



Standard Guide for Evaluating Nonmetallic Materials for Oxygen Service¹

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1. Scope

1.1 This guide applies to nonmetallic materials, (hereinafter called materials) under consideration for oxygen or oxygen-enriched fluid service, direct or indirect, as defined below. It is intended for use in selecting materials for applications in connection with the production, storage, transportation, distribution, or use of oxygen. It is concerned primarily with the properties of a material associated with its relative susceptibility to ignition and propagation of combustion; it does not involve mechanical properties, potential toxicity, outgassing, reactions between various materials in the system, functional reliability, or performance characteristics such as physical aging, degradation, abrasion, hardening, or embrittlement, except when these might contribute to an ignition.

1.2 When this document was originally published in 1980, it addressed both metals and nonmetals. Its scope has been narrowed to address only nonmetals and a separate standard Guide G94 has been developed to address metals.

1.3 *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.*

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.

NOTE 2—In evaluating materials, any mixture with oxygen exceeding atmospheric concentration at pressures higher than atmospheric should be evaluated from the hazard point of view for possible significant increase in material combustibility.

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2. Referenced Documents

2.1 ASTM Standards:²

- D217 Test Methods for Cone Penetration of Lubricating Grease
- D566 Test Method for Dropping Point of Lubricating Grease
- D1264 Test Method for Determining the Water Washout Characteristics of Lubricating Greases
- D1743 Test Method for Determining Corrosion Preventive Properties of Lubricating Greases
- D1748 Test Method for Rust Protection by Metal Preservatives in the Humidity Cabinet
- 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)
- 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

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.

2.2 Federal Standard:

Fed. Test Method Std. 91B Corrosion Protection by Coating: Salt Spray (Fog) Test³

2.3 Other Standard:

BS 3N:100: 1985 Specification for General Design Requirements for Aircraft Oxygen Systems and Equipment⁴

2.4 Other Documents:

CGA Pamphlet G4.4 Oxygen Pipeline and Piping System⁵

EIGA IGC 13-12 Oxygen Pipeline and Piping Systems

NSS 1740.15 NASA Safety Standard for Oxygen and Oxygen Systems⁶

3. Terminology

3.1 Definitions:

3.1.1 *autoignition temperature*—the temperature at which a material will spontaneously ignite in oxygen under specific test conditions.

3.2 Definitions of Terms Specific to This Standard:

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

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

3.2.3 *indirect oxygen service*—not normally in contact with oxygen, but which might be as a result of a *reasonably* foreseeable malfunction, operator error, or process disturbance. Examples: liquid oxygen tank insulation, liquid oxygen pump motor bearings.

3.2.4 *maximum use pressure*—the maximum pressure to which a material can be subjected due to a *reasonably* foreseeable malfunction, operator error, or process upset.

3.2.5 *maximum use temperature*—the maximum temperature to which a material can be subjected due to a *reasonably* foreseeable malfunction, operator error, or process upset.

3.2.6 *nonmetallic*—any material, other than a metal, or any composite in which the metal is not the most easily ignited component and for which the individual constituents cannot be evaluated independently.

3.2.7 *operating pressure*—the pressure expected under normal operating conditions.

3.2.8 *operating temperature*—the temperature expected under normal operating conditions.

3.2.9 *oxygen-enriched*—applies to a fluid (gas or liquid) that contains more than 25 mol % oxygen.

3.2.10 *qualified technical personnel*—persons such as engineers and chemists who, by virtue of education, training, or

³ Available from U.S. Government Printing Office Superintendent of Documents, 732 N. Capitol St., NW, Mail Stop: SDE, Washington, DC 20401, <http://www.access.gpo.gov>.

⁴ Available from British Standards Institute (BSI), 389 Chiswick High Rd., London W4 4AL, U.K., <http://www.bsi-global.com>.

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

⁶ National Aeronautics and Space Administration, Office of Safety and Mission Assurance, Washington, DC.

experience, know how to apply physical and chemical principles involved in the reactions between oxygen and other materials.

3.2.11 *reaction effect*—the personnel injury, facility damage, product loss, downtime, or mission loss that could occur as the result of an ignition.

4. Significance and Use

4.1 The purpose of this guide is to furnish qualified technical personnel with pertinent information for use in selecting materials for oxygen service in order to minimize the probability of ignition and the risk of explosion or fire. It is not intended as a specification for approving materials for oxygen service.

5. Factors Affecting Selection of Material

5.1 *General*—The selection of a material for use with oxygen or oxygen-enriched atmospheres is primarily a matter of understanding the circumstances that cause oxygen to react with the material. Most materials in contact with oxygen will not ignite *without a source of ignition energy*. When an energy-input rate, as converted to heat, is greater than the rate of heat dissipation, and the temperature increase is continued for sufficient time, ignition and combustion will occur. A material's minimum ignition temperature and the ignition sources that will produce a sufficient increase in the temperature of the material must therefore be considered. Ignition temperatures and ignition sources should be viewed in the context of the *entire system design* so that the specific factors listed below will assume the proper relative significance. Therefore: *material suitability for oxygen service is application-dependent*.

NOTE 3—For the safe use of materials in oxygen, in addition to the flammability and ignitability properties of the material, it is necessary to consider other physical and chemical properties such as mechanical properties, potential toxicity, etc. Consequently, because ignition and physical (or chemical) properties may be conflicting for selecting a material, it may be necessary in such cases to perform component tests simulating the most probable ignition mechanisms (e.g., a rapid pressurization test on a valve if heat of compression is analyzed as severe).

5.2 Properties of the Material:

5.2.1 *Factors Affecting Ease of Ignition*—Generally, when considering a material for a specific oxygen application, one of the most significant factors is its minimum ignition temperature in oxygen. Other factors that will affect its ignition include relative resistance to various ignition energies, geometry, configuration, specific heat, relative porosity, thermal conductivity, preoxidation or passivity, and “heat-sink effect.” Heat-sink effect is the heat-transfer capacity of the material relative to that of the material in intimate contact with it, considering the mass, physical arrangement, and physical properties of each. For instance, a gasket material may have a relatively low ignition temperature but be extremely resistant to ignition when confined between two steel flanges. The presence of a small amount of an easily ignitable contaminant, such as a hydrocarbon oil or a grease film, can promote the

ignition of the base material. Accordingly, cleanliness is vital to minimize the risk of ignition (1).⁷ See also Practice G93 and Refs. 2–3.

5.2.2 *Factors Affecting Propagation*—Once a material is ignited, combustion may be sustained or may halt. Among the factors that affect whether fire will continue are the basic composition of the material, the presence of heat-sink effects, the pressure, the initial temperature, the geometric state of the matter, and whether there is oxygen available to sustain the reaction. Combustion may also be interrupted by the presence of a heat sink.

5.2.3 *Properties and Conditions Affecting Potential Resultant Damage*—The material properties and system conditions that could affect the damage potential if ignition occurs should be taken into account when estimating the reaction effect in 7.5. These properties and conditions include the material’s heat of combustion, its mass, the oxygen concentration, flow conditions before and after ignition, and the flame propagation characteristics.

5.3 *Operating Conditions*—Conditions that affect the suitability of a material include pressure, temperature, concentration, flow, and gas velocity, and the ignitability of surrounding materials. Pressure and temperature are generally the most significant, and their effects show up in the estimate of ignition potential (5.4) and reaction effect (5.5), as explained in Section 7.

5.3.1 *Pressure*—The operating pressure is important, not only because it generally affects the generation of potential ignition mechanisms, but also because it affects the destructive effects if ignition should occur. While generalizations are difficult, approximate reaction effects would be as given in Table 1.

TABLE 1 Reaction Effect Assessment for Typical Pressures

kPa	psi	Reaction Effect Assessment
0–70	0–10	relatively mild
70–700	10–100	moderate
700–7000	100–1000	intermediate
7000–20 000	1000–3000	severe
Over 20 000	over 3000	extremely severe

NOTE 4—While the pressure generally affects the reaction as indicated in Table 1, tests indicate that it has varying effects on individual flammability properties. For example, for many materials, increasing pressure results in the following:

- (1) An increase in propagation rate, with the greatest increase in rate at lower pressures but with significant increases in rate at high pressures;
- (2) A reduction in ignition temperature, with the greatest decrease at low pressure and a smaller rate at high pressure, however, it should be noted that increasing autoignition temperatures with increasing pressures have been reported for selected polymers, due to competing kinetics (4);
- (3) An increase in sensitivity to mechanical impact;

⁷ The boldface numbers in parentheses refer to the list of references at the end of this standard.

(4) A reduction in oxygen index, as measured in an exploratory study (5), with sharper initial declines in materials of high oxygen index but with only slight relative declines in general above 10 atmospheres and up to at least 20 atmospheres;

(5) A negligible change in heat of combustion; and

(6) An increase in the likelihood of compression heating ignition, with the greatest likelihood at the highest pressures.

In the case of friction, increased pressure may improve heat dissipation and make ignition at constant frictional energy input less likely than at lower pressure. Increased pressure also reduces the likelihood of spark generation at constant electric field strength through increased breakdown voltage values.

5.3.2 *Temperature*—Increasing temperature obviously increases the risk of ignition but does not generally contribute to the reaction effect. The material should have a minimum ignition temperature, as determined by an acceptable test procedure, that exceeds the maximum use temperature (as defined in 3.2.5) by a suitable safety margin.

5.3.3 *Concentration*—As oxygen concentration decreases from 100 %, the likelihood and intensity of a potential reaction also decrease; therefore, greater latitude may be exercised in the selection of materials.

5.4 *Ignition Mechanisms*—For an ignition to occur, it is necessary to have three elements present: oxidizer, fuel, and ignition energy. The oxygen environment is obviously the oxidizer, and the material under consideration is the fuel. Several potential sources of ignition energy are listed below. The list is neither all-inclusive nor in order of importance nor in frequency of occurrence.

5.4.1 *Friction*—The rubbing of two solid materials results in the generation of heat. Example: the rub of a centrifugal compressor rotor against its casing.

5.4.2 *Heat of Compression*—Heat is generated from the conversion of mechanical energy when a gas is compressed from a low pressure to a high pressure. This can occur when high-pressure oxygen is released into a dead-ended tube or pipe, quickly compressing the residual oxygen that was in the tube ahead of it. As the ratio of final pressure to initial pressure increases, so, too, does the final theoretical temperature generated from the compression event. Example: a downstream valve in a dead-ended high-pressure oxygen manifold.

5.4.2.1 *Equation*—An equation that can be used to estimate the theoretical maximum temperature that can be developed when pressurizing oxygen rapidly from one pressure and temperature to an elevated pressure is as follows:

$$T_f/T_i = [P_f/P_i]^{(n-1)/n} \quad (1)$$

where:

- T_f = final temperature, abs,
- T_i = initial temperature, abs,
- P_f = final pressure, abs,
- P_i = initial pressure, abs, and
- $n = \frac{C_p}{C_v} = 1.40$ for oxygen,

where:

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

Table 2 gives the theoretical temperatures which could be obtained by compressing oxygen from one atmosphere (absolute) and 20°C to the pressures shown.

NOTE 5—The final temperature calculated by **Eq 1** is conservative because the equation assumes instantaneous pressurization with no heat loss (adiabatic). The equation is also conservative because it treats oxygen as an ideal gas, which potentially results in calculated final temperature values being much higher than would be realistic and higher than if calculated using real gas equations.

5.4.3 Heat From Mass Impact—Heat is generated from the transfer of kinetic energy when an object having relatively large mass or momentum strikes a material. Example: hammer striking oxygen-saturated macadam.

5.4.4 Heat from Particle Impact—Heat is generated from the transfer of kinetic and possibly thermal energy when small particles (sometimes incandescent), moving at high velocity, strike a material. Example: dirt particles striking a valve seat in an inadequately cleaned high-velocity pipeline.

5.4.5 Static Electric Discharge—Electrical discharge from static electricity, possibly generated by high fluid flow under certain conditions, may occur, especially where particulate matter is present. Example: arcing in poorly cleaned, inadequately grounded piping.

5.4.6 Electrical Arc—Electrical arcing may occur from motor brushes, electrical control equipment, instrumentation, lightning, etc. Example: defective pressure switch.

5.4.7 Resonance—Acoustic oscillations within resonant cavities are associated with rapid temperature rise. This rise is more rapid and achieves higher values where particulates are present or where there are high gas velocities. Ignition can result. For example: a gas flow into a tee and out of the side port when the remaining port presents a resonant cavity.

5.4.8 Internal Flexing—Continuous rapid flexing of a material can generate heat. Such heating may add to environmental factors and increase the possibility of ignition. For example: a gasket protruding into the fluid flow stream.

5.4.9 Other—Since little is known about the actual cause of some oxygen fires or explosions, other mechanisms, not readily apparent, may be factors in, or causes of such incidents. These might include external sources, such as defective electric

resistance-heating elements, smoking, welding sparks or spatter, and nearby open flames, or internal sources such as material fracture.

5.5 Reaction Effect—The effect of an ignition (and subsequent combustion propagation, if it should occur) has a strong bearing on the selection of a material. While it is an obviously imprecise and strongly subjective judgment, it must be balanced against factors such as those given in **5.6**. Suggested criteria for rating the reaction effect severity are given in **Table 3**, and a method of applying the rating in a material selection process is given in **Section 7**. The user should keep in mind that, in many cases, the reaction effect severity rating for a particular application can be lowered by changing other materials that may be present in the system, changing component locations, varying operating procedures, or using barricades or shields.

5.6 Extenuating Factors—Performance requirements, prior experience with the material, availability, and cost enter into the decision. For instance, while a particular material may be rated relatively low based on conventional acceptance criteria, many years of successful safe usage or full-life cycle tests might indicate its continued acceptance.

6. Test Methods

6.1 Heat of Combustion, Test Method D4809—This is a measurement of the heat evolved per unit of specimen mass when a material is completely burned in 25 to 35 atm (2.5 to 3.5 MPa) of oxygen at constant volume. The results are reported in calories per gram (or megajoules per kilogram). For many materials, measured amounts of combustion promoter must be added to ensure complete combustion. Heat of combustion is a test readily conducted and many differing bomb calorimeter methods provide results with adequate accuracy for use with this guide.

6.2 Ignition Sensitivity of Materials to Mechanical Impact in Ambient and Pressurized Oxygen Environments, Test Method G86—This is a determination of the drop-height required to produce a reaction when energy from a known mass is transmitted through a striker pin in contact with a specimen immersed in liquid oxygen or exposed to gaseous oxygen. Results are reported in drop-height and number of reactions in 20 drops. Test Method **G86** is currently the only mechanical impact test that is fully standardized, although other procedures are used in some laboratories. For this reason, and for the large quantity of background data already obtained using this procedure, Test Method **G86** is the recommended screening test to evaluate materials for mechanical impact sensitivity.

NOTE 6—Previous mechanical impact data in ambient pressure liquid oxygen may have been obtained following Test Method **D2512** procedures. In 1997, Test Method **G86** was updated to include a LOX impact test procedure that includes a more strict calibration procedure as an alternative to Test Method **D2512**. At a given plummet drop height the pressurized LOX mechanical impact system provides significantly lower impact energy than the ambient pressure LOX mechanical impact system; however, the relative ranking of materials was maintained.

NOTE 7—Test Method **G86** was developed as a screening technique for selection of nonmetallic materials for use in liquid and gaseous oxygen service components and systems; the test has proven to be consistent in its rankings. For tests in liquid oxygen, since the material specimen is

TABLE 2 Theoretical Maximum Temperature Obtained When Compressing Oxygen Adiabatically from 20°C and One Standard Atmosphere to the Pressures Shown^A

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	9883.9	3785	6845

^A See **5.4.2**.

TABLE 3 Reaction Effect Assessment for Oxygen Applications

Rating		Effect on Personnel Safety	Effect on System Objectives	Effect on Functional Capability
Code	Severity Level			
A	Negligible	No injury to personnel	No unacceptable effect on production, storage, transportation, distribution, or use as applicable	No unacceptable damage to the system
B	Marginal	Personnel-injuring factors can be controlled by automatic devices, warning devices, or special operating procedures	Production, storage, transportation, distribution, or use as applicable is possible by utilizing available redundant operational options	No more than one component or subsystem damaged. This condition is either repairable or replaceable within an acceptable time frame on site
C	Critical	Personnel injured (1) operating the system, (2) maintaining the system, or (3) being in vicinity of the system	Production, storage, transportation, distribution, or use as applicable impaired seriously	Two or more major subsystems are damaged—This condition requires extensive maintenance
D	Catastrophic	Personnel suffer death or multiple injuries	Production, storage, transportation, distribution, or use as applicable rendered impossible—major unit is lost	No portion of system can be salvaged—total loss

immersed in liquid oxygen prior to impact, and since the liquid oxygen surrounding the specimen is maintained at atmospheric pressure, two concerns must be stated. The first concern relates to the physical changes (for example, contraction, sub- T_g transitions, phase transitions) that occur in a specimen when the temperature is reduced to cryogenic conditions. Sensitivity of selected materials may be significantly affected by such physical changes. The second concern relates to test severity. Experience indicates that most materials are more sensitive to ambient or heated gaseous oxygen environments, as opposed to cryogenic oxygen environments. Also, experience shows most materials have a tendency to display increasing sensitivity with increasing oxygen pressure. As a result, tests in ambient pressure liquid oxygen may not be sufficiently severe to discriminate materials for use in ambient or elevated temperature, high-pressure gaseous oxygen systems.

6.3 Limiting Oxygen Index, Test Method D2863—This is a determination of the minimum concentration of oxygen in a flowing mixture of oxygen and nitrogen at 1 atm (0.1 MPa) that will just support flaming combustion from top ignition. The minimum oxygen concentration that will support combustion of materials in configurations that differ from the test configuration may be greater or less than the measured oxygen index value.

NOTE 8—Oxygen index data are reported as a volume percent oxygen (0 to 100). However, early work reported the volume fractional oxygen (0 to 1.0).

NOTE 9—Experience with oxygen index tests indicates that elevated temperatures enable combustion in lower oxygen concentrations and that passage of hot combustion products across an unaffected surface may preheat and promote combustion of materials in concentrations below the oxygen index value. In exploratory work to measure oxygen indices at elevated pressures up to 20 atm (2.0 MPa), it was found that the oxygen index decreased with increasing pressures, but that the ranking of materials was unchanged.

6.4 Autogenous Ignition Temperature, Test Method G72—This is a determination of the minimum specimen temperature at which a material will spontaneously ignite when heated in an oxygen or oxygen-enriched atmosphere. Autogenous ignition (commonly called the autoignition temperature) should be measured at or above the maximum anticipated oxygen concentration. The test should be continued up to the ignition point or at least to 100°C above the maximum use temperature. The temperature that will produce autoignition of materials in configurations that differ from the test configuration may be greater or less than the measured autoignition temperature.

System materials and contaminants may catalyze and lower ignition temperatures. Specimens with large surface area to volume ratios (such as powders) typically ignite at lower temperatures. Flammable vapors that evolve at elevated temperatures may promote lower ignition temperatures, or if dissipated, result in higher autoignition temperatures.

NOTE 10—Pressure has its greatest effect on autoignition temperatures at lower pressures. For instance, an autoignition temperature of a typical elastomer as measured by Test Method G72 may decrease 80°C between 1.5 and 15 psig (10 and 100 kPa), but may only decrease 10°C between 150 and 750 psig (1000 and 5000 kPa). The autoignition temperature test measures a highly behavioral property of a material, especially among polymers. Because it depends upon geometry, heating rate, temperature history of the material, trace contaminants and even catalytic effects of the environment, data collected on differing apparatuses using differing techniques may yield widely differing results. One should therefore not confuse the measured autoignition temperature minimum with the minimum temperature at which the material might ignite in actual hardware.

6.5 Gaseous Fluid Impact, Test Method G74—This is a test in which the material is subjected to a rapid oxygen pressure rise in a closed end tube. The procedure may be used as a fixed-pressure screening method or to measure a threshold pressure.

NOTE 11—This test method provides a reliable means for ranking nonmetallic materials for use in gaseous oxygen service components and systems. The test is configuration dependent and severe. Reaction threshold pressures obtained for most materials are below those pressures that would produce ignition in most common systems.

6.6 Additional Candidate Test Methods:

6.6.1 Thermal Analysis Tests—In these tests, a material's tendency to undergo exothermic or endothermic activity are observed as temperature is raised. Pilot studies have been accomplished with Accelerating Rate Calorimeters (ARC) and Pressurized Differential Scanning Calorimeters (PDSC), and data have been published for autoignition temperatures measured by Differential Thermal Analysis (DTA). These tests indicate that material reactions occur at temperatures significantly different from those measured by Test Method G72.

NOTE 12—Although some thermal analysis tests report lower autoignition temperatures than Test Method G72, one should not infer that these measurements represent the lowest levels at which ignition could conceivably occur in real systems.

6.6.2 Friction/Rubbing Test—The material is heated by friction and rubbing resulting from contact between rotating and stationary test specimens. This test permits evaluation of materials under various axial loads while exposed to elevated pressure oxygen or oxygen-enriched environments.

NOTE 13—There is no standard friction rubbing test for polymers and no plans to develop test. Preliminary tests were conducted by NASA in the late 1970s, and polymers proved difficult to ignite. At that time, test development focused on the study of metals which are more likely to experience severe rubs in actual systems. In the case of polymers, in particular nylon, the polymers melted and flowed from the friction zone.

6.6.3 Particle Impact Test—The material is struck by particles while exposed to a flowing oxygen environment.

NOTE 14—There is no standard test method for studying the ignition of nonmetals during particle impact and none is planned. Preliminary tests conducted by NASA suggest that polymers may be more difficult to ignite than metals under particle impact, possibly due to their ability to cushion an impact.

6.6.4 Promoted Ignition Test—The material is heated by exposure to an electrically-ignited promoter material having a known heat of combustion. This test method is currently being developed and permits evaluation of materials while subjected to elevated-pressure oxygen or oxygen-enriched environments.

NOTE 15—Polymers have much lower autoignition temperatures than metals and tend to ignite in a range of 150 to 450°C. Further, the combustion temperatures of most polymers exceeds the autoignition temperature of virtually all polymers. Hence tests to evaluate the ability of a promoter material or amount of promoter necessary to ignite polymers are not deemed meaningful and rather, the concept of a promoted ignition test is usually applied only to metals for which there are enormous ranges of ignition temperatures and for which the amount of polymer or metal necessary to cause ignition is more amenable to experiment.

6.6.5 Electrical Arc—This test is designed to evaluate the arc ignition characteristics of materials in pressurized oxygen or oxygen-enriched atmospheres.

NOTE 16—There is no standard test method for electrical arc ignition of nonmetals, and none is planned. Experience in oxygen and limited testing in air suggests that arc ignition of polymers as a result of static charge separation is unlikely at low pressures, perhaps also at high pressures. Further, reports on incident studies of NASA suggest that probable arcing at high pressures in oxygen did not produce ignition.

6.6.6 Special Tests—Depending on circumstances, a unique test may be required to qualify a material for a specific application, such as a resonance, internal flexing, or hot-wire ignition test.

7. Material Selection Method

7.1 Overview—To select a material for an application, first review the application to determine the probability that the material will be exposed to significant ignition phenomena in service (7.2). Then consider the material's susceptibility to ignition (7.3) and its destructive potential or capacity to involve other materials (7.4) once ignited. Next, consider the potential reaction effects of an ignition on the system environment (7.5). Finally, compare the demands of the application with the level of performance anticipated from the material in the context of the necessity to avoid ignition and decide whether the material will be acceptable (7.6).

7.2 Ignition Probability Assessment—In assessing a material's suitability for a specific oxygen application, the first step is to review the application for the presence of potential ignition mechanisms and the probability of their occurrence under both normal and *reasonably* foreseeable abnormal conditions. As shown in the Materials Evaluation Data sheets, **Appendix X1**, values may be assigned, based on the following probability scale:

- 0—Almost impossible
- 1—Remote
- 2—Unlikely
- 3—Probable
- 4—Highly probable

This estimate is quite imprecise and generally subjective, but furnishes a basis for evaluating an application through helping to focus on the most important properties. These ratings may in some cases be influenced by the materials present in the system.

7.3 Ignition-Susceptibility Determination—The next step is to determine its rating with respect to those factors which affect ease of ignition (5.2.1), assuming the material meets the other performance requirements of the application. If required information is not available in published literature or from prior related experience, one or more of the applicable tests described in Section 6 should be conducted to obtain it. The application and materials present will play a strong role in defining the most important criterion in determining the ignition susceptibility.

NOTE 17—Until an ASTM test method is established for a particular test, test results are to be considered provisional.

7.4 Post-Ignition Property Evaluation—The properties and conditions that could affect potential resultant damage if ignition should occur (5.2.3) should be evaluated. Of particular importance is the total heat release potential, that is, the material's heat of combustion times its mass (in consistent units). When available, other important postignition data of interest are the combustion reaction rate and the oxygen index.

7.5 Reaction Effect Assessment—Based on the evaluation of 7.4, and the conditions of the complete system in which the material is to be used, the reaction effect severity should be assessed using **Table 3** as a guide. In judging the severity level for entry on the Material Evaluation Data Sheets, **Appendix X1**, it is important to note that the severity level is defined by the most severe of any of the effects, that is, effect on personnel safety *or* on system objectives *or* on functional capability. The materials present in the system can affect the reaction effect assessments.

7.6 Final Selection—In the final analysis, the selection of a material for a particular application involves a complex interaction of the above steps, frequently with much subjective judgment, external influences, and compromises involved. While each case must ultimately be decided on its own merits, the following generalizations apply:

7.6.1 Use the least reactive material available consistent with sound engineering and economic practice. Attempt to maximize autoignition temperature, oxygen index, mechanical impact ignition energy, and gaseous impact pressure threshold. Attempt to minimize heat of combustion and total heat release.

Not every test need be conducted for every application, but it is best to base material selections on more than one test method.

7.6.1.1 If the damage or personnel injury potential is high (Severity Level C or D) use the best (least reactive) practical material available (see [Table 3](#)).

7.6.1.2 If the damage or personnel injury potential is low (Severity Level A or B) and the ignition mechanism probability is low (2 or less) a material with a medium resistance to ignition may be used.

7.6.1.3 If one or more potential ignition mechanisms have a relatively high probability of occurrence (3 or 4 on the probability scale, [7.2](#)) use only a material which has a very high resistance to ignition.

7.6.2 The higher the maximum use pressure, the more critical is the resistance to ignition (see [5.3.1](#)).

7.6.3 Prefer a material whose autoignition temperature in oxygen (as determined by [6.4](#)) exceeds the maximum use temperature by at least 100°C. A larger temperature differential may be appropriate for high use pressures (see [7.6.2](#)) or other mitigating factors.

7.6.4 Autoignition temperatures of 400°C or higher are preferred; 160°C or lower are unsuitable for all but the mildest applications (see [6.4](#)).

7.6.5 Resistance to ignition by impact from drop heights of 43.3 in. (1100 mm) on repeated trials is preferred, while susceptibility to ignition at 6.0 in. (152 mm) or lower would render a material unsuitable for all but the mildest applications (see [6.2](#)).

7.6.6 Heats of combustion of 2500 cal/g (10.5 MJ/kg) or less are preferred; heats of combustion of 10 000 cal/g (41.9 MJ/kg) or higher are unsuitable for all but the mildest applications (see [6.1](#)).

7.6.7 Materials with high oxygen indices are preferable to materials with low oxygen indices. For demanding applications, choose a material with an oxygen index above 55. Materials with oxygen indices below 20 are unsuitable for all but the mildest applications (see [6.3](#)).

NOTE 18—With respect to guidelines [7.6.3 – 7.6.7](#), the use of materials that yield intermediate test results is a matter of judgment involving consideration of all significant factors in the particular application.

7.6.8 Experience with a given material in a similar application or a similar material in the same application frequently forms a sound basis for a material selection. However, discretion should be used in the extrapolation of conditions.

7.6.9 Since some materials vary from batch to batch, it may be necessary to test each batch for some applications.

7.7 *Documentation*—Table X1.1 ([Appendix X1](#)) is a materials evaluation sheet filled out for a number of different applications. It indicates how a materials evaluation is made and what documentation is involved. Pertinent information such as operating conditions should be recorded; estimates of ignition mechanism probability and reaction effect ratings filled in; and a material selection made on the basis of the above guidelines. Explanatory remarks should be indicated by a letter in the “Remarks” column and noted following the table.

7.8 *Examples*—The following examples illustrate the material selection procedure applied to three different hypothetical cases involving valve seats, and one case of a gasket:

7.8.1 *High-Pressure Manifold Shutoff Valve:*

7.8.1.1 *Application Description*—An ambient-temperature 1-in. (2.54-cm) stainless steel manifold requires a manual shutoff valve located 20 ft (6.1 m) from a primary 5000-psig (34.5-MPa) pressure source. The line is to be located outdoors but near attended equipment. A primary pressure valve upstream can be opened rapidly, hence the line might be rapidly pressurized to 5000 psig. A soft-seated valve is desirable to allow ease of operation.

7.8.1.2 *Ignition Probability Assessment (see 7.2)*—Due to a small contact area and small quantity of rubbing motion during operation, friction ignition is considered to be remote. Though the valve can be opened rapidly, the maximum velocity of the seat during closure would be negligible, hence mechanical impact ignition is also rated remote. Since the system is both clean and dry, neither particle impact nor static electricity is considered to be likely. There is no electrical apparatus in the equipment, so that arc ignition is thought to be almost impossible. Since sudden pressurization of the system to 5000 psig (34.5 MPa) might occur, the theoretical temperature achievable from heat of compression ([Eq 1](#)) would be very high, and adiabatic compression ignition is thought to be a highly probable ignition source. No other ignition sources are identified, but their absence cannot be assumed. The summary of ignition probability ratings is:

Friction	1
Heat of Compression	4
Mechanical Impact	1
Particle Impact	2
Static Electricity	2
Electric Arc	0
Other	1

7.8.1.3 *Prospective Material Evaluations (see 7.3)*—Nonmetallic seat materials are reviewed, and polytetrafluoroethylene (PTFE) is found to be highly rated with regard to resistance to ignition (it has one of the highest ignition temperatures for plastics). A well-documented material, it has a very low heat of combustion of 1700 cal/g and Liquid Oxygen (LOX) impact results of passing at a 10 kg-m energy level. Hence, PTFE is considered the best available plastic.

7.8.1.4 *Post-Ignition Property Evaluation (see 7.4)*—Though PTFE is found to have a low heat of combustion, the size of the seat required is quite large. Beyond this, PTFE is a relatively dense polymer. As a consequence, ignition of the seat would be expected to release a small to moderate quantity of heat.

7.8.1.5 *Reaction Effect Assessment (see 7.5)*—Ignition of the seat might, in turn, ignite the stainless steel valve components and possibly release fire to the surroundings. Since such ignition would most likely occur while personnel are in the immediate area and since barricading is not feasible, the effect on personnel safety is rated high. Ignition would result in damage to the valve alone, which could be readily and inexpensively replaced. Interruption of the system for the required repair time is acceptable. Hence the following reaction assessment ratings are assigned:

Effect of Personnel Safety	D
Effect on System Objectives	B
Effect on Function Capability	B

Because of the importance of personnel safety, the overall rating is concluded to be a worst case D.

7.8.1.6 *Final Selection (see 7.6)*—In view of the overall catastrophic reaction effect severity (Code D), only a valve seat that is able to function successfully is concluded to be acceptable. Since there is a high probability (rating 3) that a PTFE seat would be exposed to temperatures due to heat of compression approaching the ignition point (x °F (y °C) predicted using Eq 1), PTFE is concluded to be unacceptable in this application. As a result, a metal seat is selected instead (refer to X1.1).

7.8.2 Pipeline Control Valve:

7.8.2.1 *Application Description*—Automatic flow control is required in an 8-in. (20.3-cm), 650-psig (4.6-MPa) carbon steel above-ground pipeline at ambient temperature. High flow and tight shutoff are also required. The control valve is unattended in normal operation. The line was previously blast cleaned, and a strainer will be immediately upstream of the valve. A bronze-body globe valve is under consideration. A 10 diameter length of Monel pipe is present downstream to comply with CGA Pamphlet G-4.4 (6). A soft seat is under consideration.

7.8.2.2 *Ignition Probability Assessment (see 7.2)*—Friction is negligible between the plug and seat. Also, the operational speed and load are low; frictional heating is unlikely. Rapid opening is likely to produce some adiabatic compression heating downstream of the valves and affect materials there. Rapid closure could produce inertial ram pressurization against the valve by the large upstream mass; adiabatic compression ignition poses a significant risk. There can be only a low velocity impact of the plug on the seat during closure, and the presence of a strainer renders remote chances of mechanical impact or particle impact ignition. Since the pipeline is clean, dry, and remote from electrical equipment, arc and spark from associated equipment or static discharge are unlikely. The pipeline is subject to lightning strikes, however, in the event of so intense an ignition event, the role of valve seat would be relatively unimportant. No other ignition mechanisms are identified, but their absence cannot be assumed. The summary of ignition probability ratings is:

Friction	1
Heat of Compression	3
Mechanical Impact	1
Particle Impact	1
Static Electricity	1
Electric Arc	0
Other	1

7.8.2.3 *Prospective Material Evaluations (see 7.3)*—The probable exposure to heat of compression ignition requires a material with a high ignition temperature; PTFE has one of the highest autoignition temperatures capable of withstanding the predicted high heat of compression. PTFE also has a low heat of combustion, and excellent mechanical impact test results. PTFE is superior to the aliphatic polymamides (PA, eg., nylon 66). Hence, PTFE is taken under consideration.

7.8.2.4 *Post-Ignition Property Assessment (see 7.4)*—Though PTFE has a low heat of combustion, the mass of PTFE present in the seat is large and PTFE is rather dense;

complete combustion would represent a large heat release. In contrast, the PTFE is in intimate contact with a massive bronze body and the gas-wetted area is modest. As a result, the very compatible brass body should resist ignition and remain intact. Ignition of the downstream carbon steel piping is rated unlikely because of the 10 diameter isolation section of Monel pipe.

7.8.2.5 *Reaction Effect Assessment (see 7.5)*—Ignition of the seat would be unlikely to produce a major release of fire or to ignite the pipeline. Since the valve and neighboring pipeline are unattended, the effect on personnel safety is rated negligible (A). Combustion of the seat in the absence of penetration would not interrupt oxygen supply to the pipeline, nor would the combustion products force a long-term process problem. Combustion of the seat, when the valve is closed would supply oxygen to the pipeline, but the system can safely control this flow. Hence the effect on system objectives is rated negligible (A). Finally, since only the valve seat is expected to react, the effect on functional capability is rated marginal (B). The overall reaction effect rating is therefore the marginal (B) rating of the effect on functional capability.

7.8.2.6 *Final Selection (see 7.6)*—Among the materials available for valve seats, only PTFE had an acceptable rating relative to the probable exposure to heat of compression. The destructive potential of PTFE is acceptable and yields an acceptable reaction effect. As a result, PTFE is selected for the seat application.

7.8.3 Reactor Butterfly Valve:

7.8.3.1 *Application Description*—Several 12-in. (30-cm) remotely operated butterfly valves are required for controlling flow to a reactor. The piping is stainless steel. The temperature is ambient. The operating pressure is 2 psig (13.8 kPa gauge). The gas velocity is 40 ft/s (12.2 m/s). Elastomeric linings for use as seats in cast steel valves with bronze disks are under consideration.

7.8.3.2 *Ignition Probability Assessment (see 7.2)*—A review of the operating conditions and the system indicates that no ignition mechanism is likely to be present. Valve breakaway and sealing torque are low, and the valve is slow-operating, so disk-to-seat friction and mechanical impact are rated as remote probabilities. The relatively low gas velocity and the cleanness of the stainless steel line minimize particulate impact and static electricity, which are rated unlikely and remote, respectively. Heat of compression is almost impossible at the low pressures involved. There is no electrical apparatus that could produce ignition, and therefore a remote rating is assigned. No other mechanisms of ignition are foreseen, but their absence cannot be assumed. Therefore, a summary of the ignition probability assessment is:

Friction	1
Heat of Compression	0
Mechanical Impact	1
Particle Impact	2
Static Electricity	1
Electric Arc	1
Other	1

7.8.3.3 *Prospective Material Evaluations (see 7.3)*—For economy, it is desirable to use the manufacturer's standard CR (chloroprene rubber) elastomeric liner, which also functions as a seat. Oxygen compatibility tests on the liner material give the following results:

Autoignition temperature in 2000 psig (13.8 MPa) O ₂ , °C	200
Impact, minimum drop height, in. (mm)	27 (680)
Heat of Combustion, cal/g (MJ/kg)	5800 (24.3)

7.8.3.4 *Post-Ignition Property Evaluation (see 7.4)*—The relatively high total heat release potential (5.8 kcal/g × 8.8 kg per liner = 51 000 kcal per liner) is substantial but is expected to be released at a fairly low rate in 2 psi (13.8 kPa gauge) oxygen.

7.8.3.5 *Reaction Effect Assessment (see 7.5)*—Ignition of the seat would not likely ignite the cast steel valve body or the stainless steel piping; a release of flame would also be unlikely. Also, the valves are located on top of the reactor, isolated from personnel or other equipment. As a result, the effect on personnel safety is rated negligible. Damage in the event of an ignition would likely be minimal and the process disruption would be minimal due to parallel manifolding. For these reasons, the effect on system objectives is rated negligible, and the effect on functional capability is rated marginal. The summary of the reaction effect assessment is:

Effect on Personnel Safety	A
Effect on System Objectives	A
Effect on Functional Capability	B

The overall assessment is a marginal B rating.

7.8.3.6 *Final Selection (see 7.6)*—In view of the marginal rating resulting from modest repair costs alone, the CR elastomer with a medium resistance to ignition is justified, consistent with 7.6.1.2. The judgment is reinforced by reference to Table X1.1, which indicates successful use of this material in a nearly identical situation.

7.8.4 *Pipeline Gasket:*

7.8.4.1 *Application Description*—A gasket is required for use between flanges in a 900-psig (6.2-MPa) centrifugal compressor discharge to a carbon steel pipeline. Gas temperatures of 150°C are possible. The flange is unattended and remotely located.

7.8.4.2 *Ignition Probability Assessment (see 7.2)*—There is no friction source in a flange system, therefore friction ignition is essentially impossible. Due to the inherent volume in the pipeline, pressure relieving devices, limited flow rate of the compressor, and the fact that the flange is not at a dead end, rapid pressurization is a remote possibility. In addition, there are no mechanical motions that might produce impact of the gasket. Particles might be produced and might be accelerated to the gas velocity, however, direct impact on the gasket is unlikely since the gasket will be installed by qualified mechanics and will, therefore, be properly and completely isolated between the steel flanges. The absence of associated electrical equipment and shielding indicate a remote chance of static electricity or electric arc ignition. No other sources are foreseen, but their absence cannot be assumed. The summary of ignition probability ratings is:

Friction	0
Heat of Recompression	1
Mechanical Impact	1
Particle Impact	1
Static Electricity	1
Electric Arc	1
Other	1

7.8.4.3 *Prospective Material Evaluations (see 7.3)*—A wide range of materials are available ranging from PTFE to rubber gaskets. Typical commercial gaskets of asbestos/SBR rubber are mechanically desirable and readily available. The autoignition temperatures of PTFE and the fluorocarbon chlorotrifluoroethylene (PCTFE) are greater than ca. 350°C, while that of asbestos/SBR is roughly 200°C. Mechanical creep (cold flow) of PTFE is a mechanical concern.

NOTE 19—Restoring force and resiliency of an elastomer, or similarly, creep (cold flow) resistance of a plastic are important considerations for selecting a gasket material if leakage is to be avoided. In general, elastomers and plastics cannot be used interchangeably in any application, including gaskets, due to their inherently different mechanical properties.

7.8.4.4 *Post-Ignition Property Evaluations (see 7.4)*—Available gaskets have a wide range of heats of combustion. PTFE and PCTFE have some of the lowest heats of combustion, and also are impact resistant and have high oxygen indices. The asbestos/SBR gaskets in many cases have heats of combustion as low as PTFE and CTFE. Rubber gaskets tend to have high heats of combustion. In addition, the total mass of gasket present tends to be quite small, and it is in intimate contact with massive metal flanges. As a consequence, ignition of the gasket would tend to release a small quantity of total heat, and propagation would tend to be inhibited.

7.8.4.5 *Reaction Effect Assessment (see 7.5)*—Ignition of the gasket might produce ignition of the flange. Since the area is unattended, the effect on personnel would be negligible. The delivery of product would be interrupted but could be backed-up, yielding a marginal effect on system objectives. Similarly, limited damage that is rapidly repairable would result, yielding a marginal effect on functional capability. Hence the following reaction effect assessment ratings are assigned:

Effect on Personnel Safety	A
Effect on System Objectives	B
Effect on Functional Capability	B

As a result the overall rating is a marginal B.

7.8.4.6 *Final Selection (see 7.6)*—In view of the overall marginal reaction assessment rating, a gasket of moderate compatibility is acceptable. In the case of asbestos/SBR, the heat of combustion and total heat release compare favorably with PTFE without incurring a risk of leakage due to creep (cold flow). In addition, if ignition does occur, the asbestos matrix would likely remain in the thin seal region and act to interfere with the diffusion of oxygen to the flame zone, as well as combustion products away from the flame zone; this effect in combination with the thermal mass of the flanges might aid self-extinguishment. Finally, though the autoignition temperature of the asbestos/SBR is much lower than PTFE, and, indeed, is not the desired 100°C above the use temperature, there are no foreseeable mechanisms to produce brief temperature excursions that might approach ignition in a system with such a large thermal inertia. In this case, a 50°C margin between measured autoignition temperature and use temperature is felt to be acceptable and an asbestos/SBR gasket is chosen.

NOTE 20—The analysis presented in the above sections considers only issues related to ignition and combustion properties of materials. Certain types of asbestos are known carcinogens and their use should be restricted to applications where human exposure is not possible.

7.8.5 Gas Filters:

7.8.5.1 *Application Description*—Oxygen gas for electronics-industry microchip manufacture with a purity of 99.5 % has to be filtered at a maximum pressure of 1481 kPa (200 psig) and a maximum temperature of 200°F (93.3°C). The oxygen supply stream will contain no particles greater than 100 µm in size. The maximum expected gas velocity that may impinge onto the filter surface is 20 m/s. Several stages of progressively finer filtration will be used. Some of the filters will be located in areas close to personnel.

7.8.5.2 *Ignition Probability Assessment* (see 7.2)—Since there is no physical rubbing in a filter, the prospect of friction ignition should be almost impossible. The filter might be located at the end of a piping run of significant volume that will have to be occasionally pressurized. Guide G88 (see also Eq 1, 5.4.2.1) indicates that at a 200 psig final pressure, compression of ambient-temperature, atmospheric-pressure oxygen may produce final temperatures on the order of 344°C (653°F). If the initial temperature is 200°F, the final temperature may be 496°C (926°F). Therefore, depending upon filter material and the fact that filters tend to have high surface-area-to-volume ratios and tend to collect particles that may be easily ignited, heat of compression ignition is probable. The planned filters contain no moving parts, therefore mechanical impact ignition is almost impossible. The upstream systems will contain valves that might generate particles and depending upon other metallic materials present, might develop corrosion products. As a result, the prospect of particles striking the filter surface is great. The gas velocity is well below the maximum allowed by CGA Pamphlet G-4.4 which applies for carbon steel and stainless steel piping systems in nonimpingement circumstances; however, in this case, the particles will impinge on the filter surface itself. If the particles have been heated by impacts, they may be effective ignition sources upon contact with nonmetallics, and, since a filter is an inherent impingement site, compliance with CGA Pamphlet G-4.4 by virtue of the present velocity would be questionable even for a metal filter surface. The likelihood of charge separation and electrostatic buildup is small in a metal system, although, because some filter media are excellent dielectrics, this possibility cannot be ruled out completely. There are no associated electrical services foreseen that might lead to arcing. No other ignition sources are identified but their absence cannot be assumed. The summary of ignition probability ratings is:

Friction	0
Heat of Compression	3
Mechanical Impact	0
Particle Impact (nonmetals media)	4
Particle Impact (metallic media)	3
Static Electricity	2
Electric Arc	0
Other	1

7.8.5.3 *Prospective Material Evaluations* (see 7.3)—Filter media are available as inert, inorganic materials such as fiberglass or fired ceramics; these materials are virtually inflammable in oxygen provided they do not incorporate binders. Media are also available in metals that have been sintered or spun for wire, and these typically exhibit a range of

acceptabilities and all practical metallic materials such as bronze, Monel, nickel, and stainless steel have much higher ignition temperatures than nonmetals. Finally, media are available in polymeric materials including nylon 66, PTFE and others. These nonmetallic materials include the latest membrane-type filter media which exhibit the ability to filter to very fine particle size but that utilize very thin, high-surface-area components. Thin materials are likely to be very ignition-responsive to high temperature particle contact or elevated temperatures due to heat of compression. The desirability ranking of the assorted materials was in the order glass and ceramic first (on the basis of being nonignitable), metals second (with brass, bronze, nickel and Monel much preferred over stainless steel, in accordance with Guide G94), and polymers last (with PTFE and PFA preferred over nylon 66).

7.8.5.4 *Post-Ignition Property Evaluation* (see 7.4)—Since the fiberglass and ceramic materials are basically inflammable, a fire of the media itself is not possible. In the case of metallic media, brass and bronze, Monel, Inconel 600, and nickel are shown to be highly propagation resistant 0.125-in. (0.318-cm) diameter rods, while stainless steel is likely to propagate a fire under at least some conditions of expected operation (see Guide G94). The polymeric materials are all likely to combust extensively under the service conditions outlined in 7.8.5.1. Polymers like PTFE and PFA are likely to produce much less heat release and damage than polymers such as nylon 66 and polysulfone; however, in the case of membrane-type filters, the quantity of polymer present is very large, being on the order of kilograms, such that even a fire of PTFE may cause penetration or weakening with rupture of the system as well as ignition of other system materials including piping if metals such as carbon steel or stainless steel are used.

7.8.5.5 *Reaction Effect Assessment* (see 7.5)—The ignition mechanisms would be inconsequential with fiberglass or ceramic filters having light particle loadings. The ignition mechanisms are unlikely to ignite bronze, brass, Monel, Inconel, or nickel media. A prospect of igniting stainless steel media exists, and burning stainless steel would be a powerful ignition source that may involve other materials such as carbon steel and stainless steel structural members. Burning stainless steel media, even within a copper, brass, Monel, Inconel, or nickel piping system, might melt through and release oxygen and burning metal slag. The relative ease of igniting the polymer membrane filters and their large mass also raises a likelihood of rupture, ignition or penetration of the metal piping with the release of fire. Although the filter membrane elements are large in comparison to typical polymers in an oxygen system, the overall filter assemblies are small in terms of system hardware. Therefore, replacement is possible in an acceptable time frame, however, debris released may pose a cleanup problem downstream. This debris may be irrelevant in many traditional oxygen systems, but could be unacceptable to ultraclean processes. The systems tend to be ganged, so that damage to one system would not be a major disruption. Hence the following reaction assessment ratings are assigned:

Effect on Personnel Safety:	
(fiberglass, ceramic media)	A
(brass, Monel, nickel, Inconel media)	A
(stainless steel, polymer media)	C
Effect on System Objectives:	
(fiberglass or ceramic media)	A
(brass, bronze, Monel, Inconel, nickel media)	A
(stainless steel or polymer media)	B
Effect on Functional Capability	B

As a result, the overall rating is a critical “C” for stainless steel or polymer media based upon the personnel safety effect rating and is a marginal “B” rating for fiberglass, ceramic, brass, bronze, Monel, Inconel, or nickel media based upon the less demanding effect on functional capability.

7.8.5.6 Final Selection (see 7.6)—Since some of the prospective materials yield an overall critical reaction-effect-assessment, fiberglass or ceramic media were highly preferred in combination with copper-based or nickel-alloy structural members. In this case, the requirements of the process dictate stainless steel structural members sized in general with the criteria of CGA Pamphlet G-4.4. As a result, the structural members are a conceivable participant in any significant internal fire. The desirability of the ceramic or fiberglass media are thus, accentuated. However, fiberglass media are unacceptable to the process, and existing ceramic filters cannot provide the required filtration levels. In turn, the next most desirable media was metallic with the copper-based and nickel-alloy media preferred to stainless steel. Here again, the copper-based options (including Monel) were unacceptable to the process, and, hence, nickel or Inconel are the preferred options. However, the filtration ability of available nickel-alloy mesh is inadequate to achieve the required submicrometer filtration, membrane filters were found to be required for mechanical reasons. Among the membrane filters, PTFE supported on PFA exhibits the best test results in oxygen index, ignition temperature, and heat of combustion tests (see Tables X1.2, X1.4, and X1.5), and was concluded to be the least flammable material. Because of the large mass and presumed susceptibility to ignition of the membrane configuration even with PTFE and PFA media, additional precautions were felt necessary. To mitigate against particle impact ignition, a prefilter of nickel mesh of 10–30 micron pore size was located immediately upstream of the filter. This serves to intercept any hot particles or particles that may ignite on impact that might otherwise impinge on the ignition-responsive membrane surface. Also, new operational procedures entailing both equipment redesign and implementation engineering controls were adopted to ensure that rapid pressurization of the system does not occur (for example, fast-opening valves such as ball valves are not used upstream of the filters, and operators are trained to carefully open valves slowly). Finally, installations were adopted to provide shielding of the filters by placing them behind panels or equipment where possible. In those cases where personnel frequented the immediate vicinity of any of the filters, the filter was mounted within a rigid section of firmly secured, heavy-wall pipe to serve as a shield and to safely deflect any releases. On this basis and with the precautions discussed, PTFE/PFA media were selected for the finer levels of filtration.

7.8.6 Vacuum Pump Oil:

7.8.6.1 Application Description—A lubricating oil is required for use in a rotary-vane vacuum pump used in several general service applications including: the evacuation of cylinders prior to filling, the evacuation of liquid oxygen vessel annular spaces, and the evacuation of oxygen from laboratory systems prior to maintenance. The suction of the pump can be exposed to pure oxygen because the cylinders or laboratory systems may not be completely empty and because there can be oxygen leakage into the annular region. Steps can be taken to vent oxygen or to limit its pressure through the use of relief valves.

7.8.6.2 Ignition Probability Assessment—Friction is inherently present between the vanes and the pump housing, but in a normal pump, the oil’s lubricity and heat transfer properties would tend to limit the amount of frictional heating, unless a failure occurs. Near-adiabatic compression should also be present but of limited effect because compression of the low suction pressure in the pump to one atmosphere would not yield large amounts of dense hot gas. This near-adiabatic compression would be much more significant if the feed to the pump was at a high pressure. Steps taken to prevent the application of high pressure such as the assured venting of the source of pressure prior to evacuation or the use of a pressure relief device on the pump suction can protect against this prospect. The pump vanes do not strike other components during their motion, hence mechanical impact is not expected. Particles in the suction can achieve significant velocity and strike the pump surfaces because the pressure drop across the pump can be greater than two-to-one and yield sonic velocities. The suction can be filtered to reduce this risk, and the risk is inherently less in the evacuation of clean cylinders than for vacuum space and systems using the pump in a portable fashion where frequent exposure to air may introduce contamination. Nonetheless, impact ignition of oil is not likely, and at one atmosphere, ignition of the metallic pump components is a remote prospect. The presence of generally clean dry gas and the absence of internal electrical equipment preclude electric arcing and sparking. Proper grounding gives protection against the prospect of a lightning strike. No other ignition mechanisms are identified, but inasmuch as there is a continuous rotation, a general heating of the pump is possible, and at least one incident is known where a vacuum pump in an insulated vessel experienced a fire attributed to overheating. The subject pump will enjoy good environmental air circulation. No other ignition assignments are made. The summary of ignition probabilities is:

Friction	3
Heat of Compression	2
Mechanical Impact	1
Particle Impact	2
Static Electricity	1
Electric Arc	0
Other	1

7.8.6.3 Prospective Material Evaluation (see 7.3)—Commercial vacuum pump oils are available as hydrocarbon (HC), silicone, phosphate esters (PE), and the fluorocarbons chlorotrifluoroethylene (CTFE; PCTFE) and perfluoropolyethers (PFPE). The exposure to friction and normal elevated temperatures suggest a high ignition temperature is important. To a lesser extent near-adiabatic compression also

adds to this desirability. Oils in these candidate classes are found to have the following autoignition temperatures in Table X1.2:

CTFE	374 to 427 + °C
PFPE	410 to 427 + °C
PE	235 to 266°C
Fluorosilicone	232 to 249°C
HC	190 to 199°C
Silicone	216 to 241°C

In terms of heat of combustion, Table X1.4 allows the following ranking:

PFPE
CTFE
PE
Fluorosilicone
HC
Silicone

7.8.6.4 Post-Ignition Property Evaluation (see 7.4)—Inspection of Table X1.4 reveals that the heat of combustion of the candidate oils varies widely. Since a vapor cloud or aerosol (which may burn much like a vapor cloud) might be present in the pump discharge case, a gas phase explosion is a concern and oils of greater heats of combustion will be a greater hazard due to the much smaller concentrations necessary to yield a flammable mixture, as well as the greater damage potential if they are burned. Most oil-lubricated vacuum pumps contain quantities of oil that are large compared to the amount of other nonmetallic oxygen system components. Hence, the post-ignition consequences of an oil fire would be expected to be severe and, indeed, explosions of vacuum pumps are known.

7.8.6.5 Reaction Effect Assessment (see 7.5)—Ignition of an aerosol or vapor cloud might produce an explosion and possible rupture of the pump case. If the pump is used for evacuating cylinders prior to filling, the likely presence of personnel is low and the pump can be isolated or shielded which would result in a low chance of injury. Portable use for vacuum jacket maintenance or general evacuation of oxygen systems (perhaps in a laboratory), would be much more likely to result in personnel in the vicinity of the pump. Loss of the pump during a fire could interrupt the cylinder filling operation, maintenance or lab operations, but pumps are relatively easy to replace and can be backed up for reasonable expense. Hence, the effect on system objectives is marginal at worst. Similarly, the damage can be limited to the pump itself, and, therefore, the effect on functional capability would not be rated more than marginal, and yet not negligible for pumps representing a significant cost. As a result the summary reaction effect assessments are:

Effect on personnel safety	C (general use), B (cylinder filling)
Effect on System objectives	B
Effect on functional capability	B

Consequently, the overall reaction effect assessment is a critical C rating for general use of the pump, but a milder marginal B rating for the cylinder filling function.

7.8.6.6 Final Selection (see 7.6)—In view of the overall “critical” reaction effect assessment when the pump is used for general service to do system maintenance, vacuum jacket evacuation, and cylinder evaluation prior to filling, the most fire-resistant oils are preferred. The marginal rating for the use in evacuating cylinders prior to refilling might allow some latitude in the choice of oil for this particular function. The candidate oils were found to fall into one of three categories: those having favorably high autoignition temperatures and favorably low heats of combustion (PFPE and PCTFE), those having favorable high autoignition temperature but unfavorable high heat of combustion (PE), and those having unfavorable autoignition temperature and heat of combustion (fluorosilicone and HC). Examination of the “Examples of Materials in Use” column of Table X1.9 indicates that PFPE, CTFE and PE oils have all been used in vacuum pumps. Clearly, the PFPE and CTFE options are the more desirable. However, the PE oil is a less costly alternative for lower severity systems. In this case, to control cost, one pump was dedicated solely to the lower severity cylinder filling application, because the cylinders are clean and the system is controlled to prevent contamination of the oil, as well as to minimize personnel exposure. However, a second pump was obtained and limited to PFPE and CTFE oils because the remaining application in maintaining oxygen systems, including vacuum-jacketed annuli and laboratory systems have the high severity (reaction effect assessment of “critical”). Furthermore, there is a greater chance that the oil may be exposed to contaminating materials and vapors. Since the particular property of PE oil that allows its consideration was its favorable autoignition temperature, anything (e.g., oxygen pressure or alternate ignition mechanisms) that alters its ignition properties can shift it into the unfavorable category of being both easy to ignite and destructive when burned. Hence, PE could not serve for the critical system. Data collection may be necessary for the specific oil chosen.

8. Keywords

8.1 autogenous ignition temperature; calorimetry; combustion; flammability; friction/rubbing; gaseous fluid impact; heat of combustion; ignition; impact; LOX/GOX compatibility; material evaluation; materials selection; mechanical impact; nonmetallic materials; oxygen index; oxygen service; particle impact; pneumatic impact; promoted ignition/combustion; sensitivity

APPENDIXES

(Nonmandatory Information)

X1. MATERIALS EVALUATION DATA SHEETS

X1.1 *Introduction* —The following data sheets (Table X1.1) contain examples of typical applications divided into several functional categories such as valve seats, gaskets, lubricants, etc. This table will be revised periodically to include new applications and new suggested acceptance criteria, as more and better ASTM standard test procedures are developed. The following comments apply:

X1.1.1 The applications and the values shown are typical of those encountered in industrial and Government Agency practice and were chosen as examples of how this material evaluation procedure is used.

X1.1.2 The values shown in the various test columns are not necessarily actual test results, but, as indicated, are suggested minimum (or maximum for heat of combustion) test results required for acceptance. They are not to be construed as ASTM, industry, or Government standards or specifications. Test Data for selected materials are given in Tables X1.2-X1.6.

X1.1.3 In the “Examples of Materials in Use” column of the data sheet, various materials are indicated as being in current use for particular applications. This mention of particular materials is for information purposes only and does *not* constitute an endorsement or recommendation by ASTM of a particular material. Furthermore, the omission of any material does not necessarily imply unsuitability.

X1.1.4 Unless otherwise noted, the operating conditions are for 99.5 mol %, or higher, oxygen.

X1.1.5 Tables X1.2-X1.6 list an approximate year when a material was tested (followed by the letter “T”) or when the data were listed in a report (followed by an “R”). Many data were reported in the first issue of this guide and are shown as 1980R. Actual testing and manufacturing is unknown.

TABLE X1.1 Typical Material Evaluation Data Sheet

Application	Operating Conditions		Ignition Mechanisms ^A						Suggested Acceptance Criteria						Examples of Materials In Use	Notes		
	Temperature	Gage Pressure		Friction	Heat of Compression	Mechanical Impact	Particulate Impact	Static Electricity	Electric Arc	Other	Reaction Effect ^B	Auto-ignition (Inclusion Methods), Minimum Value, °C	Impact Method D2512, Drop Height, Minimum Value, in. mm	Calorimeter Method D2382, Maximum Value, cal/g (MJ/kg) ^C			Oxygen Index Method D2863, Minimum O ₂ , %	Other ASTM Methods, Minimum Value
		°C	psi															
Valve Seat: 2-in. solenoid liquid control valve	-200 to +50	250	1700	1	1	2	1	1	2	1	B	250	X 43	5000(20.9)			PTFE, PCTFE	A B
12-in. wastewater reactor recirculation gate valve	50	2	14	1	0	1	2	1	1	1	B	160	X	9500(39.8)			EPDM elastomer, CR elastomer	C D
6-in. pressure swing adsorption switching plug valve	50	90	620	2	0	2	2	1	0	1	B	200	X	9500(39.8)			CR elastomer, CSM elastomer	D E
8-in. pipeline control valve, S.S. ball valve	50	650	4500	3	2	2	3	1	0	2	C	350	X 43	2500(10.5)			PTFE	A
1-in. manifold shut-off globe valve	120	5000	35 000	1	3	1	2	2	0	2	C	NA		NA			metal seat	
Inconel ball 0.90-in. port through ball valve	70	10 000	70 000	3	2	1	2	1	1	2	C	ID	NA	ID	3000psia	X	graphite-filled polyimide Resin	F, G, H
Manual valve seat material for liquid oxygen and gaseous oxygen service	-197 to +204	900	6200	3	3	1	4	0	0	1	B	350	X 43	2500(10.5)	95	X	PTFE, glass-filled PTFE, unplasticized PCTFE	A B
Manual valve seat material for gaseous oxygen service	-29 to +204	900	6200	3	3	1	4	0	0	1	B	350	X 43	4500(18.8)	55	X	PTFE, glass-filled PTFE, unplasticized PCTFE, FKM elastomer	A B I
Gaskets: Wastewater treatment reactor manhole	50	3	20	0	0	1	1	1	0	1	A	150	X	9000(37.7)			sponge CR elastomer	D
Liquid transfer hose	-200 to +50	250	1700	1	0	4	1	2	0	1	C	300	X 43	4000(16.7)			PTFE, asbestos-filled copper compressed asbestos sheet	A J
Piping flange	50	600	4100	0	1	1	2	1	0	2	C	160	X	5000(20.9)			bestos sheet packing lead, graphite, fiber-filled PTFE, copper	K A
Compressor head, last stage	200	600	4100	2	2	2	1	1	0	2	C	400	X	5000(20.9)				
Flowmeter, gas	120	600	4100	1	1	1	2	2	0	1	B	250	X	4000(16.7)			VMQ elastomer	L

TABLE X1.1 Continued

Application	Operating Conditions		Ignition Mechanisms ^A						Suggested Acceptance Criteria						Examples of Materials in Use	Notes				
	Temperature	Gage Pressure		Fric-tion	Heat of Com-pression	Mechan-ical Im-pact	Partic-ular Im-pact	Static Elec-tric-ity	Elec-tric Arc	Other	Reac-tion Effect ^B	Auto-ignition (Includ-ing Meth-ods), Minimum Value, °C	and or	Impact Method D2512, Drop Height, Minimum Value, in.			Calorimeter Method D2382, Maximum Value, cal/g (MJ/kg) ^C	and or	Oxygen Index Method D2863, Minimum O ₂ , %	Other ASTM Methods, Minimum Value
		°C	psi																	
Flange gasket for liquid oxygen and gaseous oxygen service	120 to -197 to +149	900	6200	0	3	1	3	1	0	2	C	200	X	2000(0.4)	X	23		compressed asbestos sheet packing	J, Y	
Reciprocating gaseous oxygen compressor discharge piping flange lubricants:	200	600	4100	2	2	2	2	0	0	3	C	400	X	ID	X			copper	X	
Vacuum pump air-cooled vane-type Static switch O-ring	65	-14.6	-100	3	2	1	2	1	0	1	A	250	X	ID	X			PCTFE, PFPE, tricresyl phosphate silicone grease	M N	
Hot gas control valve stem	50	400	2800	1	1	1	1	1	2	1	B	300	X	5000(20.9)	X					
Compressor cylinder	160	600	4100	2	2	1	1	1	0		C	400	X	1500(6.3)	X			PCTFE	M	
Cryogenic pump electric motor bearing	350	600	4100	2	2	2	2	1	1		D	450	X	1500(6.3)	X			PFPE	N	
Gearbox oil for cylinder filling liquid oxygen pump	60	0	0	2	0	1	1	1	2		B	160	X	9000(37.7)	X			silicone grease, PFPE	N	
Vacuum type used in control gas and positive pressure exposure	20	0	0	3	0	4	1	2	2		C	400	X					PFPE, PCTFE	N M	
Lubricant for gaseous oxygen handling manual valve seat	200	0	0	0	0	1	0	1	3		B	390				500°F @ 25 psia		silicone fluids, phosphate ester	V O	
Pipe-thread sealant	210	3000	20 700	2	4	1	4	0	0		C		X	1500(6.3)				PCTFE, PFPE	M N	
Wastewater treatment reactor expansion joint sealant	250	3500	24 100	2	2	1	1	1	1	1	B	350	X	2500(10.5)	X			PFPE vehicle with PTFE solids, PTFE tape AU elastomer	P A W	
	50	1	10	0	0	1	0	0	0	1	A	160	X	8000(33.5)	X					

TABLE X1.1 Continued

Application	Operating Conditions		Ignition Mechanisms ^A						Suggested Acceptance Criteria						Examples of Materials in Use	Notes		
	Temperature	Gage Pressure		Friction	Heat of Compression	Mechanical Impact	Particle Impact	Static Electricity	Electric Arc	Other	Reaction Effect ^B	Auto-ignition (Industrial Methods), Minimum Value, °C	Impact Method D2512, Drop Height, Minimum Value in. / mm	Calorimeter Method D2392, Maximum Value, cal/g (MJ/kg) ^C			Oxygen Index Method D2863, Minimum O ₂ , %	Other ASTM Methods, Minimum Value
		°C	psi															
Centrifugal compressor split-casing flange seal	130	500	3500	2	2	2	2	1	0	1	D	230	X	5000(20.9)		RTV silicone, FKM elastomer	I	
Pressure switch	50	1000	7000	1	1	1	1	1	2	1	B	250	X	5000(20.9)		PTFE, FKM elastomer	A	
Cryogenic valve stem packing	100	400	2800	1	1	1	1	1	0	1	B	250	X	5000(20.9)		PTFE, graphite fiber	A	
Rotary liquid oxygen pump face seal	20	10	70	4	1	1	2	1	2	1	B	400				graphite, carbon with additives	K	
Static and dynamic shaft seals for H.P. ball valve	70	10 000	70 000	2	2	1	1	1	1	1	C				3000psig	FKM elastomer	F	
Miscellaneous: Compressor packing ring	135	615	4200	3	2	2	1	1	1	1	C	400	X	2500(10.5)		filled PTFE	R	
Liquid level indicator sight glass	45	265	1830	0	1	1	1	1	1	1	A	ID	X	6000(25.1)		PMMA	S	
Rotary pump vane	-50	650	4500	3	2	2	1	1	1	1	A	300	X	8000(33.5)		carbon	T	
Casting impregnant	65	600	4100	1	1	1	1	1	1	1	B	250	X			sodium silicate and filler	U	
Liquid cylinder inner container support	50	2	14	0	0	3	0	0	1	1	C	ID	X	3000(12.6)		compressed asbestos board		
Liquid oxygen globe valve, seat ring	20	200	1400	2	0	4	4	0	1	1	B	350	X	2500(10.5)		PTFE, PCTFE	A, B	
Oxygen regulator diaphragm	50	200	1400	0	2	1	2	1	0	1	C	200	X	ID		CR elastomer (reinforced), FKM elastomer (reinforced)	D	
Filter elements for oxygen service	90	200	1400	0	3	0	4 (3) ^A	2	0	1	B (C) ^A	350		2500(10.5)	95	Fiberglass without binders, PTFE, PFA	I	

^A See 7.2.

^B See Table 3.

- C Metallic media.
- NA = not applicable.
- ID = inadequate data available.
- Notes:
- A Teflon TFE and Halon TFE are brands of polytetrafluoroethylene (PTFE).
- B Kel-F 81 is polychlorotrifluoroethylene (PCTFE).
- C Nordel is one brand of ethylene propylene rubber (EPDM).
- D Neoprene is one brand of chloroprene rubber (CR).
- E Hypalon is one brand of chlorosulfonated polyethylene (CSM).
- F Gaseous impact at 3000 psia.
- G Vespel SP-21 is one brand of 15 % graphite-filled polyimide resin.
- H Batch-tested.
- I Viton and Fluorel are brands of vinylidene fluoride hexafluoropropylene (FKM).
- J Durabla, Garlock 900, and JM-61 are brands of compressed asbestos sheet packing.
- K GRAFOIL is one brand of pure graphite fiber.
- L Silicone Rubber is a vinyl methyl polysiloxane (VMQ).
- M Fluorolube and Halocarbon are brands of chlorotrifluoroethylene oils (PCTFE).
- N Krytox and Fomblin are brands of perfluoroalkyl ether (PFPE).
- O Fyrquel 220 is one brand of a pure phosphate ester (PE).
- P La-Co OXYITE with Teflon is one brand of PTFE suspended in chlorinated hydrocarbon oil.
- Q Buina N is one brand of nitrile-butadiene rubber (NBR).
- R Linde 1515 is one brand of 15 % lead- and 15 % glass-filled PTFE.
- S Lucite and Plexiglas are brands of poly(methyl methacrylate) (PMMA).
- T Imprex is one brand of iron oxide and asbestos suspended in sodium silicate.
- U Transite is one brand of hard asbestos/cement board.
- V UCON is one brand of silicone fluid.
- W Adiprene and Cyanaprene are brands of polyurethane di-isocyanate (AU).
- X Gasket is in a particularly critical location. Further, if ignition occurs, severe damage frequently limits post-ignition determination of cause.
- Y Heat-sink effect of flange permits autoignition temperature less than 100°C above operating gas temperature.

TABLE X1.2 Autoignition Temperatures for Selected Materials: Plastics and Elastomers

Material	Manufacturer	Circa ^A	Description	AIT, °C	Notes
Plastics					
ABS		1996R	copolymer of acrylonitrile, butadiene, and styrene	243	A
ACLAR 22	Allied Chemical Corp.	1980R	chlorotrifluoroethylene (PCTFE)	390	
ACLAR 23	Allied Chemical Corp.	1980R	PCTFE	349	
ARMALON	E.I. du Pont de Nemours	1980R	TFE-fluorocarbon and glass	427+	
Delrin		1996R	polymethylene oxide	178	A
Halar			copolymer of ethylene and chlorotrifluoroethylene	171	A
Kel-F 81		1996R	PCTFE	388	A
Kynar		1996R	polyvinylidene fluoride (PVDF)	268	A
Lexan		1996R	polycarbonate	286	A
Mylar		1996R	polyethylene terephthalate	181	A
Noryl		1996R	polyphenylene oxide blended with polystyrene	348	A
PEEK		1996R	polyetheretherketone	305	A
PE		1996R	polyethylene	176	A
PES		1996R	polyethersulfone	373	A
PP		1996R	polypropylene	174	A
PPS		1996R	polyphenylene sulfide	285	A
PVC		1996R	polyvinyl chloride	239	A
Rulon E	The Dixon Corp.	1980R	glass-filled TFE fluorocarbon	427+	
Rulon J	The Dixon Corp.	1980R	glass-filled TFE fluorocarbon	360	
Rulon LD	The Dixon Corp.	1980R	glass-filled TFE fluorocarbon	427+	
Tedlar		1996R	polyvinyl fluoride (PVF)	222	A
Teflon A		1996R	polytetrafluoroethylene	434	A
Teflon FEP		1996R	copolymer of tetrafluoroethylene and perfluoro(propyl vinyl ether)	378	A
Teflon PFA		1996R	perfluoroalkoxytetrafluoroethylene	424	A
Tetzel		1996R	copolymer of tetrafluoroethylene and ethylene (ETFE)	243	A
Tetrafluor FCO 3		1980R	filled TFE-fluorocarbon	427+	
Tetratemp 900		1980R	polyimide	399	
Tetratemp 980		1980R	polyimide	307	
Ultem		1996R	polyetherimide	385	A
VespeL SP-21		1996R	polyimide with 15 wt % graphite	343	A
Zytel		1996R	polyamide (Nylon 6/6)	259	A
Elastomers					
Aflas		1996R	copolymer of tetrafluoroethylene and propylene + cure site monomer	254	A
Butyl Rubber		1996R	copolymer of isobutylene and small quantities of isoprene	208	A
EPDM		1996R	copolymer of ethylene, propylene, and a diene monomer	159	A
EPR Rubber		1996T	ethylene-propylene rubber	153	B
E515-80					
EPR Rubber		1996T	ethylene-propylene rubber	173	B
E692-75					
Fluorel		1996R	copolymer of vinylidene fluoride and hexafluoropropylene	302	A
Hechlor II	Hercules Inc.	1980R	epichlorohydrin rubber	305	
Hycar 1053	BF Goodrich	1980R	nitrile rubber (copolymer of butadiene and acrylonitrile)	310	
Kalrez		1996R	copolymer of tetrafluoroethylene and perfluoro (methyl vinyl ether) + cure site monomer	355	A
Neoprene		1996R	polychloroprene	258	A
Neoprene GRT		1980R	polychloroprene	166	
Nitrile		1996R	copolymer of butadiene and acrylonitrile	173	A
Polyurethane Rubber		1996R	polyurethane	181	A
Silicone Rubber		1996R	polysiloxane	262	A
Viton A		1980R	copolymer of vinylidene fluoride and hexafluoropropylene	268 to 322	A, C
Viton B		1980R		290	
Viton B-910		1980R		318	
Viton E		1980R		310	
Viton B+ 13 % MgO		1980R		304	
Composites					
epoxy/fiberglass		1997R		258	D
epoxy/aramid		1997R		217	D
epoxy/graphite		1997R		258	D
bismaleimide/graphite		1997R		340	D
Grafoil GHE	UCAR Carbon Co.		flexible graphite with SS tong metal interlayer	400+	
Grafoil GHR	UCAR Carbon Co.		flexible graphite with SS tong metal interlayer	400+	
phenolic/fiberglass	ContourComposites	1997R		155	D
phenolic/aramid	ContourComposites	1997R		265	D
phenolic/graphite	ContourComposites	1997R		312	D
vinyl ester/fiberglass		1997R		232	D

^A Approximate date of material test (T) or published report (R).

Notes:

A Tests conducted per Test Method **G72** at 10.3 MPa in 100 % oxygen. Source: Hshieh, F. Y., Stoltzfus, J. M., and Beeson, H. D., "Autoignition Temperature of Selected Polymers at Elevated Oxygen Pressure and Their Heat of Combustion," *Fire and Materials*, Vol 20, 301–303, 1996.

B Tests conducted per Test Method **G72** at 0.69 MPa in 100 % oxygen. NASA WSTF Reports 96-29810 and 96-29811.

C The AIT depends on the carbon black content in rubbers.

D Tests conducted per Test Method **G72** at 10.3 MPa in 100 % oxygen. Source: Beeson, H. D., Hshieh, F. Y., and Hirsch, D. B., "Ignitibility of Advanced Composites in Liquid and Gaseous Oxygen," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres*, ASTM STP 1319, 1997.

TABLE X1.3 Autoignition Temperatures (AIT) for Selected Materials: Lubricants and Thread Compounds^A

Material	Manufacturer	Circa ^{A,B}	Description	AIT, °C
Antiseize MIL-A-907d	Jet Lube Co.	1980R	Bronze powder plus grease	146
Antiseize MIL-A-13881B	Garm Products Co.	1980R	Mica in oil	185
Antiseize TT-A-00580d	Garm Products Co.	1980R	White lead paste	216
Armite Antiseize	Armite Corp.	1980R	Graphite grease	182
Belray Moly 16 Microfive	Bel Ray Co.	1980R	Mo S ₂ dry	246
Belmol Pure Moly	Bemol Co.	1980R	Mo S ₂ dry	232
Brayco 600	Bray Oil Co.	1980R	Perfluoroalkyl polyether oil (PFPE)	427
Brayco Micronic 803	Bray Oil Co.	1980R	Perfluoroalkyl polyether grease (PFPE)	421
Braycote 631A	Bray Oil Co.	1980R	Fluorocarbon Telomer spray	427
Braycote 667	Bray Oil Co.	1980R	Perfluoroalkyl polyether grease	427
Cellulube 90	Celanese Corp.	1980R	Triaryl phosphate ester	265
Cellulube 220	Celanese Corp.	1980R	Triaryl phosphate ester	263
Copalite Crodel	National Engineering	1980R	Thread and metal sealant	335
DAG 155	Acheson Colloids	1980R	Graphite suspension	144
DAG 211	Acheson Colloids	1980R	Graphite suspension	157
Damping fluid	General Electric Co.	1980R	Silicone damping fluid	241
DC 55M	Dow Corning Corp.	1980R	Silicone grease	216
Dixons No. 1	Joseph Dixon Crucilde Co.	1980R	Graphite flake	427
Dixons GW 430	Joseph Dixon Crucilde Co.	1980R	Graphite in isopropanol	310
Drilube Exp 1-26	Royal Engineering Co.	1980R	Fluorocarbon grease	296
Easyoff 990	Texocone Co.	1980R	Flakecopper in oil	179
Easywrap tape	JA Sexauer Inc.	1980R	PTFE pipetape	427
Electromoly No. 1	Electrofilm Inc.	1980R	Mo S ₂ dry	257
Electromoly No. 2	Electrofilm Inc.	1980R	Mo S ₂ dry	246
Epibond 104	Furane Products Co.	1980R	Epoxy cement	232
Everlube 811	E/M Lubricants Inc.	1980R	MO S ₂ in sodium silicate	271
Everlube 6711	E/M Lubricants Inc.	1980R	Colloidal graphite powder	363
Felpro C-100	Fel Pro Inc.	1980R	Antisurge black grease	177
Fluoroglide spray	Chemplast Inc.	1980R	Fluorocarbon Telomer spray	293
Fluorolube				
FS-5	Hooker Chemical	1980R	CTFE oil	399
GR362	Hooker Chemical	1980R	CTFE grease	427+
GR504	Hooker Chemical	1980R	CTFE oil	427+
HO125	Hooker Chemical	1980R	CTFE oil	388
LG160	Hooker Chemical	1980R	CTFE grease	382
MO-10	Hooker Chemical	1980R	CTFE oil	399
S30	Hooker Chemical	1980R	CTFE oil	385
T80	Hooker Chemical	1980R	CTFE oil	388
Fomblin RT-15	Montedison USA Inc.	1980R	Perfluoroalkyl polyether grease	427+
Vacuum grease	Montedison USA Inc.	1980R	Perfluoroalkyl polyether grease	427+
Y-02	Montedison USA Inc.	1980R	Perfluoroalkyl polyether oil	427+
Y04	Montedison USA Inc.	1980R	Perfluoroalkyl polyether oil	427+
Y06	Montedison USA Inc.	1980R	Perfluoroalkyl polyether oil	427+
Y-16	Montedison USA Inc.	1980R	Perfluoroalkyl polyether oil	427+
Y-25	Montedison USA Inc.	1980R	Perfluoroalkyl polyether oil	427+
YR	Montedison USA Inc.	1980R	Perfluoroalkyl polyether oil	418
YU	Montedison USA Inc.	1980R	Perfluoroalkyl polyether oil	410
Fryquel				
90	Stauffer Chemical	1980R	Triaryl phosphate ester	235
220	Stauffer Chemical	1980R	Triaryl phosphate ester	266
FS 1292 Plug grease	Dow Corning Corp.	1980R	Fluorosilicone grease	232
FS3452	Dow Corning Corp.	1980R	Fluorosilicone grease	249
Halocarbon				
4-11	Halocarbon Products Corp.	1980R	CTFE oil	427+
4-11S	Halocarbon Products Corp.	1980R	CTFE oil	402
10-25	Halocarbon Products Corp.	1980R	CTFE oil	399
20-25S	Halocarbon Products Corp.	1980R	CTFE oil	393
11-14	Halocarbon Products Corp.	1980R	CTFE oil	410
11-14S	Halocarbon Products Corp.	1980R	CTFE oil	402
11-21	Halocarbon Products Corp.	1980R	CTFE oil	385
11-21S	Halocarbon Products Corp.	1980R	CTFE oil	388
13-21	Halocarbon Products Corp.	1980R	CTFE oil	396
13-21S	Halocarbon Products Corp.	1980R	CTFE oil	388
14-25	Halocarbon Products Corp.	1980R	CTFE oil	391
14-25S	Halocarbon Products Corp.	1980R	CTFE oil	393
11B13	Halocarbon Products Corp.	1980R	CTFE grease	427+
25-5S	Halocarbon Products Corp.	1980R	CTFE grease	427+
25-10M	Halocarbon Products Corp.	1980R	CTFE grease	427+
25-20M	Halocarbon Products Corp.	1980R	CTFE grease	427+
25-20M-5A	Halocarbon Products Corp.	1980R	CTFE grease	427+
25-20M-5A	Halocarbon Products Corp.	1980R	CTFE grease	427+
X90-10M	Halocarbon Products Corp.	1980R	CTFE grease	427+
X90-15M	Halocarbon Products Corp.	1980R	CTFE grease	427+
Hyd oil MIL-H-5606B	Pennsylvania Refining Co.	1980R	Petroleum hydraulic oil	190
Hydraulic fluid MIL-H-22072	EF Houghton & Co.	1980R	Water glycol recoil fluid	241

TABLE X1.3 *Continued*

Material	Manufacturer	Circa ^{A,B}	Description	AIT, °C
Hydraulic oil MIL-H-83282	Mobile Oil Co.	1980R	Synthetic hydraulic oil	199
Kel-F-1	3M Co.	1980R	CTFE oil	374
Kel-F-3	3M Co.	1980R	CTFE oil	382
Kel-F10	3M Co.	1980R	CTFE oil	385
KM-545	Monsanto Chemical Co.	1980R	Triaryl phosphate ester	260
Krytox 143AA	E.I. du Pont de Nemours	1980R	Perfluoroalkyl polyether oil	427+
Krytox 143AB	E.I. du Pont de Nemours	1980R	Perfluoroalkyl polyether oil	427+
Krytox 143AC	E.I. du Pont de Nemours	1980R	Perfluoroalkyl polyether oil	427
Krytox 143AD	E.I. du Pont de Nemours	1980R	Perfluoroalkyl polyether oil	427+
Krytox 143AZ	E.I. du Pont de Nemours	1980R	Perfluoroalkyl polyether oil	427+
Krytox 240 AB	E.I. du Pont de Nemours	1980R	Perfluoroalkyl polyether grease	427+
Krytox 240 AC	E.I. du Pont de Nemours	1980R	Perfluoroalkyl polyether grease	427+
Lube oil Mil-L-17331	Texaco Oil Co.	1980R	Lubricating Oil 2190 TEP	210
Lube oil MIL-L-23699	Mobile Oil Co.	1980R	Synthetic turbine oil	235
McLube 99	McGee Industries Inc.	1980R	Mo S ₂ dry	271
Molykote 321	Dow Corning Corp.	1980R	Mo S ₂ fluorocarbon spray	427+
Molykote Z	Dow Corning Corp.	1980R	Mo S ₂ dry	260
Oxygen system antiseize	Rectorseal Co.	1980R	Graphite + Mo S ₂ + Fluorocarbon oil	218
Readyseal thread tape	Chemplast Inc.	1980R	PTFE Pipe Tape	427
STA-LOK-AVV	Broadview Chemical Corp.	1980R	Red Thread Sealant (Polyester)	149
STA-LOK-CV	Broadview Chemical Corp.	1980R	Blue Thread Sealant (Polyester)	152
S-22 tape	Saunders Co.	1980R	PTFE Pipe Tape	427+
Thread seal No. 121	Dodge Fluoroglas Oak Ind.	1980R	PTFE Pipe Tape	427+
Universal thread seal	W.S. Shamban & Co.	1980R	PTFE Pipe Tape	427+
Unyte all-purpose tape	JC Whitlam Mfg. Co.	1980R	PTFE Pipe Tape	427+
Utility pipe joint cpd	Stevens Industries	1980R	Pipe point paste	216
Vydax AR	E.I. du Pont de Nemours	1980R	Fluorotelomer in fluorocarbon solvent	288
Vydax 525	E.I. du Pont de Nemours	1980R	Fluorotelomer in fluorocarbon solvent	288
Vydax 550	E.I. du Pont de Nemours	1980R	Fluorotelomer in fluorocarbon solvent	288
X-15 Inorganic DryLube	Dow Corning Corp.	1980R	Mo S ₂ dry	260

^A Tests concluded in accordance with Test Method G72 at a starting pressure of 1500 psi (10.3 MPa). Source of data for materials: David W. Taylor, Naval Ship Research and Development Centre.

^B Approximate date of material test (T) or published report (R).

TABLE X1.4 Mechanical Impact Sensitivity Data for Selected Materials^A

Material	Manufacturer	Circa ^B	Description	Reactions/Tests ^C	Drop Height, in.
Buna-N Rubber		1980R	Butadiene-acrylonitrile	2/3	43.3
Fluorel	3M Co.	1980R	Vinylidene fluoride and hexafluoropropylene copolymer	0/20	43.3
Fluorolube GR 362 Grease	Hooker Chemical	1980R	Chlorotrifluoroethylene	0/20	43.3
FS 1265 Oil	Dow Corning	1980R	Fluorosilicone	13/169 4/40	43.3
					17.3
Hypalon Rubber	E.I. du Pont de Nemours	1980R	Chlorosulfonate polyethylene	4/5 1/15	43.3
					8.6
KEL-F (Plasticized)	3M Co.	1980R	Polychlorotrifluoroethylene	0/20	43.3
KEL-F (Unplasticized)	3M Co.	1980R	Polychlorotrifluoroethylene	0/20	43.3
KEL-F No. 90 Grease	3M Co.	1980R	Chlorotrifluoroethylene	0/60	43.3
KEL-F Oil No. 1	3M Co.	1980R	Chlorotrifluoroethylene	0/20	43.3
Koroseal	B.F. Goodrich Co.	1980R	Vinyl rubber	2/20	43.3
Kynar	Connecticut Hard Rubber Co.	1980R	Vinylidene fluoride	79/100	43.3
Lexan	General Electric Co.	1980R	Polycarbonate resin	20/20 3/17 0/20	43.3
					17.3
					8.6
Mylar	E.I. du Pont de Nemours	1980R	Polyethylene terephthalate resin	6/51	43.3
Nylon (Zytel)	E.I. du Pont de Nemours	1980R	Polyamide resin	21/60	43.3
Plexiglas	Rohm & Haas	1980R	Methyl methacrylate sheet	2/2	43.3
Polyethylene	DuPont	1980R	Resin	30/80 30/80 28/80 22/80 7/20	43.3 43.3 36.6 25.9 17.3 8.6
				3/20	4.3
Polyvinyl Chloride	Teledyne Corp.	1980R	Resin	2/2 2/14 0/20	43.3 17.3 4.3
Tedlar 200 AM	E.I. du Pont de Nemours	1980R	Polyvinyl fluoride film	4/29	43.3
TFE-fluorocarbon	E.I. du Pont de Nemours	1980R	Polytetrafluoroethylene	0/20	43.3
Viton A	E.I. du Pont de Nemours	1980R	Vinylidene fluoride and hexafluoropropylene copolymer	3/20	43.3

^A Data in accordance with Test Method D2512.

^B Approximate year in which material was tested (T) or data were reported (R).

^C Tests conducted per MSFC-SPEC-106B, as reported in Key, C. F., "Compatibility of Materials with Liquid Oxygen," Vol 1. NASA TM X-64711, Nat. Aeronautics and Space Administration, October 1972.

TABLE X1.5 Heats of Combustion for Selected Materials

Materials	Source (1)/Manufacturer (2) ^A	Circa ^B	Description	Heat Released, Cal/g	Source of Data	Remarks
ABS	Various	1980R	Acrylonitrile-butadiene-styrene	8500	<i>C</i>	
Acetal Plastic	Celcon (2)	1977T	Poly(oxyethylene)	4062	<i>D</i>	
Aflas		1996R	copolymer of TFE and propylene + cure site monomer	5940	<i>E</i>	
Asbestos Paper	Johns-Manville (2)	1976T		<100	<i>D</i>	
Bel-Ray FC1245	Bel-Ray Co. (2)	1979T	PCTFE oil/graphite	3709	<i>D</i>	
Bel-Ray FC1260	Bel-Ray Co. (2)	1980T		1117	<i>D</i>	
Blue Gard 3000 Gasket	Garlock Inc. (2)	1981T	Arimid/Buna N	3047	<i>D</i>	
Brisolube 427 Oil	British Solvent Oils, Ltd. (1)	1973T	Triaryl phosphate	7416	<i>D</i>	
Buna-N	UNK	1980R	Butadiene-nitrile	5400	<i>F</i>	<i>G</i>
Butyl Rubber		1996R	Copolymer of isobutylene and small quantities of isoprene	10 789	<i>E</i>	
Climax FL-5	Climax Lubricants and Equip. Co. (1)	1976T	PCTFE grease	1160	<i>D</i>	
Cotton	Various	1980R	Cotton	4000	<i>C</i>	
CPR 9501	Trymer (2)	1982T	Polyisocyanurate foam	6056	<i>D</i>	
	Trymer (2)	1983T	Polyisocyanurate foam	5960	<i>D</i>	
Cryo-polyfil Plastic	Worcester Controls Corp. (1)	1976T	Filled PTFE	2266	<i>D</i>	
Cyl-Seal Thread Sealant	West Chester Chem. Co. (1)	1976T		3294	<i>D</i>	
Delrin Plastic	DuPont (2)	1973T	Poly(acetyl)	4029	<i>D</i>	
Durabla (black)	Durabla Inc.	1980R	Asbestos in GRS binder	1600	<i>F</i>	
EPDM		1996R	Copolymer of ethylene, propylene, and a diene monomer	11 299	<i>E</i>	
epoxy/fiberglass		1997R		2495		
epoxy/aramid		1997R		6223	<i>H</i>	
epoxy/graphite		1997R		7077	<i>H</i>	
EPR Rubber	Circle Seal (1)	1975T	Ethylene propylene copolymer	8833	<i>D</i>	
FRP Boards	Raven Ind. (2)	1975T		5680	<i>D</i>	
	Spry Glass Int'l Ltd. (1)	1975T	Fiberglass/epoxy	5306	<i>D</i>	
		1976T	Arimid/epoxy	7150	<i>D</i>	
Fluorel E2160	3M Co.	1980R	Fluoroelastomer	3400	<i>I</i>	<i>J</i>
Fluorogreen E600	Peabody Dore Corp.	1980R	Glass/chromium oxide-filled TFE-fluorocarbon	2400	<i>I</i>	
Fluorogold	Fluorocarbon Co.	1980R	25 % Glass-Filled TFE-fluorocarbon	1700	<i>I</i>	
Fluorolule GR362	Hooker Chem. Co.	1978T	PCTFE/filler	4994	<i>D</i>	
Fluorolule LG160	Hooker Chem. Co.	1974T	PCTFE	2516	<i>D</i>	
Foamglass Insulation	Pittsburg Corning (2)	1973T	Cellularglass	190	<i>D</i>	
Fomblin RT-15 Grease	Montedison (2)	1974T	PFPE with PTFE filler	995	<i>D</i>	
Fomblin Y04 Oil	Montedison (2)	1973T	PFPE	923	<i>D</i>	
Fomblin Y25 Oil	Montedison (2)	1979T	PFPE	706	<i>D</i>	
Fyrquel 220	Stauffer Chem. Co. (2)	1974T	Triarylphosphate	7709	<i>D</i>	
Fyrquel 220	Stauffer Chem. Co. (2)	1974T	Triarylphosphate	7653	<i>D</i>	
Gaskets:						
Garlock 900	Garlock Inc. (2)	1973T	Asbestos/GRS	1676	<i>D</i>	
Garlock 900	Garlock Inc. (2)	1974T	Asbestos/GRS	1869	<i>D</i>	
Garlock 7021	Garlock In. (2)	1975T	Asbestos/GRS	1820	<i>D</i>	
Gylon Fawn	Garlock Inc. (2)	1973T	Filled PTFE	1069	<i>D</i>	
Gore-Tex	W. L. Gore (2)	1973T	Expanded PTFE	1431	<i>D</i>	
Grafoil Ribbon Packing	Union Carbide (2)	1975T	Graphite	7580	<i>D</i>	
Halar		1996R	Copolymer of ethylene and chlorotrifluoroethylene	3254	<i>E</i>	
Halocarbon 6-25 Wax	Halocarbon Prod. Co. (2)	1973T	PCTFE Wax	2119	<i>D</i>	
Halocarbon 11-14S Oil	Halocarbon Prod. Co. (2)	1974T	PCTFE Oil	1994	<i>D</i>	
Halocarbon 11-21E Oil	Halocarbon Prod. Co. (2)	1973T	PCTFE Oil	1347	<i>D</i>	
Halocarbon 25-5S Grease	Halocarbon Prod. Co. (2)	1973T	Filled CTFE	2366	<i>D</i>	
Halocarbon 25-20 Oil	Halocarbon Prod. Co. (2)	1979T	PCTFE Oil	1047	<i>D</i>	
Kalrez 1045	DuPont (2)	1979T	FPM elastomer	1565	<i>D</i>	
Kalrez 4079	DuPont (2)	1985T	FPM elastomer	2090	<i>D</i>	
Kaowool Insulation	Babcock and Wilcox (2)	1975T	Alumina/silica fireclay	25	<i>D</i>	
KEL-F 81 (Unplasticized)	3M Co.	1980R	Trifluorochloroethylene resin	2300	<i>I</i>	
Key Abso-Lute Thread Sealant	Key-Abso-Lute (2)	1985T		5155	<i>D</i>	
Klingersil C4400	Richard Klinger (2)	1981T	Nonasbestos gasket	1376	<i>D</i>	
Kynar	Penn Walt Corp. (1)	1976T	Poly(vinylidene fluoride)	3277	<i>D</i>	
Lexan		1996R	polycarbonate	7407	<i>E</i>	
Loctite PST	Loctite Corp. (2)	1976T	IPTFE/anaerobic organic	4204	<i>D</i>	
Loctite PST-Nuclear Grade	Loctite Corp. (2)	1982T	IPTFE/anaerobic organic	6944	<i>D</i>	
Molykote 321R (aerosol spray)	Dow Corning	1975T	Bonded MOS2	2702	<i>D</i>	
Molykote Z Powder	Dow Corning (2)	1977T	Pure MOS2	1709	<i>D</i>	
Mylar	DuPont	1980R	Polyethylene terephthalate	2300	<i>C</i>	
Neoprene	Circle Seal (1)	1975T	CR Elastomer	6386	<i>D</i>	
Neoprene	Dezurick Valves (1)	1973T	CR Elastomer	6532	<i>D</i>	
Neoprene	Parker Seal (1)	1975T	CR Elastomer	6523	<i>D</i>	

TABLE X1.5 *Continued*

Materials	Source (1)/Manufacturer (2) ^A	Circa ^B	Description	Heat Released, Cal/g	Source of Data	Remarks
Nitrile Rubber		1996R	Copolymer of butadiene and acrylonitrile	9911	<i>E</i>	
Nordel	DuPont (2)	1973T	EPDM	9220	<i>D</i>	
Noryl		1996R	Polyphenylene oxide blended with polystyrene	6615	<i>E</i>	
Nujol Oil	Plough Inc. (2)	1973T	Mineral HC	10 930	<i>D</i>	
Oxy-8 Thread Sealant Paste	Fluoramics Inc. (2)	1977T	PTFE/Oil	1153	<i>D</i>	
Oxy-Tite Thread Compound	Lake Chemical Co.	1980R	Polytetrafluoroethylene chlorinated hydrocarbon	3000	<i>K</i>	
Nylon 6/6	E.I. du Pont de Nemours UNK	1980R	Nylon	7900	<i>C</i>	
PEEK		1996R	Polyetheretherketone	7775	<i>E</i>	
Permaglass XE6/1	Permalit Gloucester (2)	1981T	50 % glass/epoxy	1452	<i>D</i>	
PES		1996R	Polyethersulfone	7522	<i>E</i>	
phenolic/fiberglass	Contour Composites (2)	1997R		2510	<i>H</i>	
phenolic/aramid	Contour Composites (2)	1999R		6609	<i>H</i>	
phenolic/graphite	Contour Composites (2)	1997R		7249	<i>H</i>	
Pilkington Crown 125	Pilkington Bros. Ltd. (2)	1975T	Fiberglass plus 6 % binder	437	<i>D</i>	
Plexiglass	Various	1980R	Polymethylmethacrylate	6000	<i>C</i>	
Polyethylene (soft plastic)	Various	1980R	Polyethylene	11 100	<i>C</i>	
Polyester Resin	Various	1980R	Isophthalate	4300	<i>C</i>	
Polyisobutylene	Various	1980R	Polyisobutylene	11 200	<i>C</i>	
Polyphenylene Sulfide	LNP Engr. Plastics (1)	1979T	PPS plastic	6853	<i>D</i>	
Polypropylene (soft plastic)	Various	1980R	Polypropylene	11 000	<i>C</i>	
Polystyrene (hard plastic)	Various	1980R	Polystyrene	9900	<i>C</i>	
Polyurethane Rubber		1996R		5206	<i>E</i>	
PVC (Unplasticized)	Various	1980R	Polyvinyl chloride	4300	<i>C</i>	
RT 60	General Electric (2)	1973T	Poly(methyl phenylsiloxane)	3289	<i>D</i>	
RT 560	General Electric (2)	1977T	Poly(methyl phenylsiloxane)	3705	<i>D</i>	
RTV 102	General Electric (2)	1976T	Poly(methyl phenylsiloxane)	4956	<i>D</i>	
Rulon A	Dixon Corp.	1980R	Mineral-reinforced TFE-fluorocarbon	1400	<i>I</i>	<i>L</i>
Saran	Atlas Mineral Products	1980R	Polyvinylidene chloride	5000	<i>K</i>	
Silicone Rubber		1996R	Polysiloxane	4156	<i>E</i>	
Tedlar		1996R	Polyvinyl fluoride	5191	<i>E</i>	
Teflon 7A		1996R	Polytetrafluoroethylene	1526	<i>E</i>	
Tefzel	DuPont (2)	1973T	ETFE	3538	<i>D</i>	
TFE-fluorocarbon FEP	E.I. du Pont de Nemours	1980R	Fluoroethyl propylene	2500	<i>I</i>	<i>L</i>
TFE-fluorocarbon PFA	DuPont (2)	1980T	PFA plastic	1250	<i>D</i>	
TFE-fluorocarbon PTFE	E.I. du Pont de Nemours UNK	1980R	Polytetrafluoroethylene	1700	<i>I</i>	<i>L</i>
		1980R		1475	<i>K</i>	
Tricresyl Phosphate		1974T	Tri-M-Tolyl phosphate	7360	<i>D</i>	
VESPEL SP-21	E.I. du Pont de Nemours UNK	1980R	Polyimide resin + 15 % graphite	6100	<i>I</i>	
	UNK	1980R		6250	<i>K</i>	<i>J</i>
	UNK	1980R		6100	<i>F</i>	
Viton 5010B	E.I. du Pont de Nemours UNK	1980R	Fluoroelastomer	3600	<i>I</i>	<i>J</i>
	UNK	1980R		3350	<i>K</i>	
	UNK	1980R		3400	<i>F</i>	<i>L</i>
Viton-Brown	Parker Seal (2)	1983T		1963	<i>D</i>	
Viton-E60C	Rubber Prod. Co. (1)	1974T		3084	<i>D</i>	
Viton A		1996R	Copolymer of vinylidene fluoride and hexafluoropropylene	3603	<i>E</i>	
Viton B	Parker Seal V494-70	1980T		3089	<i>D</i>	
Wood-White Pine		1973T		4734	<i>D</i>	
X-Pando	X-Pando Corp. (2)	1975T		481	<i>D</i>	
Zytel		1996R	Polyamide (Nylon 6/6)	7708	<i>E</i>	

^A Measured by method described in Test Method D2863.

^B Approximate date of material test (T) or published report (R).

^C Fabris, H. J., and Sommer, J. G., "Flame Retardancy of Polymeric Materials," Vol 2, 1973, p. 143, Dekker, NY.

^D Air Products and Chemicals, Inc., Allentown, PA 18195-1501.

^E Tests conducted per Test Method D240. Source: Hshieh, F.-Y., Stoltzfus, J. M., and Beeson, H. D., "Autoignition Temperature of Selected Polymers at Elevated Oxygen Pressure and Their Heat of Combustion," *Fire and Materials*, Vol 20, 301–303, 1996.

^F Airco Central Laboratories, Murray Hill, NY. Unpublished Data (ASTM Method).

^G Two different compounds of Buna-H were tested.

^H Tests conducted per Test Method D240. Source: Beeson, H. D., Hshieh, F.-Y., and Hirsch, D. B., "Ignitibility of Advanced Composites in Liquid and Gaseous Oxygen," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres*, ASTM STP 1319, 1997.

^I Kennedy Space Center, Cocoa Beach, FL. Unpublished Data (ASTM Method).

^J Vinylidene fluoride and hexafluoropropylene copolymer.

^K Lapin, A., "Oxygen Compatibility of Materials," *Reliability and Safety of Air Separation Plant*, Annexe 1973-1, au Bulletin de l'Institut International du Froid, BFRAAV 1, 1973, pp. 1–132. The heat of combustion of these samples was determined using a Parr Series 1300 oxygen bomb calorimeter. With most of the samples, due to their flame retardant properties, it was necessary to add Nujol to the sample to provide complete combustion. The samples were combusted in the presence of twenty atmospheres oxygen.

^L Heat values from source G were collected using a Series 1300 Parr Bomb Calorimeter with an oxygen pressure of 20 atm (2.0 MPa).

TABLE X1.6 Oxygen Index (OI) for Selected Materials^A

Material	Source (1)/Manufacturer (2) ^A	Circa ^B	Description	OI ^C	Reference
Polyacetal	Various	1980R		14.2–16.1	<i>D</i>
Polyacetal	Celcon (2)	1977T		16	<i>E</i>
Polymethylmethacrylate	Various	1980R		16.7–17.7	<i>D</i>
Poly(methylmethacrylate)					
Plexiglas®	Rohm & Haas (2)	1973T		17	<i>D</i>
Plexiglas®	Rohm & Haas (2)	1986T		18.5 ± 0.5	<i>E</i>
Loctite pipe sealant					
Nuclear grade PST®	Loctite Corp. (2)	1982T	Anaerobic sealant (cured) cup test ^F	17	<i>E</i>
Type PS/T	Loctite Corp. (2)	1976T	Anaerobic sealant (cured) cup test ^F	20	<i>E</i>
Polypropylene (Pure)	Various	1980R	Soft plastic	17.4	<i>D</i>
Polyethylene Sheet	Atlas Mineral Prod.	1980R	0.140-in.-thick white color	17.5	<i>G</i>
Polystyrene (Pure)	Various	1980R	Hard plastic	17.8	<i>D</i>
Buna-N		1980R	O-Ring	18.0	<i>G</i>
Hi Fax Plastic 1900	Hercules Powder	1980R	0.128-in.-thick polyethylene sheet—white color	18.0	<i>G</i>
Polypropylene Sheet	Atlas Mineral Prod.	1980R	0.127-in.-thick white color	18.0	<i>G</i>
ECO/Rubber	Sampson Gauge Co. (1)	1984T	Epichlorohydrin rubber	18.5	<i>E</i>
ABS (Flame Retardant)	Various	1980R	Acrylonitrile-butadiene-styrene	18.8–33.5	<i>E</i>
Silicone Rubber	Lehigh Rubber Co.	1980R	0.030-in.-thick red color	21.0	<i>G</i>
Flexane 95	Devcon Corp.	1980R	Curing urethane gray color	21.5	<i>G</i>
EPT	Various	1980R	Ethylene propylene terpolymer	21.9	<i>D</i>
Polycarbonate	Various	1980R		22.5–39.7	<i>D</i>
Garlock 900	Garlock Mfg. Co.	1980R	0.067-in.-thick tan color	23.0	<i>G</i>
Silicone rubber					
RTV 102	General Electric (2)	1976T		23	<i>E</i>
Silastic® 732	Dow Corning (2)	1973T		25	<i>E</i>
SMS 2454	Trist Mouldings and Seals (2)	1974T		25	<i>D</i>
RTV 60	General Electric (2)	1973T		28.5	<i>E</i>
RTV 560	General Electric (2)	1977T		29	<i>E</i>
O-ring #5028-24	Circle Seal (1)	1975T		32	<i>E</i>
RTV 560 mixture	General Electric (2)	1977T	User-added 50 % glass	36	<i>E</i>
Urethane Foam X-50 Pipe	Triangle Conduit & Cable Co.	1980R	Exterior thermal foam insulation factory-foamed on copper tubing	23.5	<i>G</i>
Asbestos Gasket J-M 61	Johns Manville	1980R	0.067-in.-thick asbestos sheet, gray color	24.0	<i>G</i>
Nylon 6	E.I. du Pont de Nemours	1980R		24–30.1	<i>D</i>
Hypalon Sheet 0.60 in.	E.I. du Pont de Nemours	1980R	Chlorosulfonated polyethylene	25.1	<i>D</i>
Polystyrene (Flame Retardant)	Koppers	1980R	Hard plastic	25.2	<i>D</i>
Nordel Sheet (EPDM)	E.I. du Pont de Nemours	1980R	0.121-in.-thick sheet ethylene propylene rubber—black color	25.5	<i>G</i>
Colma SL Sealant	Sika Chemical Co.	1980R	Self leveling, gray color	26.0	<i>G</i>
Melrath 150	Melrath Gasket & Supply	1980R	0.066-in.-thick gray color	26.0	<i>G</i>
Silicone grease	Dow Corning (2)	1982T	Cup test ^F	26 ± 1	<i>E</i>
Neoprene	E.I. du Pont de Nemours	1980R	Chloroprene rubber	26.3	<i>D</i>
Craftsman Silicone Sealant	Sears Roebuck Co.	1980R	Curing elastomer	27.0	<i>G</i>
Nomex Nylon	E.I. du Pont de Nemours	1980R	Tan cloth	27.0	<i>G</i>
Garlock 7021 gasket	Garlock Mfg. Co. (2)	1975T		27	<i>E</i>
Silicone Rubber	Various	1980R	Polysiloxane	27.9–39.2	<i>D</i>
Rectorseal® #15 Thread sealant					
	Rectorseal Corp. (2)	1974T		28 ± 2	<i>E</i>
	Rectorseal Corp. (2)	1983T		<30.0	<i>E</i>
Durabla gasket	Durabla Mfg. Co. (2)	1974T		28.0 ± .5	<i>E</i>
Urethane Foam FS/25	Owens Corning		Exterior thermal foam insulation	28.5	<i>G</i>
Polypropylene (Flame Retardant)	Avisun		Soft plastic	29.2	<i>D</i>
Neoprene			Diaphragm nylon reinforced	29.5	<i>G</i>
Fluorosilicone grease #822	Drilube Co. (2)	1978T	Cup test ^F	30	<i>E</i>
Blue Gard® gaskets	Garlock Inc. (2)				
Blue Gard® 3000		1981T	Nonasbestos gasket	30.5 ± 0.5	<i>E</i>
Blue Gard® 3200		1983T	Nonasbestos gasket	31	<i>E</i>
Blue Gard® 3400		1986T	Nonasbestos gasket	52	<i>E</i>
Blue Gard® 3700		1986T	Nonasbestos gasket	53	<i>E</i>
Blue Gard® 3200		1986T	Nonasbestos gasket	60	<i>E</i>
Blue Gard® 3000		1986T	Nonasbestos gasket	62	<i>E</i>
Blue Gard® 3300		1986T	Nonasbestos gasket	68	<i>E</i>
Nylon					
Zytel	DuPont (2)	1973T	0.625-in.-(16-mm) diameter, 0.125-in. (3-mm) thick, 0.25-36 in. (6.4-mm) hole		<i>G</i>
Nylon 66	ICI Ltd. (2)	1974T		30.5	<i>E</i>
Nylon 66 (glass filled)	ICI Ltd. (2)	1974T		23.5	<i>E</i>
Polyimide Film 0.001 in.	Various	1980R		36.5	<i>D</i>
Polyvinyl Chloride II High Impact PVC	Atlas Mineral Prod.	1980R	0.135-in.-thick sheet gray color	37.0	<i>G</i>
CYL-SEAL thread sealant	West Chester Chemical Co.	1976T		38	<i>E</i>
Polyvinylidene Fluoride					
Kynar	Penn-Walt Co. (1)	1976T		39	<i>E</i>
Fluorocarbon rubber					
Viton®	Parker Seal (2)	1983T	Brown O-ring	40.5 ± 0.5	<i>E</i>
Viton®-green	...	1983T	Green O-ring	42	<i>E</i>

TABLE X1.6 *Continued*

Material	Source (1)/Manufacturer (2) ^A	Circa ^B	Description	OI ^C	Reference
Viton A®	...	1973T		57	E
Viton A®	Asco Valve Co. (1)	1975T		57.5	E
Viton E-60C®	Rubber Products Co. (1)	1974T		60.5	E
Viton® part #5103-32	Circle Seal (1)	1975T		68	E
Viton 77-545®	Parker Seal (2)	1975T		78	E
Viton B®, #V494-70	Parker Seal (2)	1980T		DNP	D
Epoxy Compound	Crest Products Co.	1980R	7343 resin, 7139 Catalyst	41.0	G
Polyester	Various	1980R		41.5	D
Polyvinyl Chloride I	Atlas Mineral Prod.	1980R	0.129-in.-thick sheet, dark gray color	42.0	G
Balston® Filters	Balston (2)				
Type—Epoxy		1981T	Cut from cylinder	42.5	E
Type Q—fluorocarbon		1982T	Cut from cylinder	47 ± 1	E
Type H—inorganic		1981T	Cut from cylinder	CNI	E
Polyvinylidene Fluoride	Various	1980R		43.7	D
Molykote® Z powder	Dow Corning (2)	1977T	MOS ₂ , cup test ^F	45	E
Scandura 1786	Scandura Ltd.	1980R	0.066-in.-thick red color	45.5	G
Polyimide-Vespel SP21	DuPont (2)	1988R		53	E
Leotite	James Walker Co. Ltd.	1980R	0.066-in.-thick red color	54.0	G
Viton-A		1980R	O-Ring black color	57.0	G
Bel-Ray Greases					
FC 1260	Bel-Ray Co. (2)	1980T	Cup test ^F	57	E
FC 1245	Bel-Ray Co. (2)	1979T	Cup test ^F halocarbon oil/graphite	DNP	E
Klingerit 661	Richard Klinger Ltd.	1980R	0.027-in.-thick red color	59.0	G
Polyvinylidene Chloride	Various	1980R		60.0	D
Polyvinylidene Chloride	Various	1980R		60.0	D
Polyvinylidene Chloride	Atlas Mineral Prod.	1980R	0.128-in.-thick sheet, dark gray color	65.0	G
Vespel SP-21	E.I. du Pont de Nemours	1980R	0.060-in.-thick black color polyimide resin with graphite	65.0	G
Key Abso-Lute®	ACF Industries, Inc. (2)	1985T	Cup test ^F	67	E
CTFE Lubricants					
Fluorolube GR362 grease	Hooker Chemical Co. (2)	1978T	Cup test ^F	67 ± 4	E
Halocarbon 25-20 oil	Halocarbon Products Co. (2)	1979T	Cup test ^F	75	E
Halocarbon 11-14S oil	Halocarbon Products Co. (2)	1974T	Cup test ^F	DNP	E
Fluorocarbon FEP	Cole Parma Inst. Co. (1)	1985T	Tubing	77	E
Alenco Hilyn	Turner Bros. Ltd.	1980R	TFE-fluorocarbon tape thread sealant	83.0	G
Gore-Tex Joint Sealant	W. L. Gore, Inc.	1980R	0.25-in.-thick white	91.0	G
Teflon TFE	E.I. du Pont de Nemours	1980R	Polytetrafluoroethylene	95.0	D
TFE-fluorocarbon Sheet	E.I. du Pont de Nemours	1980R	0.100-in.-thick white	95.0	G
Klingerit 661	Richard Klinger Ltd.	1980R	0.048-in.-thick red color	100	G
Gore-Tex Packing	W. L. Gore, Inc.	1980R	1/8-in. rolled string gasket white color	100.0	G
TFE-fluorocarbon		1980R	O-Ring, liquid oxygen line seal	100.0	G
Fluorocarbon PFA	DuPont (2)	1980T		100	E
Fluorocarbon TFE	DuPont (2)	1981T		DNP	E
PFPE grease					
Fomblin RT15®	Montedison USA (2)	1974T	Cup test ^F	DNP	E
Krytox 283AC®	DuPont (2)	1983T	Cup test ^F	DNP	E
Krytox GPL 225®	DuPont (2)	1987T	Cup test ^F	DNP	E
Krytox GPL 205®	DuPont (2)	1987T	Cup test ^F	DNI	E
Tribolube 13C®	Aerospace Lubricants, Inc.	1986T	Cup test ^F	DNP	E
PFPE fluid					
Fomblin Y25®	Montedison-USA (2)	1979T	Cup test ^F	DNI	E
Krytox GPL 105®	DuPont (2)	1987T	Cup test ^F	DNP	E
CTFE plastic					
Kel-F 81®	Superior Valve Co. (1)	1979T	15 % glass filled	DNP	E
Kel-F 81®	Great Lakes Plastics (1)	1982T		DNP	E
Kel-F 81®	Sherwood Valve Co. (1)	1977T	Nonplasticized	DNP	E
Kel-F 81®	Fluorocarbon Co. (1)	1976T		DNP	E
Kel-F 81® (plasticized)	Sherwood Valve Co. (1)	1974T	Very rare formulation	<21	E
Perfluoroelastomer					
Kalrez® 1045	DuPont (2)	1979T	O-ring	DNP (T, B)	E
Kalrez® 1050	DuPont (2)	1980T	O-ring	DNP (T, B)	E
Kalrez® 4079	DuPont (2)	1985T	O-ring	DNP (T, B)	E
Silica gel	Fisher Scientific Co. (1)	1981	Cup test ^F	DNI	E
Blue Drierite	W. A. Hammond Drierite Co. (2)	1981	Cup test ^F	DNI	E
Kaowool Insulation	Babcock & Wilcox (2)	1975	Alumina-silica	DNI	E
Cerawool Paper	Johns-Manville (2)	1982		DNI	E
Fiberglass/cement board	Cem-FIL Corp. (2)	1978		DNI	E
Kwik Flux #54®	Special Chemical Corp. (2)	1976	Cup test ^F	DNI	E
Asbestos cement board					
Transite®	Johns-Manville (2)	1973		DNI	E
Sindanyo CS51®	Turner Asbestos Cement Co. (2)	1973		DNI	E
Turnalite TI 150®		1974		DNI	E
Asbestos paper	Johns-Manville (2)	1976	32 lb/100 ft ²	DNI	E
	D'Amiante Beaulieu (2)	1975		DNI	E

^A Measured by method described in Test Method **D2863**.

^B Year given is the year tested (T) or year of published report (R). Year of manufacture is unknown.

^C DNP (Did not propagate), DNI (Did not ignite).

^D Hilado, Carlos, J., "Oxygen Index of Materials," *Fire and Flammabilities Series*, Technomic Publishing Co., Westport, CT, Vol 4.

^E Werley, B., "An Oxygen Index Update," *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres*, ASTM STP 986, ASTM, 1988, pp. 248–261.

^F Cup test performed basically as described by Nelson and Webb.

^G Lapin, A., "Oxygen Compatibility of Materials," *Reliability and Safety of Air Separation Plant*, Bulletin de l'Institut Internationale du Froid, Annexe 1973-1, pp. 79–94.

X2. ADDITIONAL LITERATURE

X2.1 Introduction—The following are abstracts of a representative selection of articles and reports on testing and application of materials in oxygen environments. They are illustrative of the types of testing and evaluation that have been conducted on a variety of materials.

X2.2 High-Pressure Liquid and Gaseous Oxygen Impact Sensitivity Evaluation of Materials For Use at Kennedy Space Center—Twelve materials were evaluated for reactivity in liquid oxygen, pressurized liquid oxygen, and high-pressure gaseous oxygen. These included an aluminum alloy (6061-T6), a polytetrafluoroethylene, four filled polytetrafluoroethylenes, a polyimide, a polychlorotrifluoroethylene, two fluoroelastomers, a perfluoroether base grease, and a nylon polymer (7).

X2.3 Kennedy Space Center Lubricant Testing Program—This report describes a testing program to evaluate various lubricants in use and considered for use at the John F. Kennedy Space Center (KSC). The program was conducted by the Materials Testing Branch (MTB, SO-LAB-4) for the Mechanical Design Division (DD-MDD) of the Design Engineering Directorate at KSC. The overall objectives of the program were to: determine the lubrication characteristics and relative corrosion protection provided by lubricants in use or considered for use at KSC; identify materials that may be interchangeable with Kel-F-90 and Krytox 240 AC greases; and identify or develop an improved lubricant oil suitable for LOX pumps (8).

X2.3.1 The lubricants were subjected to the following:

Test Methods **D217**, **D566**, **D1264**, **D1743**, **D1748**; NAR Spec. MBO 140-005 Aluminum Shear Test; Fed. Test Method Std. 791B Corrosion Protection by Coating: Salt Spray (Fog) Test; Exposed Beach Corrosion Test

X2.4 Compatibility of Materials with 7500-psi Oxygen—A research program was conducted to develop ignition data on thread lubricants, thread sealants, fluorocarbon plastics, and metals. Spontaneous ignition temperatures were determined in both 2000 psi and 7500-psi oxygen for all the above materials except metals. The spontaneous ignition temperatures for these materials were found to be essentially the same in 7500 psi oxygen and in 2000 psi oxygen. Only three of the tested lubricants are recommended for possible use in 7500-psi systems. None of the thread sealants are recommended. Glass-filled polytetrafluoroethylene is usable only if tightly confined. The relative ease of ignition of metals and alloys was determined by promoted ignition methods in oxygen at 7500 psi. Inconel alloy 600, brass, Monel alloy 400, and nickel were found to have the highest resistance of ignition and combustion among the common alloys and metals. Of the materials tested, stainless steel and aluminum are the least satisfactory for use at

oxygen pressures of 7500 psi. A test system was constructed to evaluate the hazards in rapidly charging a 65-in.³ nickel-lined vessel with high pressure oxygen. A series of rapid charging tests up to as high as 8000 psi proceeded without incident. Electrostatic charges measured during the charging were negligible (9).

X2.5 Fire Hazards in Oxygen-Enriched Atmospheres—This manual is a source of general information for guidance in recognizing problems and finding solutions to the fire hazards associated with oxygen-enriched atmospheres. Starting with the definition of oxygen-enriched atmospheres, and where such conditions may be encountered in medical practice, industry, aviation, space and deep sea exploration and the like, this pamphlet describes numerous fire and explosion incidents to show the type of hazards encountered. Ignition and combustion mechanisms in oxygen-enriched atmospheres are discussed, followed by a detailed study of behavior of various materials used in oxygen-enriched atmospheres. The extinguishment of fires in an oxygen-enriched atmosphere is covered in the last chapter (10).

X2.6 NASA-JSC Requirements for Flight Prototype Liquid and High-Pressure Oxygen Components and Systems—This document defines the minimum NASA-JSC requirements necessary for the design and production of safe manned space-flight hardware. It is intended that this document be incorporated in the Technical Requirements Specification of all new designs for manned spaceflight or flight-prototype hardware procured or manufactured by NASA-JSC or NASA-JSC contractors(11).

X2.7 Safety Considerations Regarding the Use of High-Pressure Oxygen—Materials selection criteria and oxygen facility and test system safety concepts are discussed. Importance of contamination control is emphasized. Results of improper design or materials selection, or both, are photographically displayed. Current oxygen test activities in progress at the NASA White Sands Test Facility are addressed (12).

X2.8 Oxygen Compatibility of Materials—Air Products' activity in the area of oxygen compatibility is described. Laboratory measurements of the oxygen index, heat of combustion, and autoignition temperatures are tabulated for a large number of materials. Oxygen index method deviated slightly from ASTM procedure. These materials are subdivided into eight categories. Acceptability Index (a weighted formula using the three test data) is explained together with the Equivalency Concept. The Equivalency Concept presumes that materials with the same Acceptability Index have the same oxygen compatibility. Evaluation of materials for oxygen

service based on the index and equivalency concept is described and several examples are given (13).

X2.9 Combustion Characteristics of Polymers as Ignition Promoters—Four polymers (high density polyethylene, PTFE, unfilled polyimide, and graphite-filled polyimide) were burned in high pressure oxygen over the range 0.7 to 69.0 MPa. Three metallic materials were used as support rods (Aluminum 2216, Stainless Steel 316, and pure copper). The potential for polymer promoters to ignite the metal support is described (14).

X2.10 Fuel Cell Elastomeric Materials Oxygen Compatibility Testing: Effect of 450- and 6200-kPa Oxygen—The oxygen compatibility of five O-ring formulations (one neoprene and four fluoroelastomers) were evaluated following exposures to 450 and 6200 kPa oxygen at 121°C. Post-aging

changes in mass, dimension, tensile strength, elongation at break, durometer hardness, and compression set were determined. Aging results were compared to ignition and combustion data (15).

X2.11 Oxygen Compatibility of Polymers Including PTFE, Kel-F 81, Vespel SP-21, Viton A, Viton A-500, Fluorel, Neoprene, EPDM, Buna-N, and Nylon 6,6—Ten polymeric materials including TFE (PTFE), Kel-F 81 (PCTFE), Vespel SP-21, Viton A, Viton A-500, Fluorel, Neoprene, EPDM, Buna-N, and Nylon 6,6 were systematically evaluated for their oxygen compatibility properties like autoignition temperature, heat of combustion, and LOX mechanical impact sensitivity. The study on materials autoignition temperature was carried out using pressure vessels certified by Test Method G72 and BS 3N:100, as well as using a custom-made high-pressure vessel at pressures up to 10 000 psig (16).

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