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## Standard Guide for Control of Hazards and Risks in Oxygen Enriched Systems<sup>1</sup>

This standard is issued under the fixed designation G128/G128M; 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 ( $\epsilon$ ) indicates an editorial change since the last revision or reapproval.

### 1. Scope

1.1 This guide covers an overview of the work of ASTM Committee G04 on Compatibility and Sensitivity of Materials in Oxygen-Enriched Atmospheres. It is a starting point for those asking the question: “What are the risks associated with my use of oxygen?” This guide is an introduction to the unique concerns that must be addressed in the handling of oxygen. The principal hazard is the prospect of ignition with resultant fire, explosion, or both. All fluid systems require design considerations, such as adequate strength, corrosion resistance, fatigue resistance, and pressure safety relief. In addition to these design considerations, one must also consider the ignition mechanisms that are specific to an oxygen-enriched system. This guide outlines these ignition mechanisms and the approach to reducing the risks.

1.2 This guide also lists several of the recognized causes of oxygen system fires and describes the methods available to prevent them. Sources of information about the oxygen hazard and its control are listed and summarized. The principal focus is on Guides G63, G88, Practice G93, and Guide G94. Useful documentation from other resources and literature is also cited.

NOTE 1—This guide is an outgrowth of an earlier (1988) Committee G04 videotape adjunct entitled *Oxygen Safety* and a related paper by Koch<sup>2</sup> that focused on the recognized ignition source of adiabatic compression as one of the more significant but often overlooked causes of oxygen fires. This guide recapitulates and updates material in the videotape and paper.

1.3 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

1.4 *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 limitations prior to use.* For specific precautionary statements see Sections 8 and 11.

NOTE 2—ASTM 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.

### 2. Referenced Documents

#### 2.1 ASTM Standards:<sup>3</sup>

- D2512 Test Method for Compatibility of Materials with Liquid Oxygen (Impact Sensitivity Threshold and Pass-Fail Techniques)
- D2863 Test Method for Measuring the Minimum Oxygen Concentration to Support Candle-Like Combustion of Plastics (Oxygen Index)
- D4809 Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)
- 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
- G86 Test Method for Determining Ignition Sensitivity of Materials to Mechanical Impact in Ambient Liquid Oxygen and Pressurized Liquid and Gaseous Oxygen Environments
- G88 Guide for Designing Systems for Oxygen Service
- 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
- G124 Test Method for Determining the Combustion Behavior of Metallic Materials in Oxygen-Enriched Atmospheres

<sup>1</sup> 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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<sup>2</sup> Koch, U. H., “Oxygen System Safety,” *Flammability and Sensitivity of Materials In Oxygen-Enriched Atmospheres*, Vol 6, ASTM STP 1197, ASTM, 1993, pp. 349–359.

<sup>3</sup> For referenced ASTM standards, visit the ASTM website, [www.astm.org](http://www.astm.org), or contact ASTM Customer Service at [service@astm.org](mailto:service@astm.org). For *Annual Book of ASTM Standards* volume information, refer to the standard’s Document Summary page on the ASTM website.

**G126 Terminology Relating to the Compatibility and Sensitivity of Materials in Oxygen Enriched Atmospheres**

**G175 Test Method for Evaluating the Ignition Sensitivity and Fault Tolerance of Oxygen Pressure Regulators Used for Medical and Emergency Applications**

2.2 *ASTM Adjuncts:*

Video: **Oxygen Safety**<sup>4</sup>

2.3 *ASTM CHETAH Analytical Computer Software Program:*

**CHETAH Chemical Thermodynamic and Energy Release Evaluation**<sup>5</sup>

2.4 *Compressed Gas Association (CGA) Standards:*<sup>6</sup>

**G-4.1 Cleaning Equipment for Oxygen Service**

**G-4.4 Oxygen Pipeline and Piping Systems**

2.5 *European Industrial Gas Association (EIGA) Standards:*<sup>7</sup>

**33/XX/E Cleaning of Equipment for Oxygen Service**

**13/XX/E Oxygen Pipeline and Piping Systems**

2.6 *National Fire Protection Association (NFPA) Standards:*<sup>8</sup>

**51 Standard for the Design and Installation of Oxygen-Fuel Gas Systems for Welding, Cutting and Allied Processes**

**53 Recommended Practice on Material, Equipment, and Systems Used in Oxygen Enriched Atmospheres**

**55 Compressed Gases and Cryogenic Fluids Code**

**99 Health Care Facilities Code**

2.7 *Military Specifications:*<sup>9</sup>

**MIL-PRF-27617 Performance Specification, Grease, Aircraft and Instrument, Fuel and Oxidizer Resistant**

**DOD-PRF-24574 (SH) Performance Specification, Lubricating Fluid for Low and High Pressure Oxidizing Gas Mixtures**

### 3. Terminology

3.1 *Definitions:*

3.1.1 See Terminology **G126** for the terms listed in this section.

3.1.2 *autoignition temperature (AIT), n*—the lowest temperature at which a material will spontaneously ignite in an oxygen-enriched atmosphere under specific test conditions.

3.1.3 *hazard, n*—source of danger; something that could harm persons or property.

3.1.4 *ignition mechanisms, n*—These are the specific physical attributes and system conditions that cause the initial fire within a system. A system designer must evaluate an oxygen-enriched system for all possible ignition mechanisms. A

<sup>4</sup> Available from ASTM International Headquarters. Order Adjunct No. ADJG0088.

<sup>5</sup> Available from ASTM International Headquarters, 100 Barr Harbor Drive, West Conshohocken, PA 19428, Order # DSC 51C, Version 7.2.

<sup>6</sup> Available from Compressed Gas Association (CGA), 4221 Walney Rd., 5th Floor, Chantilly, VA 20151-2923, <http://www.cganet.com>.

<sup>7</sup> Available from European Industrial Gas Association, Publication de la Soudure Autogene, 32 Boulevard de la Chapelle, 75880 Paris Cedex 18, France.

<sup>8</sup> Available from National Fire Protection Association (NFPA), 1 Batterymarch Park, Quincy, MA 02169-7471, <http://www.nfpa.org>.

<sup>9</sup> Available from Standardization Documents Order Desk, DODSSP, Bldg. 4, Section D, 700 Robbins Ave., Philadelphia, PA 19111-5098, <http://dodssp.daps.dla.mil>.

common ignition mechanism for metals is particle impact. A common ignition mechanism for non-metals is adiabatic compression.

3.1.5 *ignition temperature, n*—the temperature at which a material will ignite under specific test conditions.

3.1.6 *impact-ignition resistance, n*—the resistance of a material to ignition when struck by an object in an oxygen-enriched atmosphere under a specific test procedure.

3.1.7 *nonmetal, n*—a class of materials consisting of polymers, certain composite materials (polymer matrix and brittle matrix composites in which the most easily ignited component is not a metallic constituent), ceramics, and various organic and inorganic oils, greases, and waxes. **nonmetallic**, adj.

3.1.8 *oxidant compatibility, n*—the ability of a substance to coexist at an expected pressure and temperature with both an oxidant and a potential source(s) of ignition within a risk parameter acceptable to the user.

3.1.9 *oxygen-enriched, adj*—containing more than 23.5 mol percent oxygen.

3.1.9.1 *Discussion*—Other standards such as those published by NFPA and OSHA differ from this definition in their specification of oxygen concentration.

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

3.1.11 *risk, n*—probability of loss or injury from a hazard.

3.1.12 *system conditions, n*—the physical parameters of a specific system. These can include local and system-wide pressure, temperature, flow, oxygen concentration, and others.

3.1.13 *wetted material, n*—any component of a fluid system that comes into direct contact with the system fluid.

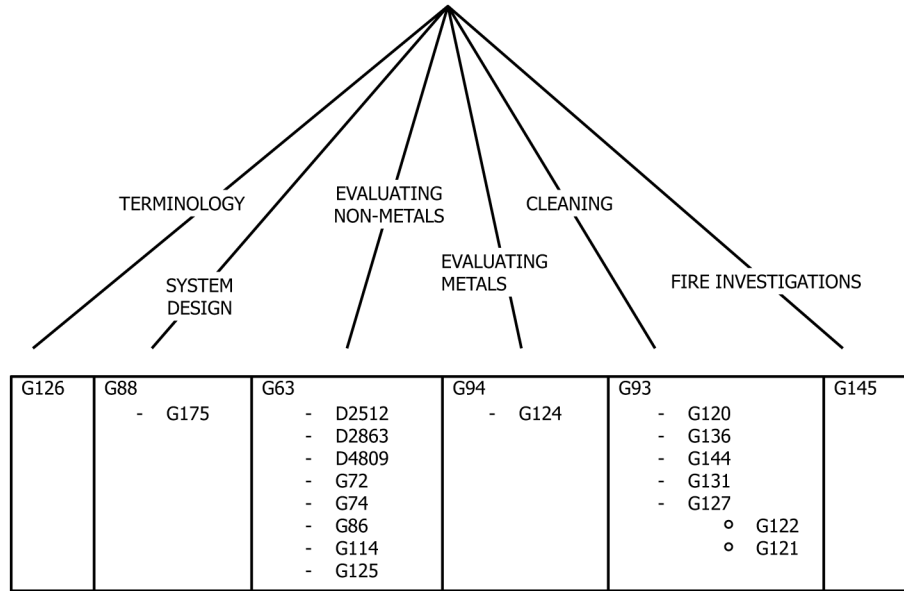
### 4. Significance and Use

4.1 The purpose of this guide is to introduce the hazards and risks associated with oxygen-enriched systems. This guide explains common hazards that often are overlooked. It provides an overview of the standards and documents produced by ASTM Committee G04 and other knowledgeable sources as well as their uses. It does not highlight standard test methods that support the use of these practices. **Table 1** provides a graphic representation of the relationship of ASTM G04 standards. **Table 2** provides a list of standards published by ASTM and other organizations.

4.2 The standards discussed here focus on reducing the hazards associated with the use of oxygen. In general, they are not directly applicable to process reactors in which the deliberate reaction of materials with oxygen is sought, as in burners, bleachers, or bubblers. Other ASTM Committees and products (such as the CHETAH program<sup>5</sup>) and other outside groups are more pertinent for these.

4.3 This guide is not intended as a specification to establish practices for the safe use of oxygen. The documents discussed

TABLE 1 Relationship of ASTM Standards for Oxygen-Enriched Systems



here do not purport to contain all the information needed to design and operate an oxygen-enriched system safely. The control of oxygen hazards has not been reduced to handbook procedures, and the tactics for using oxygen are not simple. Rather, they require the application of sound technical judgment and experience. Oxygen users should obtain assistance from qualified technical personnel to design systems and operating practices for the safe use of oxygen in their specific applications.

5. Summary

5.1 Oxygen and its practical production and use are reviewed. The recognized hazards of oxygen are described. Accepted and demonstrated methods to reduce those hazards are reviewed. Applicable ASTM standards from Committee G04 and how these standards are used to help mitigate oxygen-enriched system hazards are discussed. Similar useful documents from the National Fire Protection Association, the Compressed Gas Association, and the European Industrial Gas Association also are cited.

6. Oxygen

6.1 Oxygen is the most abundant element, making up 21 % of the air we breathe and 55 % of the earth’s crust. It supports plant and animal life. Oxygen also supports combustion, causes iron to rust, and reacts with most metals. Pure oxygen gas is colorless, odorless, and tasteless. Liquid oxygen is light blue and boils at –183°C [–297°F] under ambient pressure.

6.2 Oxygen has many commercial uses. For example, it is used in the metals industry for steel making, flame cutting, and welding. In the chemical industry it is used for production of synthetic gas, gasoline, methanol, ammonia, aldehydes, alcohol production, nitric acid, ethylene oxide, propylene oxide, and many others. It is also used for oxygen-enriched fuel

combustion and wastewater treatment. For life support systems it is used in high-altitude flight, deep-sea diving, clinical respiratory therapy or anesthesiology, and emergency medical and fire service rescues.

7. Production and Distribution

7.1 Most oxygen is produced cryogenically by distilling liquid air. The demand for ultrahigh purity within the semiconductor industry has led to a more thorough distillation of cryogenic oxygen. Further, noncryogenic production has become significant in recent years. The principal difference among these sources of oxygen is the resulting oxygen purity detailed below. The hazards of oxygen are affected greatly by purity and, in general, higher purity is more hazardous. However, fire events can and do occur in any oxygen-enriched atmosphere.

7.2 Cryogenic Production—Cryogenically produced oxygen is distilled in a five-step process in which air is: (1) filtered to remove particles; (2) compressed to approximately 700 kPa [100 psig] pressure; (3) dried to remove water vapor and carbon dioxide; (4) cooled to –160°C [–256°F] to liquefy it partially; and (5) distilled to separate each component gas. The end products are oxygen, nitrogen, and inert gases such as argon and neon; the principal secondary products are nitrogen and argon. Commercial oxygen is produced to a minimum 99.5 % purity, but typical oxygen marketed today is more likely to be near 99.9 % purity.

7.2.1 For high-volume bulk users, such as steel or chemical plants, the oxygen plant is often adjacent to the user’s facility, and gaseous oxygen is delivered by pipeline at low to medium pressures, usually 700 to 5500 kPa [100 to 800 psig].

7.2.2 Cryogenic liquid oxygen is delivered by trailer to other large-volume users, who utilize liquid storage tanks, then vaporize the liquid, and distribute the gas (Fig. 1 and Fig. 2).





**FIG. 1 Skid-Mounted Cryogenic Oxygen Storage**  
Image courtesy of Essex Industries



**FIG. 2 Cryogenic Oxygen Storage**  
Image courtesy of Air Liquide America

7.4 *Noncryogenic Production*—Noncryogenic oxygen production processes include pressure swing adsorption (PSA), vacuum swing adsorption (VSA), and membrane separation. In general, these methods produce oxygen less pure than cryogenically produced oxygen—typically <97 %, with the balance being nitrogen, argon, and carbon dioxide. However, these processes use less power and offer a cost advantage for high-volume users who do not need higher purity.

The equipment for these systems is typically large and is located on site. However, small medical-oxygen generators used in the home also are included in this category.

## 8. Hazards and Risks

8.1 How can oxygen be hazardous? It is all around us. It supports life and is used to support or resuscitate a person with oxygen deficiency (hypoxemia). It may have been used in a common familiar system for years without a problem. Could it be that oxygen is not hazardous? No, oxygen-enriched systems present definite hazards.

8.2 Oxygen makes materials easier to ignite and their subsequent combustion more intense, more complete, and more explosive than in air alone. Fires in air, which contain just 21 % oxygen, are common. The injuries, loss of life, and property damage these fires cause can be devastating. Fires and explosions that occur in oxygen-enriched atmospheres can be even more devastating due to the intensity of the combustion.

8.3 Oxygen is not flammable by itself, but it supports combustion. Fire typically occurs when an oxidant such as oxygen is combined chemically with a fuel in the presence of an ignition source or sufficient heat (Fig. 3). Hence, although oxygen is not flammable, its contribution to the production of fire is otherwise comparable to that of the fuel. If there is no fuel, there is no fire. If there is no oxygen, there is no fire.

8.4 The ability to support and enhance combustion after ignition is the hazard associated with an oxygen-enriched atmosphere. The risk to people and property that accompanies this hazard is variable. Sometimes the human risk is grave; sometimes the economic risk is severe. In these instances, the need to prevent combustion is imperative. Occasionally the risk is small enough that it can be accepted and other tactics may be developed to minimize the risk. The overall concepts of hazard and risk have been lumped into the term “oxygen compatibility.”

8.4.1 ASTM Committee G04 first codified its interpretation of the concept of “oxygen compatibility” in its Technical and

7.2.3 Most users buy oxygen in small amounts, usually in 20-MPa or 2500-psig cylinders, and use it directly from the cylinders or through manifolds and a piping distribution system. Usually, the pressure is reduced with a regulator at the cylinder or manifold.

7.3 *Ultrahigh-Purity Oxygen*—There are a few markets that require high- and ultrahigh-purity oxygen. High-purity oxygen typically delivers >99.99 % purity, whereas the demands of the semiconductor industry have resulted in the marketing of >99.999 % purity oxygen.



**FIG. 3 The Fire Triangle**

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Professional Training course textbook *Manual 36, Safe Use of Oxygen and Oxygen Systems: Guidelines for Oxygen System Design, Materials Selection, Operations, Storage, and Transportation*.<sup>10</sup>

Oxygen compatibility is the ability of a substance to coexist with both oxygen and a potential source(s) of ignition within the acceptable risk parameter of the user [at an expected pressure and temperature].

8.4.1.1 In this definition, a system is oxygen compatible if it cannot burn or is unlikely to burn, if the occurrence of fires is adequately infrequent, or even if potential fires can be isolated and their effects can be tolerated.

8.5 Other organizations have a similar respect for the hazards of oxygen. NFPA 53 is a concise, readable booklet that describes oxygen, its uses and hazards, design guidelines, aids to material selection, and references. Significantly, NFPA 53 presents more than 40 case studies of accidents with oxygen that shows just how serious, yet subtle, the hazard can be. Further, in most of its publications (NFPA 51, NFPA 55, NFPA 99), the NFPA view of oxygen compatibility is given as:

“Compatibility involves both combustibility and ease of ignition. Materials that burn in air will burn violently in pure oxygen at normal pressure and explosively in pressurized oxygen. Also many materials that do not burn in air will do so in pure oxygen, particularly under pressure. Metals for containers and piping must be carefully selected, depending on service conditions. The various steels are acceptable for many applications, but some service conditions may call for other materials (usually copper or its alloys) because of their greater resistance to ignition and lower rates of combustion. “Similarly, materials that can be ignited in air have lower ignition energies in oxygen. Many such materials may be ignited by friction at a valve seat or stem packing or by adiabatic compression produced when oxygen at high pressure is rapidly introduced in a system initially at low pressure.”

## 9. Sources of Information

9.1 Despite the hazards inherent with pure oxygen and its mixtures, the risk of injury and economic loss can largely be controlled using methods documented in ASTM publications and many other sources. This guide is an overview of such sources, intended only to assist the reader in finding additional information.

9.1.1 Designing equipment and systems to function safely in oxygen-enriched environments requires information about the behavior of materials in such environments. ASTM standard test methods have been developed to measure the ignition and combustion properties of materials in gaseous and liquid oxygen, at various concentrations and pressures, by tests that relate to the common ignition mechanisms.

9.1.2 Guides **G63** and **G94** provide the designer with compilations of data obtained by the above ASTM test methods and present a structured approach to using that data in practical applications. Guide **G88** presents a systematic approach to

system design with emphasis on the special factors that should be considered to minimize the risk of ignition and fire.

9.1.3 Practice **G93** covers the selection of methods and materials to clean equipment for oxygen service. Examples are provided for specific materials and applications.

9.1.4 ASTM Committee G04 sponsors an international Symposium on the Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres every two to three years. The papers presented at these symposia cover topics from combustion theory to practical applications and fire experiences. They are published in Special Technical Publications, which, along with their extensive list of references, represent the largest existing collection of published work on this subject.

9.1.5 A two-day Technical and Professional Training Course, “Fire Hazards in Oxygen Handling Systems,” is presented by ASTM G04 members at least twice a year at a variety of locations. This course introduces participants to the fire risk in oxygen-enriched systems and presents a systematic approach to reducing the fire risk through the application of relevant ASTM and other industry standard publications. The textbook, *Fire Hazards in Oxygen Systems*,<sup>10</sup> teaches how to apply the many resources available to reduce the risk of oxygen fires. The video used in the course, *Oxygen Safety*,<sup>4</sup> is a brief introduction to some of the hazards present in oxygen-enriched systems, particularly those often overlooked.

9.2 Industry associations such as the Compressed Gas Association, National Fire Protection Association, and European Industrial Gas Association have developed product standards, design guides, codes, and training aides to assist in reducing the risk of oxygen-enriched system fires.

9.3 Government agencies serving aerospace programs, the military, and national research laboratories, offer oxygen system safety information. In some countries, product testing and approval services are available through national laboratories.

9.4 Most oxygen producers provide their users with safety publications and offer resources to assist in design, operation, and training for personnel. A few examples of such publications are listed in **Appendix X1**. That list is neither complete nor is it an endorsement of those publications.

## 10. Causes of Fires in Oxygen

10.1 *Particle Impact*—This ignition mechanism is typically found to ignite metals. Particle impact ignition occurs when a particle at high linear velocity strikes a flammable target. The high linear velocity can occur within several components in the system. Flow control valves, orifices, regulators, check valves and other fluid components can all provide flow restrictions that result in high linear velocity. The kinetic energy of the particle creates heat at the point of impact, which can ignite the particle, the target, or both.

10.2 *Adiabatic Compression*—This ignition mechanism is typically found to ignite non-metals. Adiabatic compression ignition occurs when there is rapid pressurization of a system volume with an exposed non-metal. The rapid pressurization results in heating that causes the temperature to rise above the

<sup>10</sup> For more information regarding Standards Technology Training Courses and corresponding text material, contact ASTM International Headquarters, Standards Technology Training, 100 Barr Harbor Drive, West Conshohocken, PA 19428.

auto-ignition temperature of the non-metal material and the material starts to burn.

10.3 *Mechanical Impact*—This ignition mechanism is typically found to ignite non-metals. Mechanical impact ignition occurs when a material experiences impacts that generate heat in excess of the auto-ignition temperature and the material starts to burn.

10.4 *Galling and Friction (Frictional Heating)*—This ignition mechanism can be found to ignite both metals and non-metals. Frictional heating ignition in non-metals occurs when two surfaces are rubbing in a way that the non-metal material heats above the auto-ignition temperature. Frictional heating ignition in metals occurs when the two surfaces are rubbing and the metal oxide layer is removed, which exposes the active, bare metal to the enriched oxygen.

10.5 *Electric Arc*—This ignition mechanism can be found to ignite both metals and non-metals. Electric arc ignition occurs when powered components are ungrounded or otherwise build an electrical charge that once released provides sufficient heat to ignite the material.

10.6 *Static Discharge*—This ignition mechanism can be found to ignite both metals and non-metals. Static discharge ignition is similar to electric arc ignition. It occurs when electrical charge builds and is released providing sufficient heat to ignite the material.

10.7 *Resonance*—This ignition mechanism can be found to ignite both metals and non-metals. Resonance ignition occurs when particles or the gas molecules vibrate with increasing amplitude inside a cavity. The resonance generates sufficient heat to ignite the particles or nearby material.

10.8 *Promoted Ignition/Kindling Chain*—This ignition mechanism can be found to ignite both metals and non-metals. Promoted ignition/kindling chain ignition occurs when a burning material has a heat of combustion sufficient to ignite a nearby material. The fire continues to ignite nearby components due to either the components' inability to transmit the heat or the components' low heat of combustion.

10.9 *Thermal Ignition*—This ignition mechanism is typically found to ignite non-metals. Thermal ignition occurs when

an outside heat source raises the temperature of a material above its auto-ignition temperature and ignites the material.

10.10 There is a considerable body of useful information that can aid in understanding the principles of ignition and flammability in oxygen-enriched environments. New theories are under development, as frequently reported at Committee G04 symposia. These developments are expanding our knowledge of oxygen safety. Indeed, some oxygen fires have not been explained fully and their causes are not known. However, many common ignition mechanisms and causes of oxygen-enriched system fires are recognized and well understood. For a more detailed explanation of these ignition mechanisms please refer to the other standards published through the ASTM G04 committee.

11. Hazards

11.1 *Recognized Hazards*—Within any system, a number of conditions are recognized that can increase the hazard and make ignition more likely: (1) oxygen concentration and associated diluents; (2) pressure; (3) temperature; (4) phase; (5) velocity; (6) time and age; and (7) mechanical failure.

11.1.1 *Oxygen Concentration and Associated Diluents*—Higher oxygen concentrations increase the hazards of ignition and fire intensity because more oxygen is available to mix with the fuel. The nature of the diluent gases can have a significant effect on the overall hazard. Inert diluents of large molecular weight are most effective at reducing the hazard. In a few extreme cases, even small amounts of diluents (tenths of a percent) can reduce the flammability of some materials.

11.1.2 *Pressure*—Higher pressures increase the hazards of ignition and fire intensity. Pressure increases the density of the gas, with the same effect as increasing the concentration: more oxygen is available to the fuel, so materials ignite easier and burn faster. Pressure also increases the linear gas velocity at restrictions such as valves, regulators, and intersections which increases particle impact and compression heating effects.

11.1.3 *Temperature*—Temperatures most often encountered in oxygen-enriched systems have relatively little effect on the intensity of combustion and resulting damage. However, higher temperatures tend to increase the likelihood of ignition. They may enable combustion to occur in a system that is not otherwise flammable because less energy must be added to reach the ignition temperature of a material. In addition, high temperatures can accelerate the aging of polymers and thereby reduce their compatibility with oxygen.

11.1.4 *Phase*—Liquid oxygen exists at cryogenic temperatures, and low temperatures generally result in a decreased likelihood of ignition, fire intensity, and resulting damage. However, the density of liquid oxygen is hundreds of times greater than that of gas and it is 100 % pure, making far more oxygen available to the fuel than does high pressure gaseous oxygen. Further, combustion generates enormous pressures as the liquid changes to a gas. If liquid oxygen is mixed with high-surface-area flammable materials the resulting fire can be explosive. Indeed, liquid oxygen in combination with carbon particles has been used as a high explosive. For this reason, liquid oxygen containing fine particles represents an exceptionally severe hazard.

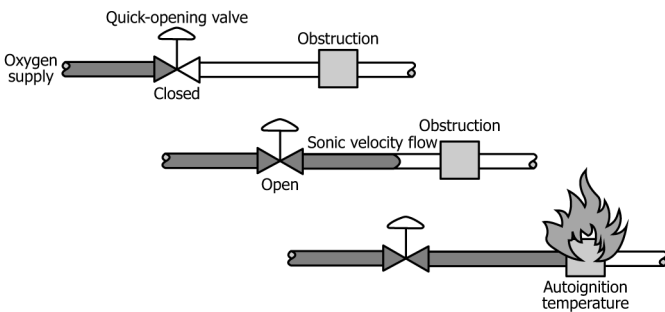


FIG. 4 Adiabatic Compression Can Occur When Oxygen Under High Pressure is Released Quickly into a Low-pressure System. The Gas Flow Can Reach the Speed of Sound, and if it Encounters an Obstruction, the Temperature Can Rise High Enough to Initiate Ignition and Cause a Fire