Designation: G88 – 05

StandardGuide for
Designing Systems for Oxygen Service[1]

This standard is issued under the fixed designation G88; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

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 Materials to 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 Regulators Used for Medical and Emergency Applications

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 *Compressed Gas Association Documents:*

CGA G-4.1 Cleaning Equipment for Oxygen Service

CGA G-4.4 Oxygen Pipeline Systems

CGA G-4.6 Oxygen Compressor Installation and Operation Guide

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 P-8.4 Safe Operation of Reboilers/Condensers in Air Separation Units

CGA P-8 Safe Practices Guide for Air Separation Plants

CGA PS-15 Toxicity Considerations of Nonmetallic Materials in Medical Oxygen Cylinder Valves

2.5 *European Industrial Gases Association Documents:*

EIGA/IGC Doc 11/82 Centrifugal Oxygen Compressor Code of Practice

EIGA/IGC Doc 13/02/E Oxygen Pipeline Systems

EIGA/IGC Doc 27/01 Centrifugal Oxygen Compressor Code of Practice

EIGA/IGC Doc 65/99/E Safe Operation of Reboilers/Condensers in Air Separation Units

EIGA/IGC Doc 73/00/E High-Pressure Breathing Gas Systems Toxicity Risks of Using Non Metallic Materials

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 test, and a

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[2] For referenced ASTM 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.

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

- 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

[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.

computer algorithm.[4] 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.

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 (**22**). The characteristic elements of forced thermal ignition in oxygen include the following:

5.2.1.1.1

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

5.2.1.1.2

A material with a spontaneous ignition temperature below the

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[4] ASTM G4Math Utility software, available from ASTM International Technical & Professional Training Course Fire Hazards in Oxygen Systems.

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

temperature created by the heat source in the given configuration and environment.

5.2.1.1.3

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, 3**), and the rates of fire propagation increase (**2, 4**). 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 (**5, 6**).

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 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 (**7**). 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 2—The pressure differential that can be tolerated to control high gas velocities is significantly smaller than for control of downstream heat of compression (**8**) (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 (**9, 10**). 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 (**8**):

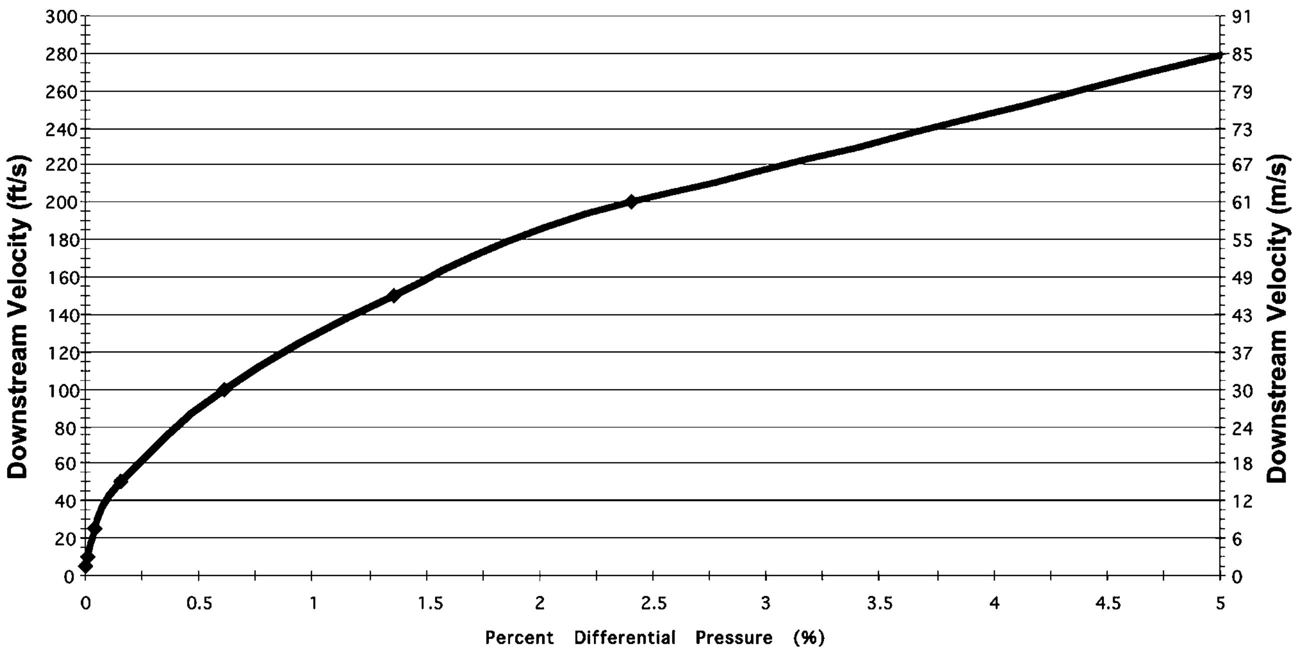

FIG. 1 Maximum Oxygen Gas Velocity Produced by Pressure Differentials, Assuming Isentropic Flow

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

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 ($\gamma = 1.4$ 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 3—Fig. 1 shows the maximum gas velocity versus pressure differential considering isentropic flow for gaseous oxygen, based on the 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 (**11**).

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 (**7**). Additionally, common nonmetal particles have been shown to be ineffective igniters of metals by particle impact (**12**), 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 (**13**). 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 (**13**).

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

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[6] Reference (**8**) 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.

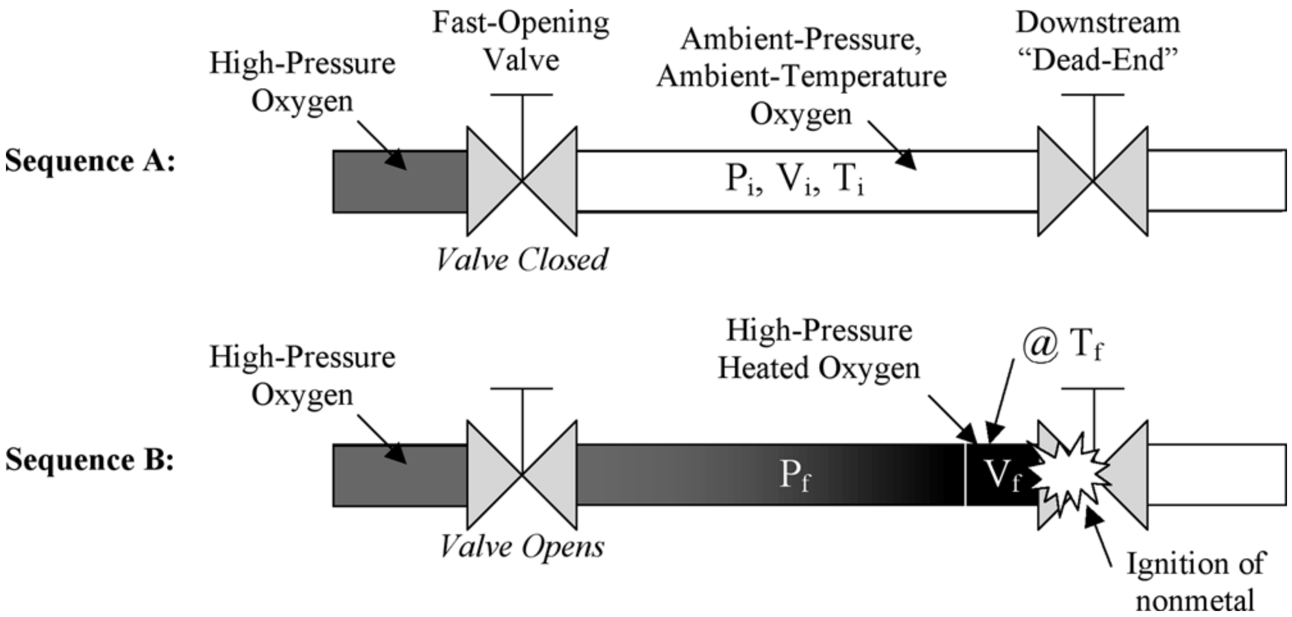

FIG. 2 Example of a Compression Heating Sequence Leading to Ignition of a Nonmetal Valve Seat

gas temperatures produced can ignite contaminants or materials in system components. The hazard of heat of compression increases with system pressure and with pressurization rates. 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 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 4—Eq 2 shows a formula[7] 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 5—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

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[7] Formula shown is based upon isentropic flow relations for a ideal gas.

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

example, Teflon-lined flexhoses can be ignited if pressurized in fractions of a second but not if pressurized in seconds (**14**).

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 low thermal diffusivities and have 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 temperature. 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) (**15**).

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 (**16**) 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 (**17**). 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 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 (**16**).

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

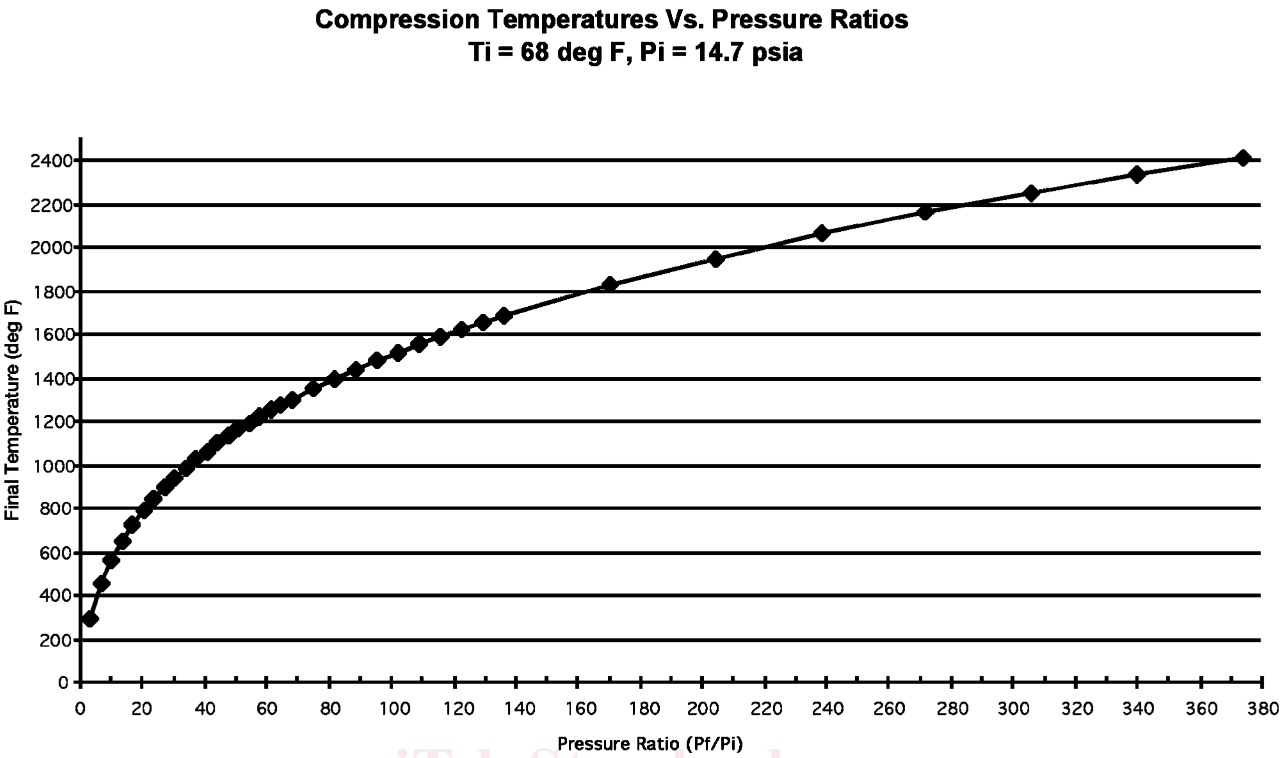

FIG. 3 Final Compression Temperatures for Pressure Ratios

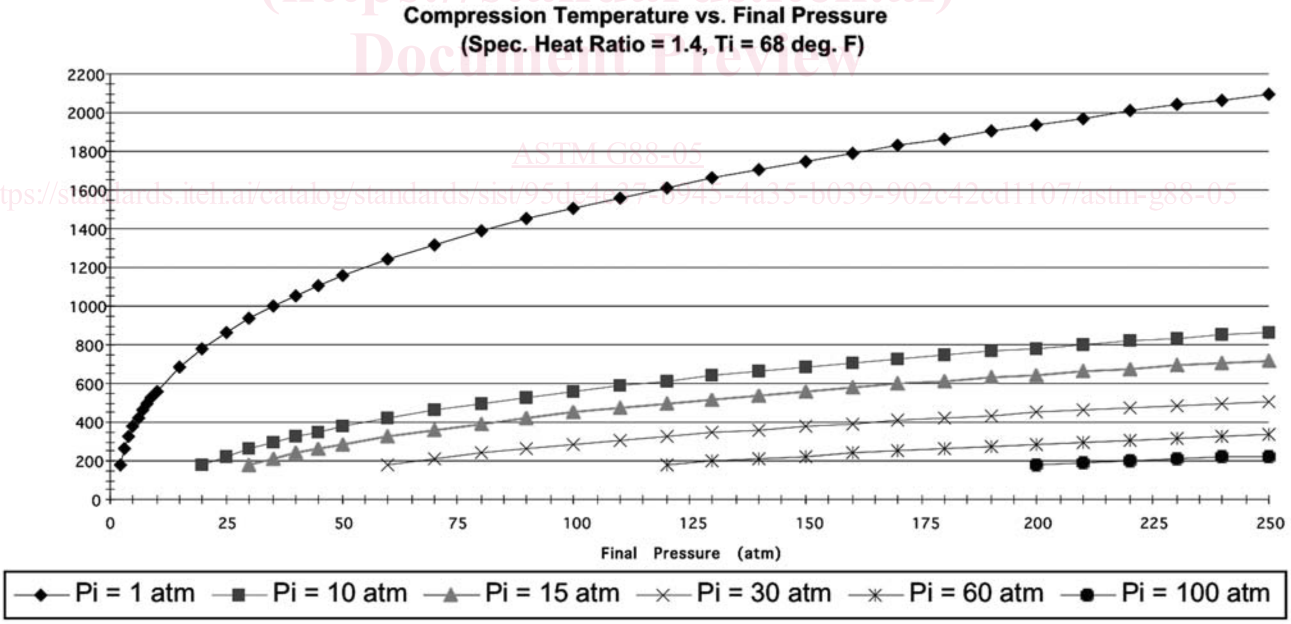

FIG. 4 Final Compression Temperatures for Final Pressures Given the Initial Presssures Shown

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

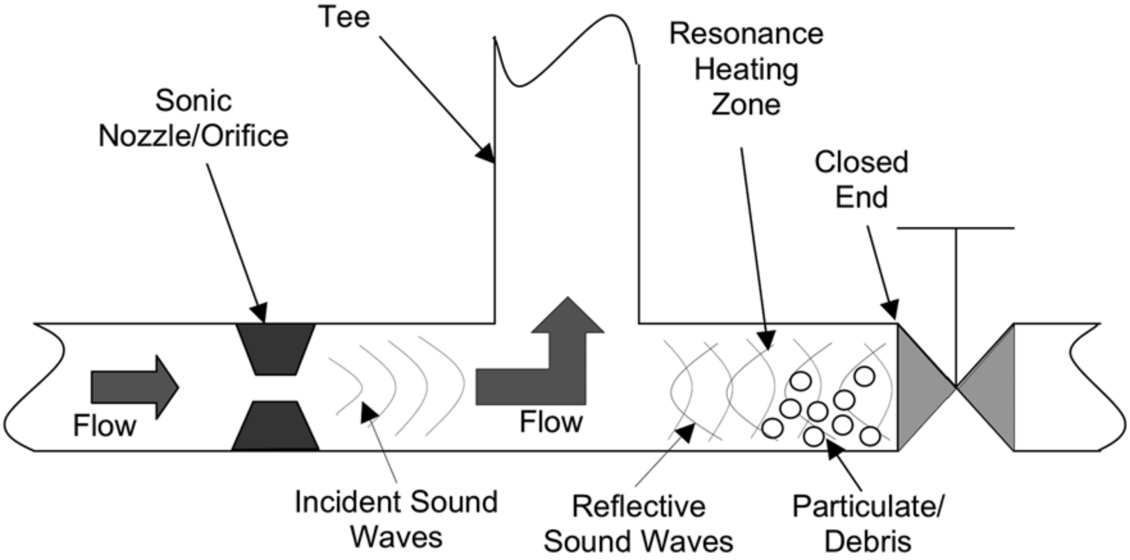

FIG. 5 Example of a System Configuration with Potential for Resonance Heating

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) (**18**). 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 (**19**, **20**). 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) (**21**).

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 (**55**). Testing has showed that the presence of contamination on hydrocarbon materials will increase the hazard (**56**). 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 impact of a wrench, and LOX overflow onto an asphalt driveway then driven over by 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 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 6—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 (**9**, **10**, **23**). 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 7—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 8—Electrical heaters on oxygen equipment may require ground fault interrupters (GFI) to prevent large energy inputs and fires due to heater failure. When 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 9—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 (**24**)). 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 10—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 11—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.