarbons such as EPDM, PVC, SBR, fluorosilicones) where practical.

NOTE 81—Toxicity of combustion products can be a crucial concern in certain equipment, such as medical oxygen hardware, and fluorinated polymers can produce especially toxic combustion and decomposition products that may offset the benefits of their superior compatibility. In these instances additional care must be applied to balance and control both sets of risks. Both the CGA and EIGA have published documents that address toxicity issues of nonmetallics in breathing gas systems (**61**, **62**).

7.22 *Provide Thorough Safety Training for all Personnel Working with Oxygen or Oxygen-Enriched Components or Systems including Design, Cleaning, Assembly, Operations, and Maintenance as Applicable to Personnel.*

NOTE 82—In the Unites States, federal requirements for training on hazardous materials are listed in the Code of Federal Regulations. 49 CFR 172.702(a) mandates that employers provide training for all employees using hazardous materials. Oxygen is on the list of hazardous materials.

7.23 *Miscellaneous.*

7.23.1 Eliminate internal mechanical collisions.

7.23.2 Ensure proper grounding and bonding of every portion of an oxygen system to avoid internal arcing or sparking. Ensure equal electrical potential is maintained between all components in an oxygen system to avoid arcing.

7.23.3 Consider lightning protection. Protection against lightning arcing across insulated flanges of cathodic corrosion-prevention systems of pipelines is particularly important. One method is the use of fusing spark gaps. NFPA 780 (**63**) addresses lightning protection in general.

7.23.4 Provide the capability to start up the system using inert gases as a means to seat surfaces, displace particulates, prove mechanical integrity, leak-test the system, etc. Following inert gas use in rotating machinery, precautions are required prior to oxygen exposure in the event that an accumulation of pyrophoric materials may have been formed by wear.

7.23.5 Eliminate valve chatter and fretting throughout the operating range (that is, check valves, relief valves, regulating components, etc.).

7.23.6 Design for maximum pressures assuming unpressurized adjacent chambers. Oxygen systems should be able to safely contain maximum anticipated pressure in any chamber, assuming any adjacent chamber contains no pressure. In one case (**64**), a LOX pump fire is believed to have occurred after a bank of cylinders was filled and the pump inlet was vented while full pressure remained on the outlet, possibly leading to a reverse-pressure failure of the discharge valve seat.

8. Examples

8.1 *System Design Procedures*—Some detailed examples of system design procedures (**11**, **65-33**) may be consulted for further reference. A video[3] illustrating the hazards when using oxygen and the selection of components for oxygen service is available.

9. Keywords

9.1 burning; burn-resistant materials; combustion; contamination; fire; heat of compression; ignition; oxygen-enriched atmosphere; oxygen service; oxygen system; particle impact; propagation; system cleanness

REFERENCES

(1) Forsyth, E. T., Newton, B. E., Rantala, J., and Hirschfeld, T., "Using ASTM Standard Guide G88 to Identify and Rank System-Level Hazards in Large-Scale Oxygen Systems," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Tenth Volume, ASTM STP 1454*, T. A. Steinberg, H. D. Beeson, and B. E. Newton, Eds., ASTM International, West Conshohocken, PA, 2003.

(2) Hirsch, D. B., Bunker, R. L., and Janoff, D., "Effects of Oxygen Concentration, Diluents, and Pressure on Ignition and Flame-Spread Rates of Nonmetals," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Fifth Volume, ASTM STP 1111*, Joel M. Stoltzfus and Kenneth McIlroy, Eds., American Society for Testing and Materials, Philadelphia, 1991.

(3) Monroe, R. W., Bates, C. E., and Pears, C. D., "Metal Combustion in High-Pressure Flowing Oxygen," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres, ASTM STP 812*, B. L. Werley, Ed., American Society for Testing and Materials, 1983, pp. 126-149.

(4) Bryan, C. J. and Lowrie, R.,"Comparative Results of Autogenous Ignition Temperature Measurements by ASTM G72 and Pressurized Scanning Calorimetry in Gaseous Oxygen," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Second Volume, ASTM STP 910*, M. A. Benning, Ed., American Society for Testing and Materials, Philadelphia, 1986, pp. 108-117.

(5) Benz, F. J., Shaw, R. C., and Homa, J. M., "Burn Propagation Rates of Metals and Alloys in Gaseous Oxygen," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Second Volume, ASTM STP 910*, M. A. Benning, Ed., American Society for Testing and Materials, Philadelphia, 1986, pp. 135-152.

(6) Benning, M. A., " Measurement of Oxygen Index at Elevated Pressures," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres, ASTM STP 812*, B. L. Werley, Ed., American Society for Testing and Materials, 1983, pp. 68-83.

(7) Benning, M. A., Zabrenski, J. S., and Le, N. B., "The Flammability of Aluminum Alloys and Aluminum Bronzes as Measured by Pressurized Oxygen Index," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres, ASTM STP 986*, D. W. Schroll, Ed., American Society for Testing and Materials, Philadelphia, 1988, pp. 54-71.

(8) Benz, F. J., Williams, R. E., and Armstrong, D., "Ignition of Metals and Alloys By High-Velocity Particles," *Flammability and Sensitivity of Materials in Oxygen- Enriched Atmospheres: Second Volume, ASTM STP 910*, M. A. Benning, Ed., American Society for Testing and Materials, Philadelphia, 1986, pp. 16-37.

(9) Castillo, D. G., and Werley, B. L., "Eliminating Bypass Valves in Selected Oxygen Systems," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Eighth Volume, ASTM STP 1319*, W. T. Royals, T. C. Chou, and T. A. Steinberg, Eds., American Society for Testing and Materials, 1997.

(10) CGA G-4.4-2003 (4th Edition)/IGC doc 13/02, *Oxygen Pipeline Systems*, Compressed Gas Association, Inc., Chantilly, VA, European Industrial Gases Association , Brussels.

(11) Beeson, H. D., Stewart, W. F., and Woods, S. S., *Safe Use of Oxygen and Oxygen Systems: Guidelines for Oxygen System Design, Materials Selection, Operations, Storage, and Transportation, ASTM Manual 36*, ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA, 19428-1959, 2000, 99 pages.

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

(13) Dees, J., Forsyth, E., Gunaji, M. V., and Stoltzfus, J. M., "An Evaluation of Polymers as Ignition Sources During Particle Impact in Oxygen," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Seventh Volume, ASTMSTP 1267*, Dwight D. Janoff, William T. Royals, and Mohan V. Gunaji, Eds., American Society for Testing and Materials, Philadelphia, PA, 1995, pp. 143-151.

(14) Forsyth, E. T., Gallus, T. D., and Stoltzfus, J. M., "Ignition Resistance of Polymeric Materials to Particle Impact in High-Pressure Oxygen," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Ninth Volume, ASTM STP 1395*, T. A. Steinberg, B. E. Newton, and H. D. Beeson, Eds., American Society for Testing and Materials, West Conshohocken, PA, 2000.

(15) Janoff, D., Bamford, L. J., Newton, B. E., and Bryan, C. J., "Ignition of PTFE-Lined Flexible Hoses by Rapid Pressurization with Oxygen," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Fourth Volume, ASTM SPT 1040*, Joel M. Stoltzfus, Frank J. Benz, and Jack S. Stradling editors, American Society for Testing and Materials, Philadelphia, 1989.

(16) Benz, F. J., and Stoltzfus, J. M., "Ignition of Metals and Alloys in Gaseous Oxygen By Frictional Heating," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Second Volume, ASTM STP 910*, M. A. Benning, Ed., American Society for Testing and Materials, Philadelphia, 1986, pp. 38-58.

(17) Phillips, B. R. and DeWitt, K. J., "Resonance Tube Ignition of Aluminum," *Combustion and Flame*, 35, 1979, pp. 249-258.

(18) Niwa, M., Santana, A. Jr., and Kessaev, K., "Development of a Resonance Igniter for GO2/Kerosene Ignition," *Journal of Propulsion and Power*, Vol 17, No. 5, September-October, 2001, pp. 995-997.

(19) Waller, J. M., Newton, B. E., Beeson, H. D., and Haas, J. P., "Comparison of the Dimensional Stability of Kel-F 81 and Neoflon CTFE M400H Polychlorotrifluoroethylenes Used in Valve Seat Applications," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Ninth Volume, ASTM STP 1395*, T. A. Steinberg, B. E. Newton, and H. D. Beeson, Eds., American Society for Testing and Materials, West Conshohocken, PA, 2000.

(20) Bryan, C. J., " NASA Mechanical Impact Testing in High-Pressure Oxygen," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres, ASTM STP 812*, B. L. Werley, Ed., American Society for Testing and Materials, 1983, pp. 9-42.

(21) Werley, B. L., Barthelemy, H., Gates, R., Slusser, J. W., Wilson, K. B., and Zawierucha, R., "A Critical Review of Flammability Data for Aluminum ," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Sixth Volume, ASTM STP 1197*, Dwight D. Janoff and Joel M. Stoltzfus, Eds., American Society for Testing and Materials, Philadelphia, 1993.

(22) Reed, R. P., Simon, N. J., and Berger, J. R., "Influence of Specimen-Absorbed Energy in LOX Mechanical- Impact Tests," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres, Fifth Volume, ASTM STP 1111*, Joel M. Stoltzfus and Kenneth McIlroy, Eds., American Society for Testing and Materials, Philadelphia, 1991.

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

(24) Moyers, C. V., Bryan, C. J., and Lockhart, B. J., "Test of LOX Compatibility for Asphalt and Concrete Runway Materials," NASA Technical Memordandum X-64086, Kennedy Space Center, FL, 1973.

(25) NASA, *Flammability, Odor, Offgassing and Compatibility Requirements and Test Procedures for Materials in Environments that Support Combustion*, NASA STD-6001, Marshall Space Flight Center, Huntsville, AL, February 9, 1998.

(26) CGA Pamphlet G-4.1, " Cleaning Equipment for Oxygen Service," Compressed Gas Association, Arlington, VA.

(27) CGA P-8.4/IGC Doc 65/99/E, "Safe Operation of Reboilers/ Condensers in Air Separation Units," Compressed Gas Association, Inc., 4221 Walney Road, 5th Floor, Chantilly, VA 20151, European Industrial Gases Association, Brussels.

(28) CGA P-8, "Safe Practices Guide for Air Separation Plants," Compressed Gas Association, Inc., 4221 Walney Road, 5th Floor, Chantilly, VA 20151.

(29) CGA G-4.8, " Safe Use of Aluminum Structured Packing for Oxygen Distillation," Compressed Gas Association, Inc., 4221 Walney Road, 5th Floor, Chantilly, VA 20151.

(30) CGA G-4.9, " Safe Use of Brazed Aluminum Heat Exchangers for Producing Pressurized Oxygen," Compressed Gas Association, Inc., 4221 Walney Road, 5th Floor, Chantilly, VA 20151.

(31) Werley, B. L., " Oil Film Hazards in Oxygen Systems," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres, ASTM STP 812*, B. L. Werley, Ed., American Society for Testing and Materials, Philadelphia, 1983, pp. 108-125.

(32) Hutchins, Ian M., *Monograph on the Erosion of Materials by Solid Particle Impact*, MTI Publication No. 10, Materials Technology Institute of the Chemical Process Industries, Inc., p. 19.

(33) Werley, B. L., " Sonic, Supersonic, and Other Extreme Velocities in Oxygen Systems," Presented at ASTM Committee G-4 Seminar, Fall 1998, Cocoa Beach FL, Air Products and Chemicals, Inc, Allentown PA, 1999, 20 pages.

(34) Quiat, L., " The Potential Use of Inconel 625 and Monel Weld Overlay in Oxygen Service," Presented at the Spring 96 Seminar Session of ASTM Committee G4, G-4 News, Vol 3, No. 1, 1996, p. 3.

(35) Barter, S. A., and Hillen, L. W., "Oxygen Fires, Materials Compatibility and System Contaminants," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Fourth Volume, ASTM STP 1040*, Joel M. Stoltzfus, Frank J. Benz, and Jack S. Stradling, Editors, American Society for Testing and Materials, Philadelphia, 1989, pp. 349-376, especially pp. 372-375.

(36) Streeter, V. L., Editor-in-Chief, *Handbook of Fluid Dynamics*, First Edition, McGraw-Hill Book Company, New York, 1961 , pp. 10-29.

(37) Werley, B. L., Editor, *Fire Hazards in Oxygen Systems*, ASTM Technical and Professional Training Course Book, Second Edition, ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA, 19428-1959, 1991, 150 pages.

(38) Werley, B. L., " A Perspective on Gaseous Impact Tests: Oxygen Compatibility Testing on a Budget," *Flammability and Sensitivity of*

Materials in Oxygen-Enriched Atmospheres: Sixth Volume, ASTM STP 1197, Dwight D. Janoff and Joel M. Stoltzfus, Eds., American Society for Testing and Materials, Philadelphia, 1993, pp. 27-42.

(39) Barthelemy, H., and Vagnard, G., "Ignition of PTFE-lined Hoses in High-Pressure Oxygen Systems: Test Results and Consideration for Safe Design and Use," *Flammability and Sensitivity of Materials in Oxygen Enriched Atmospheres, Vol 3, ASTM STP 986*, 1988, pp. 289-309.

(40) Santay, A. J., Becker, Jr., I. D., and Werley, B. L., "Design Strategies for Polymer-Lined Flex-Hose Distance/Volume Pieces," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Eighth Volume, ASTM STP 1319*, William T. Royals, Ting C. Chou, and Theodore A. Steinberg, Eds., American Society for Testing and Materials, 1997, pp. 93-107.

(41) Werley, B. L., " A Perspective on Gaseous Impact Tests: Oxygen Compatibility Testing on a Budget," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Sixth Volume, ASTM STP 1197*, Dwight D. Janoff and Joel M. Stoltzfus, Eds., American Society for Testing and Materials, Philadelphia, 1993, pp. 27-42.

(42) CGA G-4.6, " Oxygen Compressor Installation and Operation Guide," Compressed Gas Association, Inc., 4221 Walney Road, 5th Floor, Chantilly, VA 20151.

(43) EIGA/IGC Doc 11/82, " Centrifugal Oxygen Compressor Code of Practice," European Industrial Gases Association, Brussels.

(44) EIGA/IGC Doc 27/01, " Centrifugal Oxygen Compressor Code of Practice," European Industrial Gases Association, Brussels.

(45) Uhlig, L. L., and Revie, R. W., *Corrosion and Corrosion Control*, Third Edition, John Wiley and Sons, Inc., 1985, pp. 92-93.

(46) Kirby, Gary N., " Corrosion Performance of Carbon Steel," *Chemical Engineering*, March 12, 1979, p. 76.

(47) Stradling, J. S., Pippen, D. L., and Frye, G. W., "Techniques Employed by the NASA White Sands Test Facility to Ensure Oxygen System Component Safety," *Flammability and Sensitivity of Materials in Oxygen Enriched Atmospheres, ASTM STP 812*, 1983, pp. 97-107.

(48) CGA Pamphlet G-4.0, "Oxygen," Compressed Gas Association, Arlington, VA.

(49) NFPA Booklet 50-1979, "Standard for Bulk Oxygen Systems at Consumer Sites," National Fire Protection Agency.

(50) NFPA Booklet 53M-1979, "Manual on Fire Hazards in Oxygen-Enriched Atmospheres," National Fire Protection Agency.

(51) *The Welding Handbook*, Eighth Edition, Volume 1, Leonard P. Connor, Ed., American Welding Society, Miami, 1987, pp. 38,39.

(52) Kirshenbaum, A. D., *Fundamental Studies in New Explosive Reactions*, Office of Ordnance Research Contract DA-26-034-ORD-1489, The Research Institute of Temple University, April 30, 1956, 62 pages.

(53) Dunbobbin, B. R., Hansel, J. G., and Werley, B. L., "Oxygen Compatibility of High-Surface-Area Materials," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Fifth Volume, ASTM STP 1111*, Joel M. Stoltzfus and Kenneth McIlroy, Eds., American Society for Testing and Materials, Philadelphia, 1991, pp. 338-353.

(54) Kinney, G. F., and Graham, K. J., *Explosive Shocks in Air*, Second Edition, Springer Verlag, New York, 1985.

(55) Grelecki, C., *Fundamentals of Fire and Explosion Hazards Evaluation*, AIChE Today Series, American Institute of Chemical Engineers, New York, 1972, pp. A-8 to A-10.

(56) Personal communication with Werley, B. L., ref to presentation from Werley, B.L., Hansel, J. G., and Buchter, W. C., "TNT-Equivalency Concepts," Presented at the Spring 1998 seminar of ASTM Committee G-4 (22-23 April 98), Atlanta GA, Air Products and Chemicals, Inc., Allentown, PA, 1998, 14 pages.

(57) Zawierucha, R., Drnevich, R. F., White, D. E. and McIlroy, K., "Materials and Systems Considerations for Applications Involving Oxygen Enriched Atmospheres," ASME Paper 93-WA/PID-3, ASME Winter Annual Meeting, New Orleans, Louisiana, November 28th–December 3rd, 1993.

(58) Santay, A. J., " Evaluating Systems for Oxygen Service Through the Use of Quantitative Fault Tree Analysis," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Fourth Volume, ASTM STP 1040*, Joel M. Stoltzfus, Frank J. Benz, and Jack S. Stradling, Editors, American Society for Testing and Materials, Philadelphia, 1989, pp. 377-386.

(59) *NFPA 86 Standard for Ovens and Furnaces*, National Fire Protection Association, Battery Park Quincy MA, 1999.

(60) NASA Technical Memorandum 104823, " Guide for Oxygen Hazards Analyses on Components and Systems," Joel M. Stoltzfus, Jesse Dees, Robert F. Poe, October 1996.

(61) CGA PS-15, " Toxicity Considerations of Nonmetallic Materials in Medical Oxygen Cylinder Valves," Compressed Gas Association, Arlington, VA, 2003.

(62) EIGA/IGC Doc 73/00/E, " High-Pressure Breathing Gas Systems Toxicity Risks of Using Non Metallic Materials," European Industrial Gases Association, Brussels, 2000.

(63) *NFPA 780-2000, Standard for the Installation of Lightning Protection Systems*, National Fire Protection Association, Quincy, MA, 2000.

(64) Zabrenski , J. S., "Positive Displacement LOX Pump Fire," Presented at the Fall, 1998 seminar of ASTM Committee G-4 (23 September 1998), Cocoa Beach FL, Air Products and Chemicals, Inc., Allentown PA, 1998, 7 pages.

(65) Slusser, J. W. and Miller, K. A., "Selection of Metals for Gaseous Oxygen Service," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres, ASTM STP 812*, B. L. Werley, Ed., American Society for Testing and Materials, 1983, pp. 167-191.

(66) Christianson, R. C. and Plante, B. A., "Design of an Ignition-Resistant, High-Pressure, High-Temperature Oxygen Valve," *Symposium on Flammability and Sensitivity of Materials in Oxvqen-Enriched Atmospheres: Fourth Volume, ASTM STP 1040*, Joel M. Stoltzfus, Frank J. Benz, and Jack S. Stradling editors, American Society for Testing and Materials, Philadelphia, 1989, pp. 227-240.