Standard Guide for
Evaluating Metals for Oxygen Service[1]

1. Scope

1.1 This guide applies to metallic materials under consideration for oxygen or oxygen-enriched fluid service, direct or indirect, as defined in Section 3. It is concerned primarily with the properties of a metallic 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 aging, shredding, or sloughing of particles, except when these might contribute to an ignition.

1.2 This document applies only to metals; nonmetals are covered in Guide G63.

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.

1.3 The values stated in SI units are to be regarded as the standard.

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

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D2512 Test Method for Compatibility of Materials with Liquid Oxygen (Impact Sensitivity Threshold and Pass-Fail Techniques)

D2863 Test Method for Measuring the Minimum Oxygen Concentration to Support Candle-Like Combustion of Plastics (Oxygen Index)

D4809 Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)

G63 Guide for Evaluating Nonmetallic Materials for Oxygen Service

G72 Test Method for Autogenous Ignition Temperature of Liquids and Solids in a High-Pressure Oxygen-Enriched Environment

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

G124 Test Method for Determining the Combustion Behavior of Metallic Materials in Oxygen-Enriched Atmospheres

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

G128 Guide for Control of Hazards and Risks in Oxygen Enriched Systems

2.2 *ASTM Special Technical Publications (STPs) on the Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres:*

ASTM STPs in this category are listed as: 812, 910, 986, 1040, 1111, 1167, 1197, 1319, 1395, and 1454

2.3 *Compressed Gas Association Documents:*

Pamphlet G-4.4-2003 (EIGA Doc. 13/02) Oxygen Pipeline Systems[3]

Pamphlet G-4.8 Safe Use of Aluminum Structured Packing for Oxygen Distillation[3]

Pamphlet G-4.9 Safe Use of Brazed Aluminum Heat Exchangers for Producing Pressurized Oxygen[3]

Pamphlet P-8.4 (EIGA Doc. 65/99) Safe Operation of Reboilers Condensers in Air Separation Plants[3]

2.4 *ASTM Adjuncts:*

Test Program Report on the Ignition and Combustion of Materials in High-Pressure Oxygen[4]

3. Terminology

3.1 *Definitions:*

3.1.1 *autoignition temperature*—the lowest temperature at which a material will spontaneously ignite in oxygen under specific test conditions (see Guide G126).

3.1.2 *direct oxygen service*—in contact with oxygen during normal operations. Examples: oxygen compressor piston rings, control valve seats (see Guide G126).

3.1.3 *exemption pressure*—the maximum pressure for an engineering alloy at which there are no oxygen velocity restrictions (from CGA 4.4 and EIGA doc 13/02).

3.1.4 *impact-ignition resistance*—the resistance of a material to ignition when struck by an object in an oxygen atmosphere under a specific test procedure (see Guide G126).

3.1.5 *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 upset. Examples: liquid oxygen tank insulation, liquid oxygen pump motor bearings (see Guide G126).

3.1.6 *maximum use pressure*—the maximum pressure to which a material can be subjected due to a reasonably foreseeable malfunction, operator error, or process upset (see Guide G63).

3.1.7 *maximum use temperature*—the maximum temperature to which a material can be subjected due to a reasonably foreseeable malfunction, operator error, or process upset (see Guide G126).

3.1.8 *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 (see Guide G126).

3.1.9 *operating pressure*—the pressure expected under normal operating conditions (see Guide G126).

3.1.10 *operating temperature*—the temperature expected under normal operating conditions (see Guide G126).

3.1.11 *oxygen-enriched*—applies to a fluid (gas or liquid) that contains more than 25 mol % oxygen (see Guide G126).

3.1.12 *qualified technical personnel*—persons such as engineers and chemists who, by virtue of education, training, or experience, know how to apply physical and chemical principles involved in the reactions between oxygen and other materials (see Guide G126).

3.1.13 *reaction effect*—the personnel injury, facility damage, product loss, downtime, or mission loss that could occur as the result of an ignition (see Guide G126).

3.1.14 *threshold pressure*—there are several different definitions of threshold pressure that are pertinent to the technical literature. It is important that the user of the technical literature fully understand those definitions of threshold pressure which apply to specific investigations being reviewed. Two definitions for threshold pressure, based on interpretations of the bulk of the current literature, appear below.

3.1.14.1 *threshold pressure*—in a promoted ignition-combustion test series conducted over a range of pressures, this is the maximum pressure at which no burns, per the test criteria, were observed and above which burns were experienced or tests were not conducted.

3.1.14.2 *threshold pressure*—the minimum gas pressure (at a specified oxygen concentration and ambient temperature) that supports self-sustained combustion of the entire standard sample (see Guide G124).

4. Significance and Use

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

5. Factors Affecting Selection of Materials

5.1 *General:*

5.1.1 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 exceeds the configuration-dependent threshold, then ignition and combustion may occur. Thus, the material's flammability properties and the ignition energy sources within a system must be considered. These should be viewed in the context of the entire system design so that the specific factors listed in this guide will assume the proper relative significance. In summary, it depends on the application.

5.2 *Relative Amount of Data Available for Metals and Nonmetals:*

5.2.1 Studies of the flammability of gaseous fuels were begun more than 150 years ago. A wide variety of applications have been studied and documented, including a wide range of important subtleties such as quenching phenomena, turbulence, cool flames, influence of initial temperature, etc., all of which have been used effectively for safety and loss prevention. A smaller, yet still substantial, background exists for nonmetallic solids. In contrast to this, the study of the flammability of metals dates only to the 1950s, and even though it has accelerated rapidly, the uncovering and understanding of subtleties have not yet matured. In addition, the heterogeneity of the metal and oxidizer systems and the heat transfer properties of metals, as well as the known, complex ignition energy and ignition/burning mechanisms, clearly dictate that caution is required when applying laboratory findings to actual

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[4] Available from ASTM International Headquarters. Order Adjunct No. ADJG0094. Original adjunct produced in 1986.

applications. In many cases, laboratory metals burning tests are designed on what is believed to be a worst-case basis, but could the particular actual application be worse? Further, because so many subtleties exist, accumulation of favorable experience (no metal fires) in some particular application may not be as fully relevant to another application as might be the case for gaseous or nonmetallic solids where the relevance may be more thoroughly understood.

5.2.1.1 ASTM Symposia and Special Technical Publications on these symposia have contributed significantly to the study of the flammability and sensitivity of materials in oxygen-enriched atmospheres. See section 2.2 for listing of STP numbers and the References Section for key papers.

5.3 *Relationship of Guide G94 with Guides G63, G88, and G93:*

5.3.1 This guide addresses the evaluation of metals for use in oxygen systems and especially in major structural portions of a system. Guide G63 addresses the evaluation of nonmetals. Guide G88 presents design and operational maxims for all systems. In general, however, Guides G63 and G88 focus on physically small portions of an oxygen system that represent the critical sites most likely to encounter ignition. Guide G93 covers a key issue pertinent to actual operating oxygen systems; cleaning for the service.

5.3.2 The nonmetals in an oxygen system (valve seats and packing, piston rings, gaskets, o-rings) are small; therefore, the use of the most fire-resistant materials is usually a realistic, practical option with regard to cost and availability. In comparison, the choice of material for the major structural members of a system is much more limited, and the use of special alloys may have to be avoided to achieve realistic costs and delivery times. Indeed, with the exception of ceramic materials, which have relatively few practical uses, most nonmetals have less fire resistance than virtually all metals. Nonmetals are typically introduced into a system to provide a physical property not achievable from metals. Nonmetals may serve as "links" in a kindling chain (see 5.6.5), and since the locations of use are typically mechanically severe, the primary thrust in achieving compatible oxygen systems rests with the minor components as addressed by Guides G63 and G88 that explain the emphasis on using the most fire-resistant materials and Guide G93 which deals with the importance of system cleanliness.

5.3.3 Since metals are typically more fire-resistant and are used in typically less fire-prone functions, they represent a second tier of interest. However, because metal components are relatively so large, a fire of a metal component is a very important event, and should a nonmetal ignite, any consequential reaction of the metal can aggravate the severity of an

ignition many times over. Hence, while the selection of nonmetals by Guide G63 and the careful design of components by Guide G88 are the first line of defense, optimum metal selection is an important second-line of defense.

5.3.4 Contaminants and residues that are left in oxygen systems may contribute to incidents via ignition mechanisms such as particle impact and promoted ignition-combustion (kindling chain). Therefore, oxygen system cleanliness is essential. Guide G93 describes in detail the essential elements for cleaning oxygen systems.

5.4 *Differences in Oxygen Compatibility of Metals and Nonmetals:*

5.4.1 There are several fundamental differences between the oxygen compatibility of metals and nonceramic nonmetals. These principal differences are summarized in Table 1.

5.4.2 Common-use metals are harder to ignite. They have high autoignition temperatures in the range 900 to 2000°C (1650 to 3600°F). In comparison, most combustible nonmetals have autoignition temperatures in the range 150 to 500°C (300 to 1000°F). Metals have high thermal conductivities that help dissipate local heat inputs that might easily ignite nonmetals. Many metals also grow protective oxide coatings (see 5.5) that interfere with ignition and propagation.

5.4.3 Once ignited, however, metal combustion can be highly destructive. Adiabatic flame temperatures for metals are much higher than for most polymers (Table X1.7). The greater density of most metals provides greater heat release potential from components of comparable size. Since many metal oxides do not exist as oxide vapors (they largely dissociate upon vaporization), combustion of these metals inherently yields coalescing liquid metal oxide of high heat capacity in the flame zone at the oxide boiling point (there may be very little gaseous metal oxide). In comparison, combustion of polymers yields gaseous combustion products (typically carbon dioxide and steam) that tend to dissipate the heat release.

5.4.4 Contact with a mixture of liquid metal and oxide at high temperature results in a massive heat transfer relative to that possible upon contact with hot, low-heat-capacity, gaseous combustion products of polymers. As a result, metal combustion can be very destructive. Indeed, certain metal combustion flames are an effective scarfing agent for hard-to-cut materials like concrete (1).[5]

5.4.5 Finally, because most polymers produce largely inert gas combustion products, there is a substantial dilution of the oxygen in the flame that inhibits combustion and if in a stagnant system, may even extinguish a fire. For many metals, combustion produces the molten oxide of negligible volume condensing in the flame front and, hence, oxygen dilution is much less.

5.5 *Protective Oxide Coatings:*

5.5.1 Oxides that grow on the surfaces of metals can play a role in the metal's flammability. Those films that interfere with ignition and combustion are known as protective oxides. Typically, an oxide will tend to be protective if it fully covers the exposed metal, if it is tenaciously adherent, and if it has a

TABLE 1 Comparison of Metals and Nonmetals Flammability

	Metals	Nonmetals
Combustion products	molten metal oxide	hot gases
Autoignition temperatures	900–2000°C	150–500°C
Thermal conductivities	higher	lower
Flame temperature	higher	lower
Heat release	higher due to density	lower
Surface oxide	can be protective	negligible

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

high melting point. Designers have very limited control over the integrity of an oxide layer; however, since oxide can have significant influence on metal's test data, an understanding of its influence is useful.

5.5.2 A protective oxide provides a barrier between the metal and the oxygen. Hence, ignition and combustion can be inhibited in those cases where the oxide barrier is preserved. For example, in some cases, an oxide will prevent autogenous ignition of a metal up to the temperature at which the metal melts and produces geometry changes that breach the film. In other cases (such as anodized aluminum wires), the oxide may be sufficiently sturdy as either a structure or a flexible skin to contain and support the molten base metal at temperatures up to the melting point of the oxide itself. In either of these cases autogenous ignition may occur at much lower temperatures if the metal experiences mechanisms that damage the oxide coating. Oxide damaging mechanisms may include mechanical stresses, frictional rubs and abrasion, or chemical oxide attack (amalgamation, etc.). Depending upon the application, a high metal autoignition temperature, therefore, may be misleading relative to the metal's flammability.

5.5.3 One criterion for estimating whether an oxide is protective is based upon whether the oxide that grows on a metal occupies a volume greater or less than the volume of the metal it replaces. Pilling and Bedworth (2) formulated an equation for predicting the transition between protective and nonprotective oxides in 1923. Two forms of the Pilling and Bedworth (P&B) equation appear in the literature and can yield different results. ASTM Committee G04 has concluded that the most meaningful formulation for the P&B ratio in oxide evaluations for flammability situations is:

$$P\&B\ Ratio = Wd/awD \qquad (1)$$

where the metal, M, forms the oxide MaO_b, a and b are the oxide stoichiometry coefficients, W is the formula weight of the oxide, d is the density of the metal, w is the formula weight of the metal, and D is the density of the oxide. The other form of the equation treats the stoichiometry coefficient as unity and thus for those oxides that have a single metal atom in the formula, the two equations yield the same results. Pilling and Bedworth ratios should always reference an oxide rather than the metal of oxide origin, because for many metals, several different oxides can form each having a different P&B ratio. For example, normal atmospheric corrosion of iron tends to produce the oxide, Fe_2O_3, whereas the oxide that forms for iron at the elevated temperatures of combustion is Fe_3O_4. In cases where a mixture of oxides forms, the stoichiometry coefficients, a and b, may be weighted to reflect this fact. Table 2 presents numerous P&B ratios for a number of metal oxides. The P&B ratio suggests whether a grown metal oxide is sufficient in volume to thoroughly cover a metal surface, but it does not provide insight into the tenacity of the coating or whether it does indeed grow in a conformal fashion. The ratios in Table 2 have been segregated into those oxides that one would suspect to be nonprotective (P&B < 1) and those that might more likely be protective (P&B ≥ 1). Note also that if the P&B ratio >> 1 (as in the case of Fe_2O_3) the volume of the oxide can increase so dramatically that chipping, cracking or breaking can occur that may reduce its "protection." The effect

TABLE 2 Pilling and Bedworth Ratios[A] of Metal Oxides

Nonprotective Oxides		Potentially Protective Oxides	
Oxide	P&B < 1	Oxide	P&B ≥ 1
BaO	0.685	Al_2O_3	1.29
CaO	0.663–0.637	CuO	1.71–1.77
MgO	0.806	Cu_2O	1.68
		Cr_2O_3	2.02
		FeO	1.78
		Fe_2O_3	2.15
		Fe_3O_4	2.09
		CoO	1.76
		MoO_2	2.10
		NiO	1.70
		PbO	1.28–1.52
		SnO	1.15–1.28
		SnO_2	1.19–1.33
		TiO_2	1.76–1.95
		ZnO	1.59

[A] The Pilling and Bedworth (P&B) ratio is the ratio of the volume of a metal oxide compared to the volume of metal from which it was grown. A P&B ratio ≥ 1 suggests the potential for an oxide to be protective if it is also conformal and tenaciously adherent. All data are calculated and do not always agree with P&B ratios in the literature (1-5).

of protective oxides on alloys is a still more complex aspect of a metals flammability.

5.6 *Operational Hazard Thresholds:*

5.6.1 Most practical oxygen systems are capable of ignition and combustion to some extent under at least some conditions of pressure, temperature, flow, etc. The key to specifying oxygen-compatible systems is avoiding the circumstances in which ignition is likely and in which consequential combustion may be extensive. This often involves avoiding the crossing of hazard thresholds. Guide G128 is very useful in assessing hazards and risks in oxygen systems.

5.6.2 For example, many materials exhibit a bulk system-related ignition temperature that represents a hazard threshold. When a region of a system is exposed to a temperature greater than its bulk in-situ autoignition temperature, the likelihood of an ignition increases greatly; a hazard threshold has been crossed.

5.6.3 Hazard thresholds can be of many types. Ignition may depend upon a minimum heat energy input, and the threshold may be different for heat inputs due to heat transfer, friction, arc/spark, etc. Propagation may require the presence of a minimum oxygen concentration (the oxygen index is one such flammability limit) or it may require a minimum oxygen pressure (a threshold pressure below which propagation does not even occur in pure oxygen). It may also require a specific geometry.

5.6.4 For a fire to occur, it may be necessary to cross several thresholds of hazard simultaneously. For example, brief local exposure to high temperature above the ignition temperature might not produce ignition unless the heat transferred also exceeds the minimum energy threshold. And even if a local ignition results, the fire may self-extinguish without propagation if the pressure, oxidant concentration, or other conditions, are not simultaneously in excess of their related hazard threshold. It is desirable to operate on the conservative side of as many hazard thresholds as possible.

5.6.5 *Kindling Chains*—A kindling chain reaction can lead to the crossing of a hazard threshold. In a kindling chain,

ignition of an easily ignited material (such as a contaminant by adiabatic compression) may not release enough heat to, in turn, ignite a valve body, but may be sufficient to ignite a valve seat, which, in turn, may release sufficient heat to ignite the larger, harder-to-ignite valve body.

5.7 *Practical Metal Systems:*

5.7.1 It is not always possible to use the most fire-resistant metals in practical systems. As a result, operation below every hazard threshold may not always be used to minimize the chance of a fire. Guide G128 is very useful in assessing hazards and risks in oxygen systems. Additional conservatism is often used to increase the safety margins where possible. For example, if the pressure and temperature of an application are such that particle impact may cause an ignition, the remedy has been to limit the severity of particle impacts by limiting gas velocity and filtering or screening of particles. This, in effect, limits the application severity by constraining the operation conditions; CGA Pamphlet G-4.4-2003 (EIGA Doc. 13/02) details an industry practice using this approach.

5.7.1.1 A joint CGA-EIGA Task Force recently issued a "harmonized" document CGA G-4.4-2003 (EIGA Doc. 13/02) which has produced a unified view on velocity limitation guidance and other mitigating approaches.

5.8 *Properties of the Metal:*

5.8.1 *Ease of Ignition*—Although metals are typically harder to ignite than nonmetals, there is a wide range of ignition properties exhibited among potential structural materials, and, indeed, some metals are difficult to ignite in some ways while being relatively easy to ignite in others. The principal recognized sources of metal ignition include:

5.8.1.1 Contaminant promotion where the contaminant itself may be ignited by mechanical impact, adiabatic compression, sparks, or resonance.

5.8.1.2 Particle impact ignition in which a particle may ignite and promote ignition of the metal.

5.8.1.3 Friction ignition where the friction results from mechanical failure, cavitation, rubs, etc.

5.8.1.4 Bulk heating to ignition.

5.8.2 Ignition may also result from the following mechanisms, though these are not thoroughly studied nor understood for metals, nor have they been implicated in significant numbers of incidents relative to those in 5.8.1.

5.8.2.1 Mechanical impact.

5.8.2.2 Resonance.

5.8.2.3 Fresh metal exposure.

5.8.2.4 Crack propagation.

5.8.2.5 Electric arc or spark.

5.8.2.6 Puncture.

5.8.2.7 Trapped volume pressurization.

5.8.2.8 *Autoignition*—In the preceding mechanisms, heating to the autoignition temperature can result. For some of them, the achievement of ignition also can result from the material self heating as the freshly exposed metal oxidizes.

5.8.3 Ignition can result from bulk heating to the autoignition temperature, but this is rare in oxygen systems unless an environmental fire is present or unless electrical heaters experience runaways. Autoignition temperatures are often used to compare metals, but they can yield rankings that disagree with observed experience. This is because ignition is a very complex process. For example, where a metal grows a protective oxide, the autoignition temperature can vary widely depending upon such things as the adherence of the oxide, its degree of protection (as indicated in part by its Pilling and Bedworth number), and its melting point. A more likely effect of temperature on the ignition of a metal is via a promoted ignition-combustion mechanism.

5.8.4 *Properties and Conditions Affecting Potential Resultant Damage*—A material's heat of combustion, its mass, its geometry (thick versus thin), the oxygen concentration and pressure, the presence of gaseous versus liquid oxygen, the flow conditions before and after ignition, and the flame propagation characteristics affect the potential damage if ignition should occur. They should be taken into account in estimating the reaction effect in 8.5. Since so much damage in metal fires is attributable to direct contact with the molten oxide and from radiation due to its extremely high temperature, the probable flow path or trajectory of the molten oxide should be considered in predicting the zones of greatest damage.

5.9 *Extenuating Factors:*

5.9.1 In choosing major structural members of a system, practicality becomes a critical factor. Frequently, the more fire-resistant materials are simply impractical or uneconomical. For example, their strength-to-weight ratios may not meet minimum mechanical standards for turbine wheels. The cost or availability of an alloy may also preclude its use in a long pipeline. Corrosive environments may preclude still other materials. In contrast, there may be a base of experience with traditional metals in oxygen service, such as carbon steel pipelines, that clearly demonstrates suitability for continued service with appropriate safeguards. As a result, where these extenuating factors are present, less than optimum metals are frequently selected in conjunction with operational controls (such as operating valves only during zero-flow), established past practice (such as CGA Pamphlet G-4.4 for steel piping), or measures to mitigate the risk (such as use with a shield or removal of personnel from the vicinity).

5.10 *Operating Conditions:*

5.10.1 Conditions that affect the suitability of a material include the other materials of construction and their arrangement and geometry in the equipment and also the pressure, temperature, concentration, flow, and velocity of the oxygen. For metals, pressure, concentration or purity, and oxygen flow rate are usually the most significant factors. Temperature is a much less significant factor than is the case for nonmetals because ignition temperatures of metals are all significantly higher than those of nonmetals. The effects of these factors show up in the estimate of ignition potential (8.2) and reaction effect assessment (8.5), as explained in Section 8.

5.10.2 *Pressure*—The oxygen pressure is important, because it generally affects the generation of potential ignition mechanisms, and because it affects the destructive effects if ignition should occur. While generalizations are difficult, rough scales would be as given in Table 3.

NOTE 3—While the pressure generally affects the reaction as given in Table 3, data indicate that it has varying effects on individual flammability

TABLE 3 Effect of Pressure on Typical Metal Burning Reactions

kPa	psi	Pressure Effect Assessment[A]
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

[A] See 5.10.2.

properties. For example, for many metals, increasing pressure results in the following:

(*a*) A reduction in the oxygen concentration required to enable propagation;

(*b*) Differing effects on autoignition temperature, with many metals having invariant autoignition temperatures, many metals having decreasing autoignition temperatures, and some metals having increasing autoignition temperatures;

(*c*) An increase in sensitivity to mechanical impact;

(*d*) A negligible change in heat of combustion;

(*e*) An increase in the difficulty of friction ignition, apparently due to increased convective heat dissipation;

(*f*) An increase in the likelihood of adiabatic compression ignition, however, adiabatic compression is an unlikely direct ignition mechanism for metals except at pressures in excess of 20 000 kPa (3 000 psi); and

(*g*) An increase in the rate of combustion.

5.10.3 *Concentration*—As oxygen concentration decreases from 100 %, the likelihood and intensity of a potential fire also decrease. Therefore, greater latitude may be exercised in the selection of materials. For all metals, there is an oxygen concentration (a flammability limit analogous to the oxygen index), below which (in the specific metal combustion tests undertaken) propagating combustion will not occur, even in the presence of an assured (very high energy) ignition. This concentration decreases with increasing pressure above a threshold pressure (below which the metal will not burn even in pure oxygen). The concentration may approach an asymptote at high pressures, Fig. X1.2, Fig. X2.1, and Fig. X2.3.

Note 4—Some metals are extremely sensitive to oxygen purity. Since many metal oxides do not exist as gases, the combustion products of some metals do not interfere with the combustion as is the case with polymers. Therefore, small amounts of inert gases in the oxygen can accumulate and control the combustion. In a research project, Benning et al. (6) found that as little as 0.2 % argon could increase the minimum pressure at which 6.4-mm (0.25-in.) diameter aluminum rods sustained combustion from 210 kPa (30 psi absolute) to 830 kPa (120 psi absolute). This effect is believed to be most significant for "vapor-burning" metals such as aluminum and less significant for "liquid-burning" metals such as iron. Theory is found in Benning (6) and Glassman (7-9).

5.10.4 *Flow and Oxygen Inventory*—The quantity of oxygen present and the rate at which it can flow to an ignition site affects the intensity and scale of a metal fire. Since many metals do not form gaseous combustion products, self extinguishment through accumulation of combustion products cannot occur as it does with polymers. However, accumulation of inert gases in the oxygen may cause extinguishment. Since the density of oxygen gas is much lower than the metal density, the quantity of metal that can burn is often limited by the quantity of oxygen present or the rate at which it can be supplied.

5.10.5 *Temperature*—Increasing temperature obviously increases the risk of ignition, as well as the prospect for sustained combustion. Indeed, an increase in temperature may enable combustion in cases where propagation would not be possible

at lower temperature. The influence of environmental temperature on metals is much less significant than for nonmetals; this is because the autoignition temperature of the most sensitive bulk metal (perhaps carbon steel at (~900°C (~1650°F)) is significantly greater than for the most resistant polymers (for example PTFE at (~480°C (~900°F)).

5.10.5.1 Although autoignition temperatures of metals in oxygen atmospheres have been cited as a means of ranking materials for service in high temperature oxygen, promoted ignition-combustion of metals in high temperature oxygen may be more appropriate. Zawierucha et al. (10) have reported on elevated temperature promoted ignition-combustion resistance.

5.10.6 *LOX versus GOX*—Combustion of aluminum in LOX has led to extremely serious combustion events known as Violent Energy Releases (VERs) in both operating systems and experiments. In GOX aluminum will experience rapid combustion but not VERs. The destruction caused by a VER is more typical of an explosion than simple combustion. Numerous investigators have duplicated this phenomenon (11-24). Key Aluminum-LOX incidents are referenced (25-27). Mitigating approaches are described in CGA pamphlets G4.8, G4.9 and P-8.4 for aluminum air separation plant components.

5.10.7 *Geometry*—The geometry of the component can have a striking effect on the flammability of metals. Generally, thin components or high-surface-area-to-volume components will tend to be more flammable. For example, both Stoltzfus et al. (28) and Dunbobbin et al. (29) have shown that materials such as thin wire mesh and thin layered sheets can become much more flammable than might be expected on the basis of tests of rods. In these works, copper and brass alloys that typically resist propagation in bulkier systems were capable of complete combustion. Zabrenski et al. (30) have found that thin-wall tubes of 6.4-mm (0.25-in.) diameter stainless steel would propagate combustion at atmospheric pressure while solid rods required pressures of 5.0 MPa [740 psi absolute]. Samant et al. (31) in promoted ignition-combustion studies of Nickel 200, Monel 400, Hastelloy C-276, Copper, and Stainless Steels at pressures up to 34.6 MPa show that Nickel 200 was the most combustion resistant in thin cross sections while 316/316L stainless steel was the least.

5.11 *Ignition Mechanisms*—For combustion to occur, it is necessary to have three elements present: oxidizer, fuel, and ignition energy. The oxygen environment is obviously the oxidizer, and the system itself is the fuel. Several potential sources of ignition energy are listed below. The list is not all-inclusive or in order of importance or in frequency of occurrence.

5.11.1 *Promoted Ignition*—A source of heat input occurs (perhaps due to a kindling chain) that acts to start the metal burning. Examples: the ignition of contamination (oil or alien debris) which combusts and its own heat release starts a metal fire.

5.11.2 *Friction Ignition*—The rubbing of two solid materials results in the generation of heat and removal of protective oxide. Example: the rub of a centrifugal compressor rotor against its casing.

5.11.3 *Heat from Particle Impact*—Heat is generated from the transfer of kinetic, thermal, or chemical energy when small

particles (sometimes incandescent, sometimes igniting on impact), moving at high velocity, strike a material. Example: high velocity particles from a dirty pipeline striking a valve plunger.

5.11.4 *Fresh Metal Exposure*—Heat is generated when a metal with a protective surface oxide is scratched or abraded, and a fresh surface oxide forms. Titanium has demonstrated ignition from this effect, but there are no known cases of similar ignition of other common metals. Nonetheless, fresh metal exposure may be a synergistic contributor to ignition by friction, particle impact, etc. Example: the breaking of a titanium wire in oxygen.

5.11.5 *Mechanical Impact*—Heat is generated from the transfer of kinetic energy when an object having a large mass or momentum strikes a material. Aluminum and titanium have been experimentally ignited this way, but stainless steels and carbon steels have not. Examples: a backhoe rooting-up an oxygen line; a fork truck penetrating an oxygen cylinder.

5.11.6 *Heat of Compression*—Heat is generated from the conversion of mechanical work when a gas is compressed from a low 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. An effective ignition mechanism with polymers, the much higher heat capacity and thermal conductivity of significantly sized metals greatly attenuates high temperature produced this way. Example: a downstream valve or flexible lined pigtail in a dead-ended high-pressure oxygen manifold.

5.11.7 *Electrical Arc*—Electrical arcing can occur from motor brushes, electrical control instrumentation, other instrumentation, electrical power supplies, lightning, etc. Electrical arcing can be a very effective metal igniter, because current flow between metals is easily sustained, electron beam heating occurs, and metal vaporizes under the influence of the plasma. All of these are conducive to combustion. Example: an insulated electric heater element in oxygen experiences a short circuit and arcs through to the oxygen gas.

5.11.8 *Resonance*—Acoustic oscillations within resonant cavities are associated with rapid gas 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 if the heat transferred is not rapidly dissipated, and fires of aluminum have been induced experimentally by resonance.

Example: a gas flow into a tee and out of a side port such that the remaining closed port forms a resonance.

5.11.9 *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 welding spatter, or internal sources, such as fracture or thermite reactions of iron oxide with aluminum.

5.12 *Reaction Effect*—The effect of an ignition (and subsequent propagation, if it should occur) has a strong bearing on the selection of a material. While reaction effect assessment is an obviously imprecise and strongly subjective judgment, it must be balanced against extenuating factors such as those given in 5.9. Suggested criteria for rating the reaction effect severity have been developed in Guide G63 and are shown in Table 4, and a method of applying the rating in a material selection process is given in Section 8. Note that, in some 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 shields and the like (see Guide G88). The combustion of aluminum in LOX has generated combustion phenomena, VERs, that are explosive on systems and test facilities.

5.12.1 *Heat of Combustion*—The combustion of a metal releases heat, and the quantity has a direct effect on the destructive nature of the fire. On a mass basis, numerous metals and polymers release about the same amount of heat. However, because of its much larger mass in most systems, combustion of many metals has the potential for release of the major amount of heat in a fire. Combustion of aluminum in LOX is an example of an explosive phenomenon.

5.12.2 *Rate of Combustion*—The intensity of a fire is related to both the heat of combustion of the materials and the rate at which the combustion occurs. The rates of combustion of various metals can vary more than an order of magnitude, and for some metals can be so rapid as to be considered explosive.

6. Test Methods

6.1 *Promoted Combustion Test*—A metal specimen is deliberately exposed to the combustion of a promoter (easily ignited material) or other ignition source. Metal specimens reported in

TABLE 4 Reaction Effect Assessment for Oxygen Applications

Code	Severity Level	Effect on Personnel Safety	Effect on System Objectives	Effect on Functional Capability
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 on site within an acceptable time frame.
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.

the literature have varied in length and thickness. The promoter may be standardized, in which case the test ranks those materials that resisted ignition as being superior to those that burned; varying the oxygen pressure, oxygen purity or specimen temperature allows further ranking control. The promoter mass may also be varied, in which case, the metals are ranked according to the quantity of promoter required to bring about combustion. In yet another variation, ignition of the test specimen is ensured and the velocity of propagation or the specimen regression rate is measured. The regression rate is the velocity at which the combustion zone moves along the metal; the molten material that drains away may not be completely combusted. A low propagation rate ranks a metal higher (more desirable). (

Note 5—ASTM Committee G04 has sponsored a series of metal-promoted combustion tests at the NASA White Sands Test Facility using the methodology reported by Benz et al (32). These data, along with similar data generated by NASA, are included in Table X1.1. This table ranks metals according to (1) the highest pressure at which combustion was resisted, (2) for metals that ranked comparably above, according to the average propagation rate, and (3) for metals that ranked comparably by both (1) and (2), above, according to the average burn length below the threshold. Test Method G124 has been developed for determining the combustion behavior of metallic materials in oxygen enriched atmospheres.

6.2 *Frictional Heating Test*—One metal is rotated against another in an oxygen atmosphere. Test variables include oxygen pressure, specimen loads, and linear velocity. At constant test conditions, a material is ranked higher if it exhibits a higher Pv product at ignition (where P is the force divided by the initial cross-sectional area, and v is the linear velocity).

Note 6—ASTM Committee G04 has sponsored a series of metals friction ignition tests at the NASA White Sands test facility using the methodology reported by Benz and Stoltzfus (33). Due to the high cost of the apparatus and tests, round robin testing is not realistic and this procedure is not being developed into an ASTM standard; however, these data, along with similar data generated by NASA, are included in Table X1.2 (see Adjunct Par 2.3). Friction ignition is a very complex phenomenon. Test data suggest there is significance to the Pv product at the time of ignition (where P is the mechanical loading in force per apparent area, and v is the linear velocity), and this is the ranking criterion used in Table X1.2. Pressure affects friction ignition in that it has been harder to ignite metals at higher pressures above a minimum Pv value. In addition, in limited testing to date, the relative rankings of metals may change at different linear velocities.

6.3 *Particle Impact Test*—An oxidant stream with one or more entrained particles is impinged on a candidate metal target. The particles may be incandescent from preheating (likely for smaller particles) due to earlier impacts. The particles may be capable of ignition themselves upon impact (in this case, the test resembles a promoted ignition test under flowing conditions with the burning particle being the promoter). Test variables include pressure, particle and gas temperature, nature of particle, size and number of particles, and gas velocity.

Note 7—ASTM Committee G04 has sponsored a series of industry-funded particle impact tests at the NASA White Sands Test Facility using the methodology reported by Benz et al. (34) in ASTM STP 910. Due to high cost of the apparatus and test, round robin testing is not realistic, and this procedure is not being developed into an ASTM standard. Because of

the scatter in these data, they are portrayed graphically and qualitatively ranked in Fig. 1. The results are qualitatively similar to those from the promoted combustion test (6.1), but with several significant exceptions. For example, aluminum bronze resisted particle impact ignition much better than aluminum; in the promoted combustion test, the results were more comparable.

6.4 *Limiting Oxygen Index Test*—This is a determination of the minimum concentration of oxygen in a flowing mixture of oxygen and a diluent that will just support propagation of combustion. There is a test method (see Test Method D2863) that applies to nonmetals at atmospheric pressure. While no standard ASTM Oxygen Index Test method has specifically been designated for metals, oxygen index data can be obtained using Test Method G124 and prepared oxygen gas mixtures of various purities.

Note 8—The existence of an oxygen index for metals is established. The index of carbon steel decreases with increasing pressure. Data on the oxygen index of carbon steel was first reported by Benning and Werley (36), and the data are included in Table X1.4 and Fig. X1.2.

6.5 *Autoignition Temperature Test*—A measurement of the minimum sample temperature at which a metal will spontaneously ignite when heated in an oxygen or oxygen-enriched
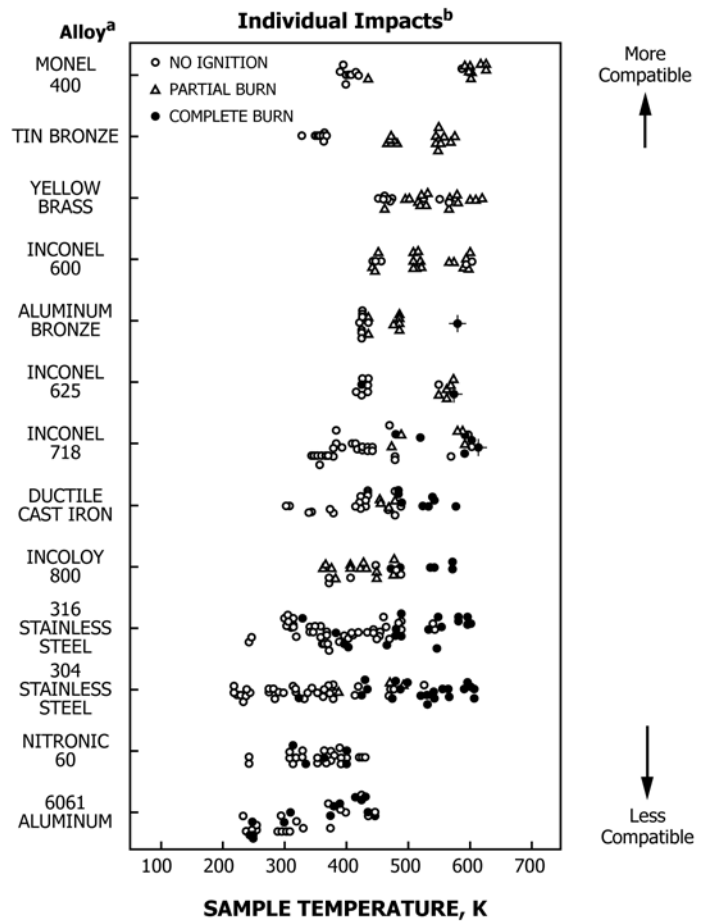
Note 1—0.2-cm. (0.5-in.) diameter by 0.24-cm. (0.60-in.) thick specimens impacted with 1600-µm aluminum particles in 1000-psig oxygen, velocity ~1360 m/s.
Note 2—See Adjunct, Par. 2.3.
[A] See Table X1.9 for alloy compositions.
[B] From Benz et al. (34), Stoltzfus (35)
FIG. 1 Particle Impact Test Results

atmosphere. Autoignition temperatures of nonmetals are commonly measured by methods such as Test Method G72. Metals autoignite at much higher temperature than nonmetals (**37-39**). These temperatures are much higher than would occur in actual systems. Further, the experimental problems of containing the specimens, effects of variable specimen sizes and shapes, effects of protective oxides that may be removed in actual systems, difficulty in measuring the temperature, and problems in deciding when ignition has occurred have prevented development of a reliable standard test procedure to yield meaningful data.

6.6 *Mechanical Impact Test*—A known mass is dropped from a known height and impacts a test specimen immersed in oxidant. Two procedures, Test Methods D2512 and G86 have been used with nonmetals and are discussed in Guide G63. Mechanical impact ignitions of metals are much less likely than for nonmetals; occasional ignitions have occurred during impact of zirconium, titanium, magnesium, and aluminum; however, ranking of other metals has not been achieved.

6.7 *Calorimeter Test*—A measurement of the heat evolved per unit mass (the heat of combustion) when a material is completely burned in 25 to 35 atm (2.5 to 3.5 MPa) of oxygen at constant volume. Several procedures such as Test Methods D4809, D2382 (discontinued), and D2015 (discontinued) have been used in the past. . The results are reported in calories per gram (or megajoules per kilogram). For many fire-resistant materials of interest to oxygen systems, measured amounts of combustion promoter must be added to ensure complete combustion.

NOTE 9—Heats of combustion for metallic elements and alloys have been reported by Lowrie (**40**) and are given in Table X1.5. In practice, it

is usually not necessary to measure an alloy's heat of combustion, since it may be calculated from these data using the formula

$$\Delta H = \sum C_i \Delta H_i \qquad (2)$$

where:
C_i = fractional weight concentration of the alloying element, and
ΔH_i = heat of combustion of the alloying element (in consistent units).

Heat of combustion per unit volume of metal can be calculated by the product of ΔH and density, ρ.

7. Pertinent Literature

7.1 *Periodic Chart of the Elements*— The periodic chart can provide insight into the oxygen compatibility of elemental metals. Grosse and Conway (**1**) and McKinley (**41**) have elaborated on this correlation. For example, Fig. 2 depicts the cyclic nature of heats of formation, and Fig. 3 shows the periodic chart with selected similar metals highlighted. Observe that the periodic chart shows how elements of demonstrated combustion resistance (such as the vertical columns Cu, Ag, Au, and Ni, Pd, Pt) are clustered together, as are elements of known flammability (such as Be, Mg, Ca, etc., and Ti, Zr, Hf, etc.).

7.2 *Burn Ratios*—A number of attempts have been made in the literature to relate the physicochemical properties of metals to their oxygen compatibility. Monroe et al. (**42, 43**) have proposed two "burn ratios" for understanding metals combustion: the melting-point burn ratio, BR_{mp}, and the boiling-point burn ratio, BR_{bp}. Although these factors lend insight into the burning of metallic elements, their application to alloys is complicated by imprecise melting and boiling points, vapor pressure enhancements and suppressions, potential preferential

FIG. 2 Heat of Formation of the Metal Oxides Versus Atomic Numbers

FIG. 3 Periodic Table Location of Some Hazardous Oxygen Service Metals

combustion of flammable constituents, and an importance of system heat losses that can alter the alloys rankings by these parameters.

7.2.1 *Melting Point Burn Ratio*—Numerous metals burn essentially in the molten state. Therefore, combustion of the metal must be able to produce melting of the metal itself. The BR_{mp} is a ratio of the heat released during combustion of a metal to the heat required to both warm the metal to its melting point and provide the latent heat of fusion. It is defined by:

$$BR_{mp} = \Delta H_{combustion} / (\Delta H_{rt-mp} + \Delta H_{fusion}) \qquad (3)$$

where:

ΔH = heat of combustion,
ΔH_{rt-mp} = heat required to warm the metal from room temperature, rt, to the melting point, mp, and
ΔH_{fusion} = latent heat of fusion.

Clearly, a metal that does not contain sufficient heat to melt itself (that is, one that has a $BR_{mp} < 1$) is severely impeded from burning in the molten state. Monroe et al. (**42, 43**) have calculated numerous BR_{mp}s and they are given in Table X1.6.

7.2.2 *Boiling Point Burn Ratios*—Several metals burn essentially in the vapor phase. Therefore, combustion of the metal must be able to produce vaporization of the metal itself. The BR_{bp} is a ratio of the heat released during combustion of a metal to the heat required to warm the metal to its boiling point and provide the latent heat of vaporization. It is defined by:

$$BR_{bp} = \Delta H_{combustion} / (\Delta H_{rt-mp} + \Delta H_{fusion} + \Delta H_{mp-bp} + \Delta H_{vap}) \qquad (4)$$

where:

ΔH_{mp-bp} = heat required to warm the metal from the melting point to the boiling point, and
ΔH_{vap} = latent heat of vaporization.

Clearly, a metal that does not contain sufficient heat to vaporize itself (that is, one that has a $BR_{bp} < 1$) is severely impeded from vapor-phase combustion. Monroe et al. (**42, 43**) have calculated several BR_{bp} and they are given in Table X1.7. Since pure hydrocarbon materials burn in the vapor phase, a few BR_{bp} for hydrocarbons have been included in Table X1.7 for perspective.

7.3 *Flame Temperature*—The adiabatic flame temperature of a combusting material affects its ability to radiate heat. As a result, the adiabatic flame temperatures of metals give insight into the oxygen compatibility. Grosse and Conway (**1**) have tabulated the flame temperature for numerous metals and they are given in Table X1.8. These are compared to the flame temperatures of normal fuel gases reported by Lewis and Von Elbe (**44**). The adiabatic flame temperature is related to a material's heat of combustion. Other things being equal, a material of lower flame temperature is preferred.

8. Material Selection Method

8.1 *Overview*—To select a material for an application, the user first reviews the application to determine the probability that the chosen material will be exposed to significant ignition phenomena in service (8.2). The user then considers the prospective material's susceptibility to ignition (8.3) and its destructive potential or capacity to involve other materials once ignited (8.4). Next, the potential effects of an ignition on the

system environment are considered (8.5). Finally, the user compares the demands of the application with the level of performance anticipated from the material in the context of the necessity to avoid ignition and decides if the material will be acceptable (8.6). Examples of this regimen are given in 8.8.

8.2 *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 Sheet, Fig. X1.1, values may be assigned, based on the following probability scale:

8.2.1 *0—*Almost impossible,

8.2.2 *1—*Remote,

8.2.3 *2—*Unlikely,

8.2.4 *3—*Probable, and

8.2.5 *4—*Highly probable.

8.2.6 This estimate is quite imprecise and generally subjective, but furnishes a basis for evaluating an application.

8.3 *Prospective Material Evaluation—* The next step is to determine the material's rating with respect to those factors which affect ease of ignition (5.8.1), assuming the material meets the other performance requirements of the application. If the required information is not available in the included tables (Tables X1.1-X1.8) 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. Typically, the most important criteria in the determination of a metal's susceptibility are dependent upon the application.

NOTE 10—Until an ASTM procedure is established for a particular test, test results are to be considered provisional.

8.4 *Post-Ignition Property Evaluation—* The properties and conditions that could affect potential resultant damage if ignition should occur should be evaluated (5.8.4). Of particular importance is the total heat release potential, that is, the material's heat of combustion times its mass (in consistent units) and the rate at which that heat is released.

8.5 *Reaction Effect Assessment—*Based on the evaluation of 8.4, and the conditions of the complete system in which the material is to be used, the reaction effect should be assessed using Table 4 as a guide. In judging the severity level for entry on the Material Evaluation Data Sheet, Fig. X1.1, 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.

8.6 *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 influence, and compromise involved. While each case must ultimately be decided on its own merits, the following generalizations apply:

8.6.1 Use the least reactive material available consistent with sound engineering and economic practice. When all other things are equal, stress the properties most important to the application. Attempt to maximize frictional thresholds, pro-

moted combustion thresholds, and oxygen index. Attempt to minimize heat of combustion, rate of propagation, flame temperature and burn ratios.

8.6.1.1 If the personnel injury or damage potential is high (Code C or D) use the best (least reactive) practical material available (see Table 4).

8.6.1.2 If the personnel injury or damage potential is low (Code A or B) and the ignition mechanism probability is low (2 or less), a material with medium reactivity may be used.

8.6.1.3 If one or more potential ignition mechanisms have a relatively high probability of occurrence (3 or 4 on the probability scale of 8.2), use only a material with a high resistance to ignition.

8.6.2 Metals of greater fire resistance should be chosen whenever a system contains large quantities of nonmetals, when less than optimum nonmetals are used, or when sustained scrupulous cleanliness cannot be guaranteed.

8.6.3 The higher the maximum use pressure, the more critical is the metal's resistance to ignition and propagation (see 5.10.2).

8.6.4 Metals that do not propagate promoted combustion at pressures at or above the service pressure are preferred for critical applications or where ignition mechanisms are operative (see 6.1).

8.6.5 For rotating machinery, metals are preferred with the highest P_v values at ignition (see 6.2, Note 6) that are consistent with practical, functional capability.

8.6.6 Materials with high oxygen indices are preferable to materials with low oxygen indices. When a metal is used at concentrations below its pressure-dependent oxygen index, greater latitude may be exercised with other parameters (see 6.4).

NOTE 11—With respect to Guidelines 8.6.4 – 8.6.6, the use of materials that yield intermediate test results is a matter of judgment involving consideration of all significant factors in the particular application.

8.6.7 Experience with a given metal in a similar or more severe 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. Similarities may be inferred from comparisons of test data, burn ratios, or use of the periodic chart of the elements.

8.6.8 Since flammability properties of metals can be very sensitive to small fractions of constituents, it may be necessary to test each alloy or even each batch, especially where very flammable elements are minor components.

8.7 *Documentation—*Fig. X1.1 is a materials evaluation sheet filled out for a number of different applications. It indicates how a material's 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.

8.8 *Examples*—The following examples illustrate the metal selection procedure applied to three different hypothetical cases involving two centrifugal pumps and one case of a pipeline valve.

8.8.1 *Trailer Transfer Centrifugal Pump:*

8.8.1.1 *Application Description*—A pump is required to transfer liquid oxygen from tankers at 0 to 0.17 MPa (0 to 25 psig) to customer tanks at 0 to 1.7 MPa (0 to 250 psig). The pump will be remotely driven. Normal service vibration from over-the-road transport and frequent fill/empty cycles will make the introduction of contamination (hydrocarbon, lint, particles, etc.) a concern and may compromise pump reliability.

8.8.1.2 *Ignition Probability Assessment (see 8.2 and 5.11)*—Because of the demanding over-the-road use, frequent start-up, and potential contamination, the prospect of a rub, debris, or cavitation is significant. Hence, promoted ignition, particle impact and especially friction rubbing, are all rated likely.

8.8.1.3 Sources of heating are not present, nor is a mechanical impact. No other ignition sources are identified, but their absence cannot be assumed. The summary of ignition probability ratings is:

Promoted ignition	3
Friction	4
Particle impact	3
Temperature runaway	1
Mechanical impact	1
Other	1

8.8.1.4 *Prospective Material Evaluations (see 8.3)*—Pumps were found to be commercially available in stainless steels, aluminum, aluminum bronze and tin bronze. Among these, tin bronze ranks superior in tests of ignition by friction and promoted combustion; stainless steel and aluminum bronze rank lower; and aluminum ranks lowest (see Table X1.1 and Table X1.2).

8.8.1.5 *Post-Ignition Property Evaluation (see 8.4)*—Both bronze and tin bronze have very low heats of combustion in the range of 650 to 800 cal/g. Further, in promoted combustion tests (Table X1.1), tin bronze resisted propagation in 48-MPa (7000-psig) gaseous oxygen. Stainless steel propagated combustion in 7 MPa (1000 psig), but not 3.5 MPa (500 psig). Aluminum bronze propagated at its lowest test pressure of 3.5 MPa (500 psig). Aluminum propagated at its lowest test pressure of 1.7 MPa (250 psig).

NOTE 12—With respect to stainless steel data it should be acknowledged that thin specimen cross sections (< 0.125 in./3.2mm) and the presence of flow can result in stainless steel combustion at lower pressures than are cited in this example, both factors of which are under study and the most current results should be incorporated in a thorough review. However, for the sake of brevity, the example, based on the 1980's data, does not address them or attempt to be comprehensive.

8.8.1.6 *Reaction Effect Assessment (see 8.5)*—A rub or an ignition in the pump might expose the back of the tanker to fire and a potentially massive release of liquid oxygen. The tanker is equipped with tires and may have road tars and oils coating it. The driver is always present and might be injured, and the customer's facility could be damaged, as well. Hence, the following reaction effect assessment code ratings are assigned:

Effect on personnel safety	D
Effect on system objectives	C
Effect on function capability	C

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

8.8.1.7 *Final Selection (see 8.6)*—In view of the overall catastrophic reaction assessment rating (Code D), only the most compatible available materials (bronze and tin bronze) are felt to be acceptable. An ignition event is likely to occur during the pump's life; however, Table X1.1 suggests bronze and tin bronze should be resistant to propagation. As a result, bronze was chosen on the basis of availability.

8.8.2 *Ground-Mounted Transfer Pump:*

8.8.2.1 *Application Description*—A pump is required to fill a high-pressure liquid oxygen storage tank at gauge pressure of 0 to 1.7 MPa (0 to 250 psig) from a tanker at 175 kPa (25 psig). The pump will be remotely operated and will have a high duty cycle. It will be ground-mounted with a filtered suction line, and a metal perimeter wall will shield it from other equipment. Remote valves will enable isolation of the liquid oxygen supplies in the event of a fire and shutdown devices protect it against cavitation. The area is isolated. Due to the high duty cycle, an efficient pump is desirable.

8.8.2.2 *Ignition Probability Assessment (see 8.2 and 5.11)*—Because of the rigid installation, semicontinuous operation, filtered suction, and permanent piping to its inlet, the worst operating problems are minimized. However, wear and mechanical failure can still operate to yield a frictional rub. Mechanical impact and a heat source are not foreseen. No other ignition sources are identified, but their absence cannot be assumed. The summary of ignition probability ratings is:

Promoted ignition	2
Friction	3
Particle impact	2
Temperature runaway	1
Mechanical impact	1
Other	1

8.8.2.3 *Prospective Material Evaluation (see 8.3)*—Pumps were found to be commercially available in stainless steels, aluminum, aluminum bronze, tin bronze, and bronze. Among these, bronze and tin bronze ranked highest with stainless steel and aluminum bronze in a lower category, and aluminum ranked lowest (see Table X1.1 and Table X1.2).

8.8.2.4 *Post-Ignition Property Evaluation (see 8.4)*—Both bronze and tin-bronze have low heats of combustion in the range from 650 to 800 cal/g. Both resisted propagation in 48-MPa (7000-psig) gaseous oxygen. Stainless steel alloys, specifically alloy 316 propagated in 7 MPa (1000 psig), but not 3.5 MPa (500 psig). Aluminum bronze propagated at its lowest test pressure of 3.5 MPa (500 psig). Aluminum ranked lowest and propagated at its lowest test pressure of 1.7 MPa (250 psig) with aluminum being the most energetic (heat of combustion of 7500 cal/g, see Table X1.5).

NOTE 13—See Note 12 in section 8.8.1.5.

8.8.2.5 *Reaction Effect Assessment (see 8.5)*—A rub or ignition in the pump might release fire into the metal shield. Sustained liquid oxygen flow is unlikely because of shutoff devices outside the shield. Personnel do not approach the pump during operation, therefore risk of injury is minimal. Loss of

the pump would be economically significant but the reliability of the overall arrangement render it an acceptable event. A spare pump is likely to be in inventory or on line. The plant mission would be interrupted for repairs, but replacement or repair can be obtained quickly, and, therefore, a fire would be a tolerable disruption. Hence, the following reaction effect assessment code ratings were assigned:

Effect of personnel safety	A
Effect on system objectives	B
Effect on function capability	B

The overall assessment is a marginal B rating.

8.8.2.6 *Final Selection (see 8.6)*—In view of the overall marginal reaction assessment rating (Code B), and, in particular, the safety of personnel, a wide latitude is acceptable in material selection. Since an event is possible due to mechanical failure, and since it can have the same impact (due to the failure itself) on system objectives and functional capability, and further since availability, operating economy and the like are important in this application, it was decided to choose any of the candidate metals that yielded the best reliability and efficiency, but if other things are equal, then to apply the ranking preference; bronze, tin bronze, stainless steels, aluminum bronze, aluminum. In order to have a rigid piping system, minimize flange loadings, and avoid flexible connections, a pump with a strong stainless steel case and a tin bronze impeller was chosen.

8.8.3 *Burner Isolation Valve:*

8.8.3.1 *Application Description*—A 50.8-mm (2-in.) carbon steel pipeline supplies gaseous oxygen to a burner from a 1.4-MPa (200-psig) liquid oxygen storage vessel. An isolation valve is required to allow periodic maintenance of the burners. The isolation valve is manually-operated and requires a high capacity to satisfy flow requirements. The valve is operated infrequently to apply initial pressure to the system. Gas velocities in the piping during normal operating conditions are limited to the values specified in CGA Pamphlet G-4.4.

8.8.3.2 *Ignition Probability Assessment (see 8.2 and 5.11)*—Due to a carbon steel system, some oxide particles are sure to be present and represent potential ignition sources at impact sites and for system polymers. Speed of valve operation is low in comparison to machinery, and friction ignition is, therefore, unlikely. Rapid opening of the valve can produce downstream adiabatic compression or turbulence that is undesirable in carbon steel piping. Heat inputs to the valve are not foreseen, and even rapid opening would not be expected to produce significant mechanical impact. Other ignition sources are not identified, but their absence cannot be assumed. The summary of ignition probability ratings is:

Promoted ignition	1
Friction	2
Particle impact	3
Temperature runaway	1
Mechanical impact	1
Other	1

8.8.3.3 *Prospective Material Evaluations (see 8.3)*—Valves of carbon steel, stainless steel, or brass are the most readily available and economical. Nickel/copper alloys (such as UNS N04400 Monel 400), and aluminum-bronze are less available alternatives at much greater cost. Regardless of material, heat

of compression downstream of the valve and particle impingement are of concern. Using Table X1.1, these metals rank in decreasing compatibility in the order: nickel/copper and brass (similar), stainless steel, and aluminum bronze. Though carbon steel was not tested, a ranking below stainless steel would be anticipated.

8.8.3.4 *Post Ignition Property Evaluation (see 8.4)*—At the pressure of 1.4 MPa (200 psig), nickel/copper alloy and brass should resist combustion very effectively, having resisted propagation at 48 MPa (7000 psig) in the promoted combustion test. Stainless steel resisted propagation at 3.5 MPa (500 psig). Although these data (Table X1.1) do not prove that propagation will never occur in the valve, they are favorable in comparison to aluminum bronze's results in which propagation occurred at 3.5 MPa (500 psig), its lowest test pressure. Carbon steel is likely to propagate a substantial fire at this pressure with extensive damage potential, and carbon steel is present in the downstream piping material.

NOTE 14—See Note 12 in section 8.8.1.5.

8.8.3.5 *Reaction Effect Assessment (see 8.5)*—Since ignition is most likely during valve operation, and since the operation is manual, injury is likely. Ignition of the valve might yield ignition of the piping and significant propagation is likely regardless of valve material choice. A reaction of the valve would interrupt the plant operation; however, the repair would be relatively straightforward. Hence, the following reaction effect assessment code ratings are assigned:

Effect on personnel safety	D
Effect on system objectives	C
Effect on functional capability	B

The overall rating is D-catastrophic.

8.8.3.6 *Final Selection (see 8.6)*—In view of the overall catastrophic reaction assessment, a highly fire-resistant alloy was felt to be required. Hence, brass or nickel/copper alloy were the choices. Welded connections to brass are a problem. Further, since turbulence downstream of the valve poses a concern, conversion from carbon steel piping to copper, brass or nickel/copper alloy was also felt necessary for at least 10 diameters downstream of the point of return to normal gas velocities (in keeping with CGA Pamphlet G-4.4). Even these steps, however, would not prevent rapid opening of the high-capacity valve, and a high-capacity valve itself would be difficult to obtain in a valve design that favored slow opening (in a plug valve as opposed to a ball valve). As a result, a different strategy was selected. A small bypass, globe valve of brass was piped around the main valve with copper tubing. Operating procedures were written to require that this fire-resistant bypass valve be used to do all pressurization slowly. Since the main valve is to be operated only under no-flow conditions, its risk of an ignition event is very low, and a carbon steel ball valve was selected.

9. Keywords

9.1 alloys; autoignition; autoignition temperature; burn ratios; calorimetry; combustion; flammability; friction/rubbing; gaseous impact; heat of combustion; ignition; LOX/GOX compatibility; materials selection; mechanical impact; metal

combustion; metal flammability; metals; oxygen; oxygen index; oxygen service; particle impact; promoted combustion; sensitivity

APPENDIXES

(Nonmandatory Information)

X1. MATERIALS EVALUATION DATA SHEETS

X1.1 *Introduction* —The data sheet (Fig. X1.1) contains examples of typical applications divided into several functional categories such as valve components, piping, rotating machinery, etc. This data sheet 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 prac-

tice 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 X1.1-X1.9.

APPLICATION	OPERATING CONDITIONS			IGNITION MECHANISMS							REACTION EFFECT	SUGGESTED ACCEPTANCE CRITERIA												Examples of Materials in Use	Notes
	Tem-perature	Gage Pressure		Promoted Ignition	Friction Ignition	Particle Impact	Arc/Spark	Mech. Impact	Others			Minimum Promoted Ignition Result			Minimum Friction Test Result			Minimum Particle Impact Result			Maximum Heat of Combustion			Other Methods		
	C	psi	kPa										and	or		and	or	C	F	and	or	MJ/kg	cal/g	and	or		

FIG. X1.1 Typical Material Evaluation Sheet

TABLE X1.1 Promoted Combustion Test Results
(0.23-g Aluminum Promoter)[A]

Note 1—See Adjunct, Par. 2.3.

Material[B]	Initial Pressure		Number of Tests	Average Propagation Rate		Average Burn Length		
	MPa	(psig)		cm/s	(in./s)	cm	(in.)	
Copper 102	6.9	1000[C]	2	NP[D]		...	...	↑
	34.5	5000	2	NP		...	...	More
	55.1	8000	2	NP		...	...	Compatible
Monel 400	3.5	500	1	NP		1.0	0.4	
	6.9	1000[C]	1	NP		...	...	
	34.5	5000	2	NP		...	...	
	55.1	8000	3	NP		...	...	
Nickel 200	6.9	1000[C]	1	NP		...	...	
	34.5	5000	1	NP		...	...	
	55.1	8000	6	NP		...	...	
Red brass	17.2	2500	1	NP		1.0	0.4	
	34.5	5000	1	NP		1.5	0.6	
	48.3	7000	2	NP		0.6	0.2	
Tin bronze	17.2	2500	1	NP		0.8	0.3	
	34.5	5000	1	NP		0.8	0.3	
	48.3	7000	2	NP		0.3	0.1	
Yellow brass	6.9	1000	1	NP		1.0	0.4	
	17.2	2500	1	NP		1.0	0.4	
	34.5	5000	1	NP		0.8	0.3	
	48.3	7000	2	NP		0.5	0.2	
Inconel 600	6.9	1000	4	NP		0.5	0.2	
	17.2	2500	3	NP		0.9	0.4	
	17.2	2500	1	0.41	0.16	...	...	
	24.8	3600	1[C]	CB[D]		...	...	
	34.5	5000	1	0.50	0.19	...	...	
Stellite 6B	6.9	1000	4	NP[D]		0.7	0.3	
	17.2	2500	2	NP		2.9	1.2	
	17.2	2500	4[E]	CB[D]		...	...	
	17.2	2500	1	1.17	0.46	...	...	
	34.5	5000	1	1.15	0.45	...	...	
Inconel 625	6.9	1000	5	NP		2.2	0.9	
	17.2	2500	1	0.99	0.39	...	...	
	17.2	2500	3[E]	CB		...	...	
Incoloy 800	6.9	500	5	NP		1.1	0.4	
	6.9	1000	1	NP		2.8	1.1	
	6.9	1000	1	1.02	0.38	...	...	
	17.2	2500	1	1.12	0.44	...	...	
	17.2	2500	1[E]	CB		...	...	
Inconel 718	3.5	500	2	NP[D]		0.5	0.2	
	6.9	1000[C]	4	1.12	0.44	...	...	
	6.9	1000	3	1.22	0.48	...	...	
	27.6	4000	6	1.33	0.52	...	...	
	48.2	7000	5	1.50	0.59	...	...	
	68.9	10000	5	1.68	0.66	...	...	
304 Stainless steel	3.5	500[C]	10	NP		...	...	
	3.5	500	1	NP		2.3	0.9	
	17.2	2500	1	1.12	0.44	...	...	
	20.7	3000	10	1.19	0.47	...	...	
	34.5	5000	1	1.30	0.51	...	...	
316 Stainless steel	3.5	500[C]	4	NP[D]		...	...	
	3.5	500	1	NP		3.3	1.3	
	6.9	1000[C]	5	1.12	0.44	...	...	
	6.9	1000	1	1.02	0.40	...	...	
	20.7	3000	2	1.22	0.48	...	...	
	27.6	4000	6	1.24	0.49	...	...	
	48.2	7000	5	1.44	0.57	...	...	
	68.9	10000	4	1.58	0.62	...	...	
Ductile cast iron	3.5	500	1	0.36	0.14	...	...	
	6.9	1000	1	0.69	0.27	...	...	
	17.2	2500	8[E]	CB[D]		...	...	
Nitronic 60	3.5	500	1	0.84	0.33	...	...	
	6.9	1000	1	CB		...	...	
	17.2	2500	6	CB		...	...	
9 % Nickel steel	3.5	500	1	0.96	0.38	...	...	
	6.9	1000	1	1.35	0.53	...	...	
	17.2	2500	1	1.70	0.67	...	...	
	17.2	2500	1[E]	CB		...	...	
Aluminum-bronze	3.5	500	1	2.77	1.09	...	...	
	6.9	1000	1	2.79	1.10	...	...	
	17.2	2500	1	3.30	1.30	...	...	

TABLE X1.1 *Continued*

Material[B]	Initial Pressure		Number of Tests	Average Propagation Rate		Average Burn Length		
	MPa	(psig)		cm/s	(in./s)	cm	(in.)	
	17.2	2500	3[E]	CB		...	...	
	34.5	5000	1	CB		...	...	
Aluminum 6061	1.7	250	1	4.57	1.80	...	...	
	3.5	500	1	5.84	2.30	...	...	
	6.9	1000[C]	4	6.42	2.53	...	...	
	13.8	2000	2	8.85	3.48	...	...	↓
	17.6	4000	7	13.86	5.46	...	...	Less
	34.4	5000	2	14.82	5.83	...	...	Compatible
	48.2	7000	2	18.93	7.45	...	...	
	68.9	10000	3	24.51	9.65	...	...	

[A] From Benz et al. (32), Stoltzfus (35), specimens 3.2 mm (⅛ in.) in diameter by 127 mm (5 in.) long.
[B] See Table X1.8 for alloy compositions.
[C] A 3-L accumulator was added to the test chamber on all tests that were conducted at 3.5 or 6.9 MPa (500 or 1000 psig), except on those tests marked with Footnote C.
[D] NP = Nonpropagating (less than 5 cm of the specimen length was consumed), CB = Completely burned.
[E] These tests were conducted using the video setup. No burn rate was calculated.

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.

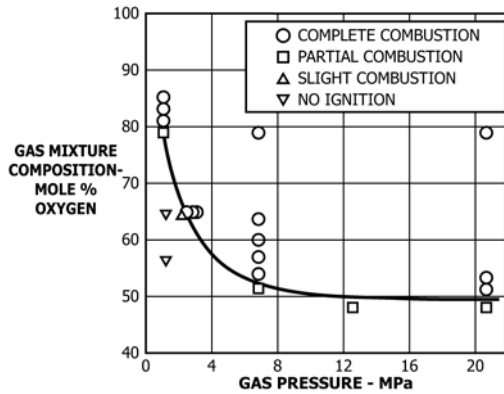X1.1.4 Unless otherwise noted, the operating conditions are for 99.5 mol %, or higher, oxygen.

FIG. X1.2 Oxygen Index of Carbon Steel (Data from Table X1.4)

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TABLE X1.2 Friction Ignition Test Data for Similar Pairs of Test Specimens

NOTE 1—2.5-cm (1-in.) diameter by 0.25-cm (0.1-in.) wall by 2-cm (0.8-in.) specimens rotated axially, horizontally in stagnant 6.9-MPa (1000-psia) aviator's breathing grade oxygen. Tests were conducted by keeping v constant and increasing P at a rate of 35 N/s until ignition.
P—specimen contact pressure at ignition (loading force/initial contact area).
v—specimen linear velocity is 11 m/s.

NOTE 2—All unreferenced data is from previously unpublished frictional heating tests performed at NASA White Sands Test Facility.

Test Materials[A]		Pv Product at Ignition	
Stator	Rotor	$W/m^2 \times 10^{-8}$	($lbf/in.^2 \times ft/min \times 10^{-6}$)
Inconel MA 754	Inconel MA 754	3.96–4.12[B]	11.30–11.75
Haynes 214	Haynes 214	3.05–3.15	8.73–8.98
Inconel MA 758	Inconel MA 758	2.64–3.42	7.53–9.76
Nickel 200	Nickel 200	2.29–3.39	6.50–9.66[C]
Tin bronze	Tin bronze	2.15–2.29	6.15–6.55[D]
Hastelloy C-22	Hastelloy C-22	2.00–2.99	5.72–8.52
Inconel 600	Inconel 600	2.00–2.91	5.70–8.30[C]
Inconel MA 6000	Inconel MA 6000	1.99–2.66	5.68–7.59
Glidcop Al-25	Glidcop Al-25	1.95–3.59	5.56–10.24
Hastelloy 230	Hastelloy 230	1.79–2.19	5.10–6.24
NASA-Z	NASA-Z	1.77–2.63	5.05–7.52
Cu Zr	Cu Zr	1.68–3.19	4.81–9.11
Inconel 625	Inconel 625	1.63–1.73	4.65–4.94
Hastelloy B-2	Haselloy B-2	1.61–2.16	4.60–6.12
Waspaloy	Waspaloy	1.55–2.56	4.45–7.05
Monel 400	Monel 400	1.44–1.56	4.12–4.46[C]
Haynes 230	Haynes 230	1.40–1.82	4.00–5.20
Monel K-500	Monel K-500	1.37–1.64	3.91–4.68[C]
13-4 PH	13-4 PH	1.31–2.06	3.74–5.88[D]
Hastelloy C-276	Hastelloy C-276	1.21–2.82	3.45–8.06
Incoloy 903	Incoloy 903	1.20–1.44	3.41–4.11
Inconel 718	Inconel 718	1.10–1.19	3.13–3.37
17-4 PH (H 900)	17-4 PH (H 900)	1.00–1.21	2.87–3.45
Yellow brass	Yellow brass	0.97–1.22	2.77–3.49
Hastelloy X	Hastelloy X	0.93–1.05	2.66–3.02[C]
Hastelloy G30	Hastelloy G30	0.91–1.29	2.58–3.68
14-5 PH	14-5 PH	0.88–1.04	2.51–2.96
304 SS	304 SS	0.85–1.20	2.33–3.41
17-4 PH	17-4 PH	0.85–1.07	2.42–3.05
Inconel 706	Inconel 706	0.81–1.21	2.33–3.51
303 SS	303 SS	0.78–0.91	2.25–2.60
Stellite 6	Stellite 6	0.79–0.82	2.25–2.35
Brass CDA 360	Brass CDA 360	0.70–1.19	1.98–3.41[C]
17-4 PH (Condition A)	17-4 PH (Condition A)	0.61–1.05	1.75–2.99
Invar 36	Invar 36	0.60–0.94	1.71–2.68[C]
Incoloy MA 956	Incoloy MA 956	0.53–0.75	1.67–2.02
316 SS	316 SS	0.53–0.86	1.50–2.50[C]
440 C stainless steel	440 C stainless steel	0.42–0.80	1.19–2.28
Nitronic 60	Nitronic 60	0.29–0.78	0.82–2.22
Incoloy 909	Incoloy 909	0.29–1.15	0.85–3.30
Aluminum 6061-T6	Aluminum 6061-T6	0.061	0.18[C]
Ti-6Al-4V	Ti-6Al-4V	0.0035	0.01[C]

[A] Table X1.9 will be updated as required.
[B] This material did not ignite at these Pv products.
[C] From Benz and Stoltzfus (33).
[D] From Stoltzfus et al. (34).

TABLE X1.3 Friction Ignition Test Data for Dissimilar Pairs of Test Specimens

NOTE 1—2.5-cm (1-in.) diameter by 0.25-cm (0.1-in.) wall by 2-cm (0.8-in.) specimens rotated axially, horizontally in stagnant 6.9-MPa (1000-psia) aviator's breathing grade oxygen. Tests were conducted by keeping v constant and increasing P at a rate of 35 N/s until ignition.
P—specimen contact pressure at ignition (loading force/initial contact area).
v—specimen linear velocity is 11 m/s.

NOTE 2—All unreferenced data is from previously unpublished frictional heating tests performed at NASA White Sands Test Facility.

Test Materials[A]		Pv Product at Ignition	
Stator	Rotor	$W/m^2 \times 10^{-8}$	$(lbf/in.^2 \times ft/min \times 10^{-6})$
Monel K-500	Hastelloy C-22	1.57–3.72	4.51–10.61
Monel K-500	Hastelloy C-276	1.41–2.70	4.00–7.70
Monel K-500	Hastelloy G30	1.34–1.62	3.81–3.87
Ductile cast iron	Monel 400	1.28–1.45	3.65–4.13[B]
Gray cast iron	410 SS	1.19–1.48	3.39–4.24[B]
Gray cast iron	17-4 PH (H 1150 M)	1.17–1.66	3.35–4.75[B]
Cu Be	Monel 400	1.10–1.20	3.14–3.42
Ductile cast iron	410 SS	1.10–1.23	3.12–3.43[B]
AISI 4140	Monel K-500	1.09–1.35	3.10–3.85[B]
Ductile cast iron	17-4 PH (H 1150 M)	1.09–1.17	3.00–3.35[B]
Monel 400	Nitronic 60	1.03–1.69	2.93–4.78
Inconel 718	17-4 PH SS	1.02–1.12	2.91–3.20
Bronze	Monel K-500	0.99–1.84	2.82–5.26[B]
Tin bronze	304 SS	0.97–1.25	2.78–3.56[B]
Monel K-500	Inconel 625	0.93–2.00	2.67–5.70
17-4 PH SS	Hastelloy C-22	0.93–1.00	2.65–2.86
Monel K-500	304 SS	0.92–1.13	2.63–3.24
Inconel 718	304 SS	0.90–1.18	2.58–3.37
17-4 PH SS	Hastelloy C-276	0.89–1.10	2.55 3.14
Bronze	17-4 PH (H 1150 M)	0.89–1.02	2.55–2.90[B]
316 SS	303 SS	0.89–0.90	2.53–2.57
Inconel 718	316 SS	0.86–0.96	2.44–2.73
Monel 400	304 SS	0.85–0.94	2.43–2.69
17-4 PH SS	Hastelloy G30	0.84–1.02	2.41–2.90
Monel K-500	303 SS	0.84–1.00	2.41–2.88
Ductile cast iron	Stellite 6	0.84–1.16	2.39–3.32[B]
Cu Zr	316 SS	0.83–0.90	2.39–2.58
Ductile cast iron	Tin bronze	0.81–1.69	2.32–4.82[B]
Monel K-500	17-4 PH SS	0.80–1.00	2.27–2.39
Bronze	410 SS	0.79–1.20	2.25–3.60[B]
304 SS	303 SS	0.77–0.78	2.21–2.26
Tin bronze	Aluminum bronze	0.77–0.84	2.20–2.38[B]
316 SS	17-4 PH SS	0.77–0.85	2.18–2.41
Monel 400	303 SS	0.76–0.93	2.17–2.67
304 SS	17-4 PH SS	0.75–1.09	2.14–3.12
Inconel 718	303 SS	0.75–0.86	2.14–2.48
Monel K-500	316 SS	0.73–0.91	2.10–2.61
316 SS	304 SS	0.68–0.91	1.93–2.60
Stellite 6	Nitronic 60	0.66–0.77	1.90–2.18[B]
Monel 400	17-4 PH SS	0.66–1.53	1.89–4.38
303 SS	17-4 PH SS	0.65–0.88	1.86–2.51
17-4 PH SS	Inconel 625	0.64–1.09	1.83–3.11
304 SS	Cu Be	0.63–1.24	1.81–3.54
Monel 400	316 SS	0.62–0.91	1.75–2.59
Ductile cast iron	Nitronic 60	0.44–0.75	1.25–2.15[B]
Aluminum bronze	C355 aluminum	0.30–0.32	0.85–0.91[B]
Nitronic 60	17-4 PH (H 1150 M)	0.28–0.61	0.80–1.75[B]
Babbitt on bronze	17-4 PH (H 1150 M)	0.09–0.21	0.25–0.60[B]
Babbitt on bronze	Monel K-500	0.09–0.19	0.25–0.55[B]
Babbitt on bronze	410 SS	0.08–0.09	0.24–0.27[B]

[A] Table X1.9 will be updated as required.
[B] From Stoltzfus et al. (34).

TABLE X1.4 Oxygen Index of Carbon Steel[A]

Gage Pressure		O₂ Concentration, mol %	Result	Gage Pressure		O₂ Concentration, mol %	Result
MPa	psi			MPa	psi		
1.03	150	56.7	N[B]	6.9	1000	50.7	S[C]
		56.8	N			51.0	P[D]
		64.5	N			51.0	P
		79.2	S			53.0	C[E]
		79.2	P			55.3	C
		80.9	C			56.8	P
		82.2	C			60.0	C
		84.2	C			63.0	C
						79.2	C
2.1	300	65.0	S	12.4	1800	48.5	P
2.4	350	65.0	S	20.7	3000	48.5	P
		65.0	C			51.0	C
						53.0	N
						53.1	C
						79.2	C
2.8	400	64.6	P				
		64.6	C				
3.1	450	64.6	C				

[A] From Benning and Werley **(36)**.
[B] N—no ignition.
[C] S—slight combustion, not defined precisely in paper.
[D] P—partial combustion, not defined precisely in paper.
[E] C—complete combustion C-1018 carbon steel specimens, 25-mm diameter by 4.8-mm wall, 76.2 mm total length including threaded section, room temperature, 0.3-m/s downward gas velocity through specimen, upward propagation.

TABLE X1.5 Heat of Combustion of Metals and Alloys

Material (Oxide Formed)	$-\Delta H_c$, cal/g[A]		$-\Delta H_c$, cal/cc[B]	
Beryllium (BeO)	15 865		29 350	
Aluminum (Al₂O₃)	7 425		20 062	
Magnesium (MgO)	5 900		10 266	
Titanium (TiO₂)	4 710		21 195	
Chromium (Cr₂O₃)	2 600		18 720	
Ferritic and martensitic stainless steels	1 900	−2 000	14 726	−15 500
Austenitic stainless steels	1 850	−1 900	14 850	−15 251
Precipitation hardening stainless steels	1 850	−1 950	14 390	−15 167
Carbon steels	1 765	−1 800	13 872	−14 147
Iron (Fe₂O₃)	1 765		13 872	
Manganese	1 673	[C]	12 200	
Molybdenum	1 458	[C]	14 900	
Inconel 600	1 300		10 960	
Aluminum bronzes	1 100	−1 400	8 250	−10 500
Zinc (ZnO)	1 270		9 068	
Tin (SnO₂)	1 170		7 628	−8 517
Tungsten (WO₃ assumed)	1 093	[D]	21 094	
Cobalt (CoO)[E]	970	[E]	8 633	
Nickel (NiO)	980		8 722	
Monel 400	870		7 682	
Yellow brass, 60 Cu/40 Zn	825		6 914	
Cartridge brass, 70 Cu/30 Zn	790		6 615	
Red brass, 85 Cu/15 Zn	690		5 966	
Bronze, 10 Sn/2 Zn	655		5 751	
Copper (CuO)	585		5 218	
Cadmium (CdO)	541	[D]	4 679	
Lead (PbO)	250		2 837	
Palladium (PdO)	192	[D]	2 308	
Platinum (PtO₂)	164	[D,E]	3 520	
Silver (Ag₂O)	35		368	
Gold	1	.9[C]	37	

[A] 1 cal/g = 4.186 kJ/kg. Except as noted, from Lowrie **(40)**.
[B] Calculated from $-\Delta H_c$·density. 1 cal/cc = 4.186 J/cc.
[C] From Hust and Clark **(45)**.
[D] Heat of formation from Weast **(46)** and converted to cal/g.
[E] From Grosse and Conway **(1)**.

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TABLE X1.6 Calculated Melting-Point Burn Ratios[A]

Material	$(BR)_{mp}$
Silver	0.40
Copper	2.00
90:10 copper-nickel[B]	2.39
CDA 938 tin bronze[B]	2.83
CDA 314 leaded commercial bronze[B]	2.57
Monel 400[B]	3.02
Cobalt	3.50
Monel K500[B]	3.64
Nickel	3.70
CDA 828 beryllium copper[B]	4.49
AISI 4140 low alloy steel[B]	5.10
Ductile iron	5.10
Cast iron	5.10
AISI 1025 carbon steel[B]	5.10
Iron	5.10
17-4 PH[B]	5.32
410 SS[B]	5.39
CA 15 stainless steel[B] (see A296)	5.39
304 stainless steel[B]	5.39
Titanium	13.1
Lead	18.6
Zinc	19.3
Lead babbit[B]	20.6
Magnesium	22.4
Aluminum	29.0
Tin babbit[B]	42.6
Tin	44.8

[A] From Monroe et al. (42, 43).
[B] Presented for comparison only. Alloys may exhibit flammability vastly inconsistent with the BR_{mp} ranking.

TABLE X1.7 Calculated Boiling Point Burn Ratios[A]

Material	$(BR)_{bp}$
Tin babbit[B]	0.78
Tin	0.8
Lead	0.9
Lead babbit[B]	1.0
Titanium	1.7
Aluminum	2.2
Zinc	2.4
Magnesium	3.6
Nonmetals[C]	
Ethylene glycol	~17
Methyl alcohol	~18
Acetone	~54
Toluene	~79
Ethyl ether	~99

[A] Metals data from Monroe et al. (42, 43).
[B] Presented for comparison only. Alloys may exhibit flammability vastly inconsistent with the $(BR)_{bp}$ ranking.
[C] Calculated.

TABLE X1.8 Ranking of Metals and Selected Gases by Adiabatic Flame Temperature (1-atm Gaseous Oxygen)

Metals in 1-atm Gaseous Oxygen[A]	Temperature, K
Hf	4800
Zr	4800
Th	4700
Be	4300
Al	3800
Ca	3800
Sr	3500
Mn	3400
Mg	3350
Cr	3300
Ti	3300
Mo	3000
Fe	3000
Ba	3000
B	2900
Sn	2700
Li	2600
Zn	2200
Na	2000
Bi	2000
Pb	1800
K	1700
Ca	1700
Gases[B]	
21 % NH_3 in air	1973
10 % CH_4 in air	2148
9 % C_2H_2 in air	2598
78 % H_2 in O_2	2933
70 % CO in O_2	3198
44 % C_2H_2 in O_2	3410

[A] From Grosse and Conway (1).
[B] From Lewis and Von Elbe (44).

TABLE X1.9 Composition of Alloys

Metal/Alloy	UNS Number	Chemical Composition (by Weight Percent)																						
		Al	B	Be	C	Cb+Ta	Co	Cr	Cu	Fe	Mg	Mn	Mo	Ni	P	Pb	S	Sb	Si	Sn	Ti	W	Zn	Other
Tin bronze	C90700	0.005	...	...	...	...	...	...	88–90	0.15	...	...	...	0.50	0.30	0.50[A]	0.05	0.20	0.005	10–12	...	...	0.50	...
Stellite 68	R30006	...	...	...	1.26	...	59.02	30.30	...	0.97	...	0.11	0.03	2.09	...	...	...	...	1.19	...	...	4.53	...	0.50
Nitronic 60	S21800	...	...	...	0.75	...	...	16.60	0.42	60.85	...	8.33	0.21	8.27	0.37	...	0.0014	...	4.05	...	...	...	...	0.15
Ductile cast iron	F33100	...	...	...	3.57	...	...	0.005	...	91.59	0.052	0.38	...	1.23	0.028	...	0.010	...	3.14	...	...	...	...	...
Beryllium copper	C17200	0.03	...	1.84	...	...	0.22	...	97.637	0.11	...	...	...	0.04	...	0.003	...	...	0.10	0.005	...	...	0.01	...
Yellow brass	C36000	...	...	...	...	...	...	...	61.79	0.10	...	...	...	...	...	3.10	...	...	...	...	...	...	35.01	...
410 stainless steel	A41000	...	...	...	0.14	...	...	13.3	...	85.21	...	0.67	...	0.38	0.03	...	0.014	...	0.26	...	...	...	...	...
Inconel 625	N06625	0.24	...	...	0.02	3.51	...	22.12	...	4.31	...	0.09	8.64	60.65	0.006	...	0.001	...	0.14	...	...	...	...	...
AISI 4140	G41400	...	...	...	0.40	...	...	1.0	0.08	97.019	...	0.89	0.22	0.15	0.006	...	0.015	...	0.22	...	0.27	...	...	...
Monel 400 (cast)	N04400	0.06	...	...	0.18	...	...	...	30.79	1.78	...	1.02	...	65.92	...	...	0.003	...	0.24	...	...	...	...	...
Aluminum bronze	C64200	7.0	...	...	...	...	...	...	91.2	...	...	...	...	...	...	...	...	...	1.8	...	...	...	...	...
C355 aluminum	A03550	92.96	...	...	...	...	...	...	1.2	0.06	0.59	...	...	...	...	...	...	...	5.0	...	0.12	...	0.02	0.361
17-4 PH (H 1150 M)	S17400	...	...	...	0.036	...	...	15.43	3.740	...	...	0.43	0.230	4.28	0.020	<0.001	0.024	...	0.330	...	...	...	...	...
Red brass	C23000	...	...	...	...	...	...	...	84.81	0.013	...	0.64	...	...	...	0.007	...	...	0.18	...	0.45	...	15.17	...
Incoloy 800	N08800	0.50	2.12	...	0.07	...	...	20.20	0.44	45.30	...	...	...	32.22	...	...	0.001	...	3.32	...	...	...	...	...
Colmonoy Alloy No. 70	N/A	...	...	...	0.66	...	0.04	11.43	...	3.71	...	...	...	65.76	...	...	0.001	...	0.14	...	...	15.08	...	...
Monel K-500 (wrought)	N05500	2.92	...	...	0.16	...	...	...	30.29	0.60	...	0.70	...	64.69	...	...	0.001	...	0.14	...	0.50	...	...	...
9 % nickel steel	K81340	...	...	...	0.06	...	...	0.13	...	90.026	...	0.61	...	9.06	0.003	...	...	...	0.24	...	...	...	...	...
6061 aluminum	A96061	97.643	...	...	0.04	...	...	...	0.17	0.41	0.91	...	...	...	...	...	...	...	0.60	...	...	...	0.069	0.028
304 stainless steel	S30430	...	...	...	0.021	...	0.08	18.50	0.38	69.206	...	1.44	0.24	9.36	0.027	...	0.026	...	0.70	...	0.02	...	...	...
Gray cast iron	F10006	...	...	...	3.32	...	...	...	...	93.783	...	0.90	...	...	...	...	0.097	...	1.90	...	...	...	...	...
Inconel 600	N06600	...	...	...	0.07	...	...	15.05	0.36	9.42	...	0.38	...	74.63	...	...	0.004	...	0.09	...	...	...	...	...
SAE 11 babbitt	N/A	...	...	...	...	...	...	...	5.7	...	...	...	...	...	...	0.17	...	6.67	...	86.46	...	...	...	...
Bronze	C93800	0.005	...	...	...	...	...	...	75–79	0.15	...	...	...	1.0	0.5	13–16	0.08	0.80	0.005	7.5	...	...	0.8	...
14-5 PH stainless steel	S45000	...	...	...	0.024	...	...	14.03	1.44	76.788	...	0.44	1.32	5.35	0.016	...	0.002	...	0.29	...	...	...	...	0.015
13-4 stainless steel	J91540	...	...	...	0.062	...	...	12.23	...	82.579	...	0.65	0.45	3.50	0.018	...	0.011	...	0.50	...	...	...	...	0.30

[A] Maximum.

X2. ADDITIONAL LITERATURE

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

X2.2 *Promoted Combustion:*

X2.2.1 *Compatibility of Materials With 7500-psi Oxygen* (**47**)—A research program was conducted to develop ignition data on thread lubricants, thread sealants, fluorocarbon plastics and metals. The relative ease of ignition of metals and alloys was determined by promoted ignition methods in oxygen at 7500 psi (52 MPa). Inconel alloy 600, brass, Monel alloy 400, and nickel were found to have the highest resistance to ignition and combustion among the common alloys and metals. Of the metals tested, stainless steel and aluminum are the least satisfactory for use at oxygen pressures of 7500 psig (52 MPa). Although the test results for aluminum are better than those for copper, the authors rank aluminum least satisfactory "because of its violent reaction once it becomes ignited." The test involved heating a specimen of 0.005-in. metal foil and a variable quantity of neoprene promoter to the promoter's ignition temperature, and ranking the metals by the quantity of promoter required to completely combust the metal. Ten metals that were ranked at 7500 psi (52 MPa) are given in Table X2.1.

X2.2.2 *Selection of Metals for Gaseous Oxygen Service* (**48**)—Selection of metals for gaseous oxygen service requires consideration of compatibility test data and the design of the specific component. Of the various oxygen compatibility tests, the promoted ignition test provides one measure of the performance of a metal in gaseous oxygen. Promoted ignition test results for copper alloys, nickel alloys, and iron alloys are reviewed. The use of the extended fire triangle to predict the performance of a component is discussed. Materials are selected for a hypothetical control valve for 1.7-MPa (250-psi) oxygen service by considering compatibility test data and valve design. The authors rank four metals in terms of the percentage loss after ignition in 1.7-MPa oxygen flowing through the specimen:

	% Loss
Monel	1.1
304 stainless steel	3.4 and 3.5
Gray cast iron	5.1 and 8.3
Carbon steel	100 and 100

TABLE X2.1 Compatibility of Materials with 7500-psi Oxygen

	Required Promoter
Gold	only melts
Silver	only melts
Nickel	48–56 mg (est.)
Monel 400	18–19 mg (est.)
Yellow brass (partial combustion only)	11.8–15.2 mg
Inconel 600	13.2 mg
Aluminum	11.0–16.4 mg
Copper	10.5 mg (est.)
Inconel X-750	9.0 mg
Stainless steel	7.1–8.5 mg

TABLE X2.2 Combustibility and Ignitability of Metal Tubing in Stationary and Flowing Oxygen

Copper	D-CuF 25	More
Ferritic chromium steel	G-X 40 Cr Si 22	compatible
Austenitic chromium steel	X 5 Cr Ni 189	↑
Brass	So Ms 58 Al 2	
Brass	G-So Ms 57 F45	
Nickel-aluminum bronze	G-Ni Al Bz F60	
Tin bronze	G-Sn Bz 10	
Gun metal	Rg 10	
Flake graphite iron	GG26	
Spheroidal graphite iron	GGG38	
Aluminum	Al 99	
Aluminum	Al Mg 5	↓
Steel	30 Cr Mo V9	Less
Steel	St 35	compatible

X2.2.3 *Studies on Combustibility and Ignitability of Metal Tubing in Stationary and Flowing Oxygen* (**49**)—Tubes of 4-mm inside diameter by 3.0-mm wall by 500 mm long of 14 different metals were tested by igniting the inner walls using fuse-wire-ignited Perbunan of mass 3.4 g enclosed in 0.5-mm-thick I ST V23 (steel) sheet of mass 12 g. Oxygen pressure of 16 atm was used. Extensive discussion is included on theory and practice of metal use. An overall order of merit for the metals is given in Table X2.2.

X2.2.4 *Promoted Ignition Behavior of Engineering Alloys in High Pressure Oxygen* (**50**)—Promoted ignition involves a scenario in which a substance with low compatibility with oxygen ignited and promotes the ignition of a more oxygen-compatible material. For example, in oxygen systems, hydrocarbon contaminants could result in the promoted ignition of a structural alloy. An investigation of the promoted ignition behavior of several engineering alloys was made in oxygen at pressure up to 38.6 MPa (5600 psig) (see Table X2.3). Aluminum, carbon steel, cuprous, nickel, and stainless steel alloys were investigated. The effects of different promoters were observed. Alloy composition, oxygen pressure, and promoter type were found to be significant variables in the

TABLE X2.3 Burn Rates of Various Alloys in High Pressure Oxygen

Alloy	Test Pressure		Burn Rate,
	MPa	psig	cm/s
Carbon steel	20.8	3020	1.21
Carbon steel	10.8	1584	0.94
430 stainless steel	34.1	4950	1.24
430 stainless steel	8.3	1200	0.71
304 stainless steel	35.2	5100	1.24
304 stainless steel	20.8	3020	1.08
304 stainless steel	7.6	1100	0.88
316 stainless steel	35.1	5090	1.24
316 stainless steel	21.7	3150	1.08
Aluminum bronze, 11 % Al	35.3	5120	4.2
Aluminum bronze, 11 % Al	38.3	5550	2.0
Inconel 718	35.5	5150	1.37
Incoloy 825	35.9	5200	1.34
1100 aluminum[A]	7.6	1100	5.10

[A] Aluminum alloy 1100 exhibited the highest burn rate of the alloys tested even though the maximum test pressure was only 20 % of the highest oxygen pressures tested.

promoted ignition tests. The following table reports the measured upwards burn rates of 8 alloys for ⅛-in. diameter rod samples. Aluminum has the highest rate and is surprisingly followed by aluminum bronze. Inconel 718, Incoloy 825, stainless steel, and carbon steel burn at a nominal rate of 1 cm/s.

X2.2.5 *Material Compatibility and Systems Considerations in Thermal EOR Environments Containing High Pressure* (**51**)—This paper considers the application of carbon steel and other alloys in hostile corrosion environments and high pressure gaseous oxygen. Testing of ⅛-in. diameter metal samples in the promoted metals ignition tester using oil as the promoter showed that carbon steel is consumed at pressures of 700 psi and higher. Other alloys showed no ignition at 5000-psi oxygen: these included 304SS, Monel 400, Inconel 600 and 625, Hastelloy C-276, Incoloy 825, 90/10 Cupronickel, and aluminum bronze. With an oil plus iron wire promoter, testing allows the ranking of the alloys in the following manner:

Best:	Monel 400, Inconel 600, 90-10 Cupronickel
Intermediate:	Inconel 625, Hastelloy C-276, Incoloy 825
Worst:	Stainless Steels and Aluminum Bronze (10 %)

X2.2.5.1 For carbon steel, Fig. X2.1 is shown comparing sample upwards burn rate at 1500 and 3000 psig, gas pressure with oxygen concentration above 50 %.

X2.2.6 *Promoted Ignition-Combustion of Wire Mesh and Simulated Sintered Filter Elements in Oxygen Enriched Atmospheres* (**52**)—The minimum oxygen pressure required to support self-sustained combustion was used as a ranking criterion in this study. Tables X2.4 and X2.5 report threshold pressures for wire mesh and simulated sintered filter element configurations. The importance of specimen configuration and alloy composition on promoted combustion is a key observation in these studies.

X2.2.7 *Promoted Ignition-Combustion Transition Curves* (**53**)—Promoted ignition-combustion tests were conducted us-
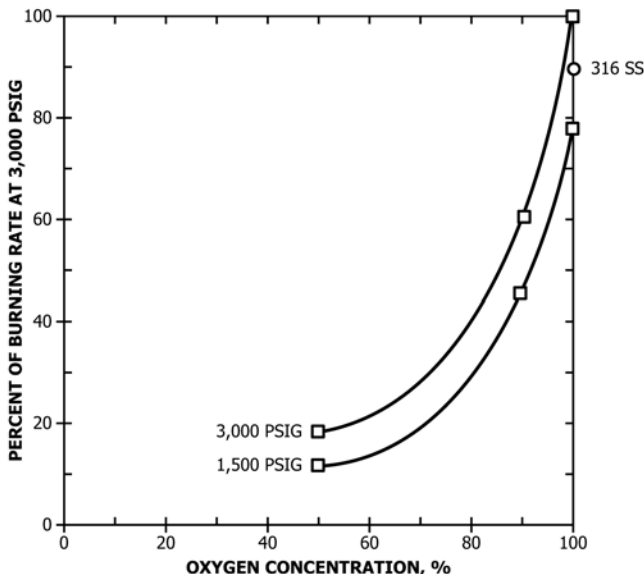
TABLE X2.4 Threshold Pressure in Oxygen of 60 by 60 Wire Meshes Rolled into 0.64-mm (0.25-in.) Diameter Cylinders Ignited at the Bottom

Material	Threshold Pressure	
	MPa	psia
Nickel 200	>69[A]	>10 000[A]
Copper 100	≤0.3[B]	≤47[B]
Monel 400	≤0.085	≤12.4
316 SS	≤0.085	≤12.4
304 SS	≤0.085	≤12.4
Carbon Steel	≤0.085	≤12.4

[A] WSTF unpublished data.
[B] Copper 100 burned at this pressure, but there is not sufficient data to determine where Copper 100 is not flammable.

TABLE X2.5 Threshold Pressures for Metals Configured Similarly to Sintered Filter Elements

Material	Threshold Pressure	
	MPa	psia
Monel 400	0.69	100
316L SS	0.082	12.4
Tin-Bronze 10P	>68.9	>10 000
Tin-Bronze 90P	>68.9	>10 000
Tin-Bronze 250P	>68.9	>10 000
Tin-Bronze 153A	37.9	5500
Tin-Bronze 103A	68.9	10 000
Tin-Bronze 61A	>68.9	>10 000
Tin-Bronze 68HP	>68.9	>10 000
Tin-Bronze 23HP	>68.9	>10 000

ing 3.2 mm (0.125 in.) rods of Hastelloy C-22, C-276, G-3 and G-30 in oxygen-enriched atmospheres with purities ranging from 40 to 99.7 % at pressures up to 34.6 MPa (5000 psig). The test data confirmed a strong purity effect on combustion behavior. It also confirmed that alloy modifications to enhance properties such as corrosion may adversely affect combustion behavior. The C series had better combustion resistance than the G series alloys. Of considerable note was the discovery of promoted ignition-combustion transition curves (PICT); a schematic of which is shown in Fig. X2.2. On the upper shelf of the PICT curve, ignition is difficult in service and combustion is unlikely. On the lower shelf complete combustion occurs in the test and is likely in service, if ignition occurs. A transition zone exists between the upper and lower shelves.

X2.2.8 *Effects of Mill Forms and Oxygen Purity on Promoted Ignition-Combustion Behavior* (**54**)—The bulk of the promoted ignition-combustion data has been generated with wrought mill forms. Yet many engineering alloys have cast analogs; also, weld filler metals may have different compositions from the metals they join. In this study promoted ignition-combustion tests were conducted on three casting alloys (CW6MC, CW2M, CX2MW), four wrought alloys (Inconel 601, 602CA, Inconel 617, Hastelloy C-4, Hastelloy X) and two weld fillers (Inconel 117, Inconel 82) at pressures up to 34.5 MPa (5000 psi). The threshold pressures for the cited alloys, above which combustion occurred, ranged from 2.17 MPa (300 psig) to 17.3 MPa (2,500 psig) indicating a need to characterize individual alloys and mill forms. For the Hastelloy X tests oxygen purity was varied from 70-99.7+ %; see Fig. X2.3 which demonstrates the importance of purity. Promoted

FIG. X2.1 Carbon Steel Burning Rate versus Oxygen Concentration
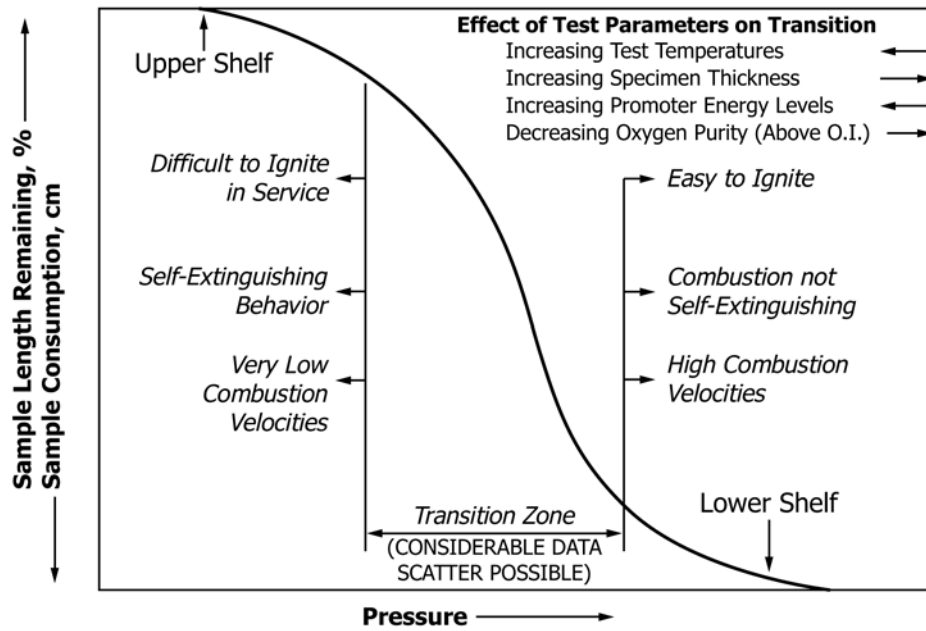
Curve shows three distinct zones: Upper Shelf, Transition Zone and Lower Shelf

FIG. X2.2 Schematic of the Promoted Ignition-Combustion Transition (PICT)
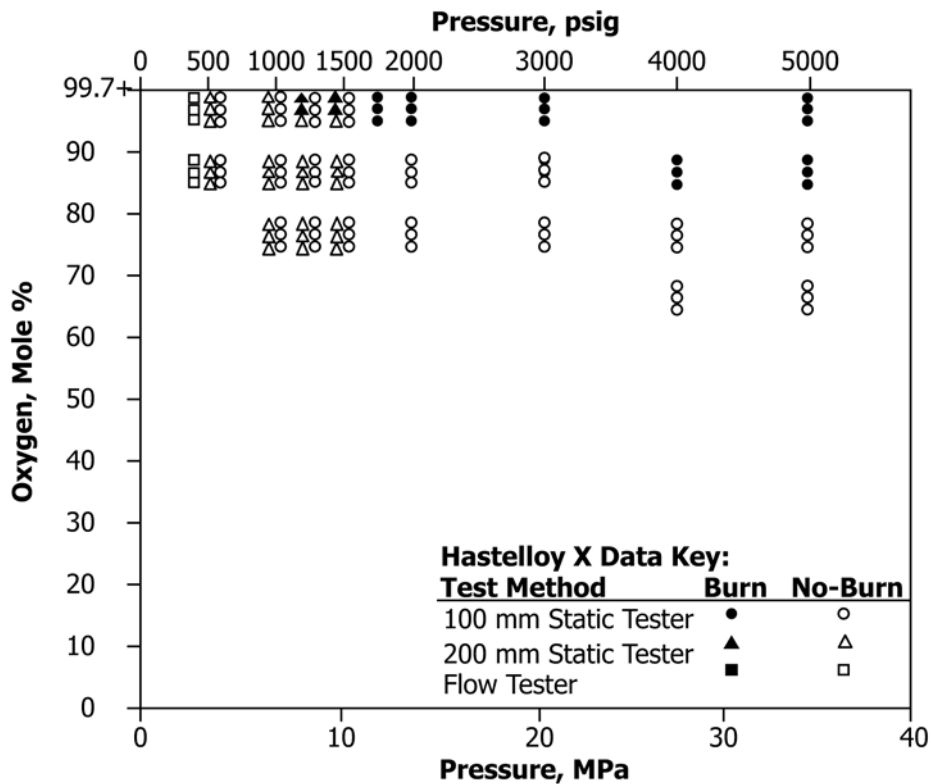

FIG. X2.3 Flammability Data for 3.175 mm (0.125 in.) Diameter Rods of Hastelloy X in Oxygen-Nitrogen Gas Mixtures as a Function of Oxygen Purity and Pressure

ignition-transition behavior was evident in the studies. See Fig. X2.4 which shows Hastelloy X data.

X2.2.9 *Promoted Ignition-Behavior of Stainless Steel in Flowing and Nonflowing Oxygen* (**55**)—The promoted ignition

and burning behavior of 316, 316L and CF8M stainless steels was studied in various thicknesses under flowing and nonflowing conditions at pressures up to 1500 psia. Anomalous results
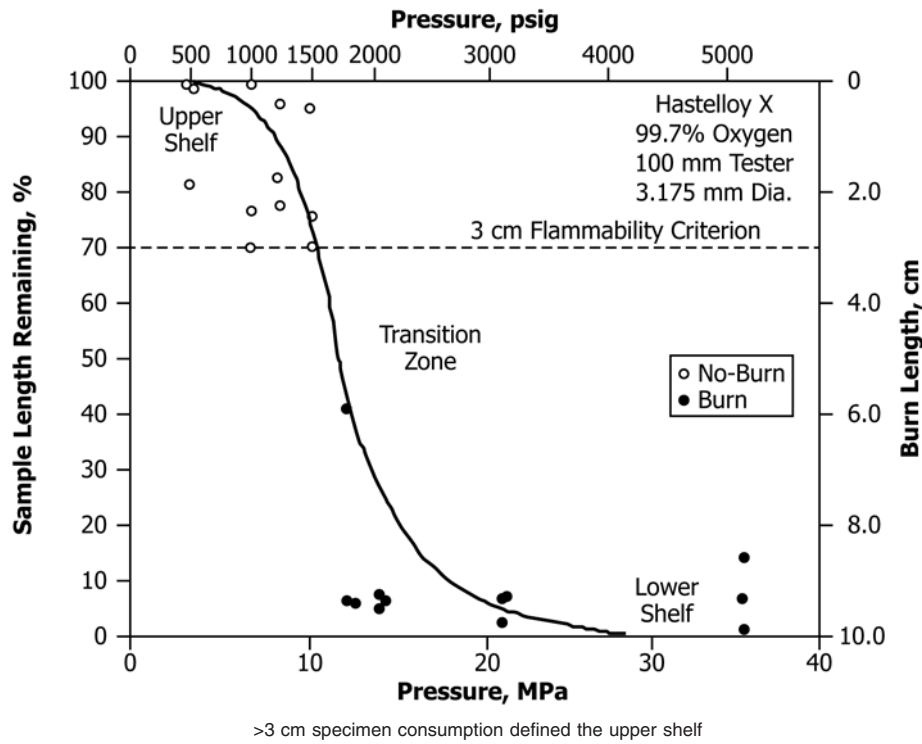
FIG. X2.4 Promoted Ignition-Combustion Transition (PICT) for Hastelloy X

were observed. *The major conclusion is that the CGA velocity curve may not be conservative for stainless steel.* Further work planned.

X2.2.10 *Promoted Combustion Behavior of Pure Metals in Oxygen- Enriched Atmosperes* (**56**)—The promoted combustion test data of 29 pure metals in air (ambient) and aviation grade oxygen at pressures up to 69 MPa (10 000 psia) is tabulated in Table X2.6. Rod specimens of 3.2 mm (0.13 in.) were evaluated per the procedure described in Test Method G124. Nickel, cobalt, copper, platinum, gold and silver had threshold pressures in excess of 69 MPa (10 000 psia). Low threshold pressures were exhibited with light metals such as aluminum and titanium as well as the refractory metals.

X2.2.11 *Promoted Ignition-Combustion Behavior of Engineering Alloys and Elevated Temperatures in Oxygen Gas Mixtures* (**57**)—Promoted ignition-combustion test data at elevated temperatures are scarce. A test data summary of the reported results using a heated flowing oxygen apparatus, 3.2 mm diameter by 10 mm long rods, carbon steel promoter, 3 cm burn criterion, and oxygen gas mixtures ranging from 50.3 to 84.8 % appear as Table X2.7. The results of promoted ignition-combustion tests conducted in an induction heater test apparatus at NASA-WSTF are shown in Table X2.8.

X2.3 *Frictional Heating:*

X2.3.1 *Friction-Induced Ignition in Oxygen* (**58**)—The friction-induced ignition of structural materials in oxygen has been investigated. A test arrangement has been designed that allows basic data for the oxidation reaction rate to be determined for various materials or pairs of materials. The rate at

which oxidation energy is released at the rubbing interface is obtained from the difference in measured friction power necessary to produce the same interface temperatures in tests with oxygen and an inert gas. These results are then correlated by the Arrhenius rate law, allowing the oxidation reaction rate factors for the different materials to be determined. The theoretical simulation of the ignition process for the test arrangement using these data is in good agreement with the observed experimental results. This suggests that the geometry, ambient temperature, and gas velocity, that have a primary effect on heat dissipation are adequately taken into account by the theoretical model. In addition to the collection of these basic data, the test allows materials to be classified for oxygen compatibility under friction simply by means of comparing the axial load necessary for ignition. Of the pairs of materials tested, Monel was found to give the highest ranking, followed by stainless steel/cast iron and bronze. The propagation of combustion after ignition was smallest with Monel, followed by bronze, and was largest for stainless steel/cast iron.

X2.4 *Particle Impact*:

X2.4.1 *Investigations on the Safe Flow Velocity to be Admitted for Oxygen in Steel Pipe Lines* (**59**)—Risks of fire due to solid contamination in steel oxygen pipelines was investigated. The velocity of oxygen through an ST40 nominal width 40 trial section of pipe was varied to try and cause ignition. The trial section was either straight or contained a sequence of four right-angle elbows. Pressures were in the range 27 to 29 atm, and the gas stream entrained 1 to 2 kg of solid materials in the form of sand, rust, flue dust, mill cinder,

TABLE X2.6 Threshold Pressures of Elements per Test Method G124

Element	Threshold Pressure		Next Lower Pressure Tested	
	MPa	psia[A]	MPa	psia[A]
Li	≤ Ambient Air[B]		None	None
Be	4.1	600	3.4	500
C (as graphite)	0.34	50	0.17	25
Mg	≤ 0.007	≤ 1	None	None
Al	≤ 0.17	25	None	None
Si	27.6	4000	20.7	3000
Ti	≤ 0.007	≤ 1	None	None
V	1.4	200	0.7	100
Cr	4.1	600	3.4	500
Fe	0.5	≤ 70	None	None
Co	> 69[C]	> 10000[C]	None	None
Ni	> 69[C]	> 10000[C]	None	None
Cu	> 69[C]	> 10000[C]	None	None
Zn	5.5	800	4.8	700
Sr	≤ Ambient Air[B]		None	None
Zr	≤ 0.06	≤ 8	None	None
Cb	≤ 0.7	≤ 100	None	None
Mo	0.7	100	0.34	50
Ag	> 69	> 10000[C]	None	None
In	0.14	20	0.08[D]	12.3[D]
Sn	1.0	150	None	None
Sb	4.1	600	3.4	500
Yb	0.08[D]	12.3[D]	Ambient Air[D]	
Hf	0.07	10	None	None
Ta	0.14	20	None	None
W	0.34	50	0.07	10
Pt	> 69[C]	> 10000[C]	None	None
Au	> 69[C]	> 10000[C]	None	None
Pb	5.2	750	3.4	500

[A] Pressures above 100 psi are psig rather than psia.
[B] Sample burned completely in ambient air. 85 kPa (12.3 psia) is the atmospheric pressure at NASA JSC White Sands Test Facility.
[C] Sample did not support combustion in at least 3 tests at this pressure. The threshold pressure, if it exists, is greater than this pressure.
[D] These tests were run in 85 kPa (12.3 psia) oxygen.

TABLE X2.7 Elevated Temperature Flammability Tests

Alloy	Temperature, °C	Oxygen Purity, %	Pressure, kPa	Result, Burns/Total Tested
2.5 Cr-0.5 Mo	691	89.8	274	5/5
2.5 Cr-0.5 Mo	691	50.3	274	0/5
316 SS	857	99.995	274	4/5
316 SS	857	50.3	274	0/5
Incoloy 800	482	99.8	1756	0/3
Incoloy 800	482	99.86	3549	1/3
Incoloy 800	482	99.86	6996	3/3
Monel 60	482	99.86	6996	0/5
INCO A	538	99.83	3549	0/5
Inconel 600	482	99.86	3549	0/5
Inconel 600	482	99.86	6996	0/3
Inconel 600	857	99.995	274	0/5

TABLE X2.8 Elevated Temperature Flammability Tests Conducted in Induction Heated Test Apparatus at NASA-WSTF

NOTE 1—The nominal specimen diameter was 0.32 cm and a burn criterion of 3 cm was utilized.

Alloy	Temperature, °C	Oxygen Purity, %	Pressure, kPa	Result, Burns/Total Tested
Inconel 600	1093	99.7	1438	0/5
HR 160	1093	99.7	1567	0/5
Inconel 617	982	99.7	1398	1/5
Inconel 617	982	99.7	241	0/5
Incoloy 800 HT	982	99.7	1426	1/5
Incoloy 800 HT	982	99.7	245	0/5

welding cinder, coke, steinkohl (a bituminous coal), or a mixture of 20 % iron powder and 80 % sand. The noncombustible solids of rust, fluedust, and sand did not produce steel fires nor were glowing particles observed at the outlet. Mill cinder produced glowing particles at 28 m/s and pipe ignition at 52 m/s. Welding cinder produced glowing particles at the vent at 44 m/s in the straight pipe and at 17 m/s in the circuitous pipe, but pipe fires did not occur even at 53 m/s. Coke, steinkohl, and iron powder produced pipe fires. Glowing particles of coke emerged from the straight pipe at 30 m/s, from the circuitous pipe at 17 m/s, and a pipe fire occurred at 53 m/s. Stone coal ignited in the straight and circuitous pipe at 13 m/s, and pipe fire resulted at 34 m/s. The iron powder mixture exhibited sparks at 13 m/s, and pipe fires resulted at 28 m/s. Most pipe fires occurred immediately downstream of elbows.

X2.4.2 *Expansion of Low Velocity Particle Impact Data To Higher Pressures* (**60**)—The traditional CGA curve was limited to a pressure of 6.9 MPa (1,000 psig). In this study the particle impact database was extended to 34 MPa (5000 psig) for carbon steel. Limited data were also obtained with austenitic stainless steels as well as Incoloy 825. See Fig. X2.5 for a data summary of this work.

X2.4.3 *Ignitability of Engineering Alloys in Supersonic Particle Impact Tests* (**53**)—The particle impact tests were conducted on 23 alloys from the aluminum, ferrous, copper and nickel families using aluminum particles, oxygen pressures ranging from 3.6 to 4.0 MPa (520 to 580 psig) and target temperatures from subambient up to 371°C (200°F). Test data is shown in Table X2.9 K-Monel and Haynes 214 were the most ignition resistant in the tests; closely followed by other nickel and copper alloys. Stainless steels and 6061 aluminum were easily ignitable by particle impact.
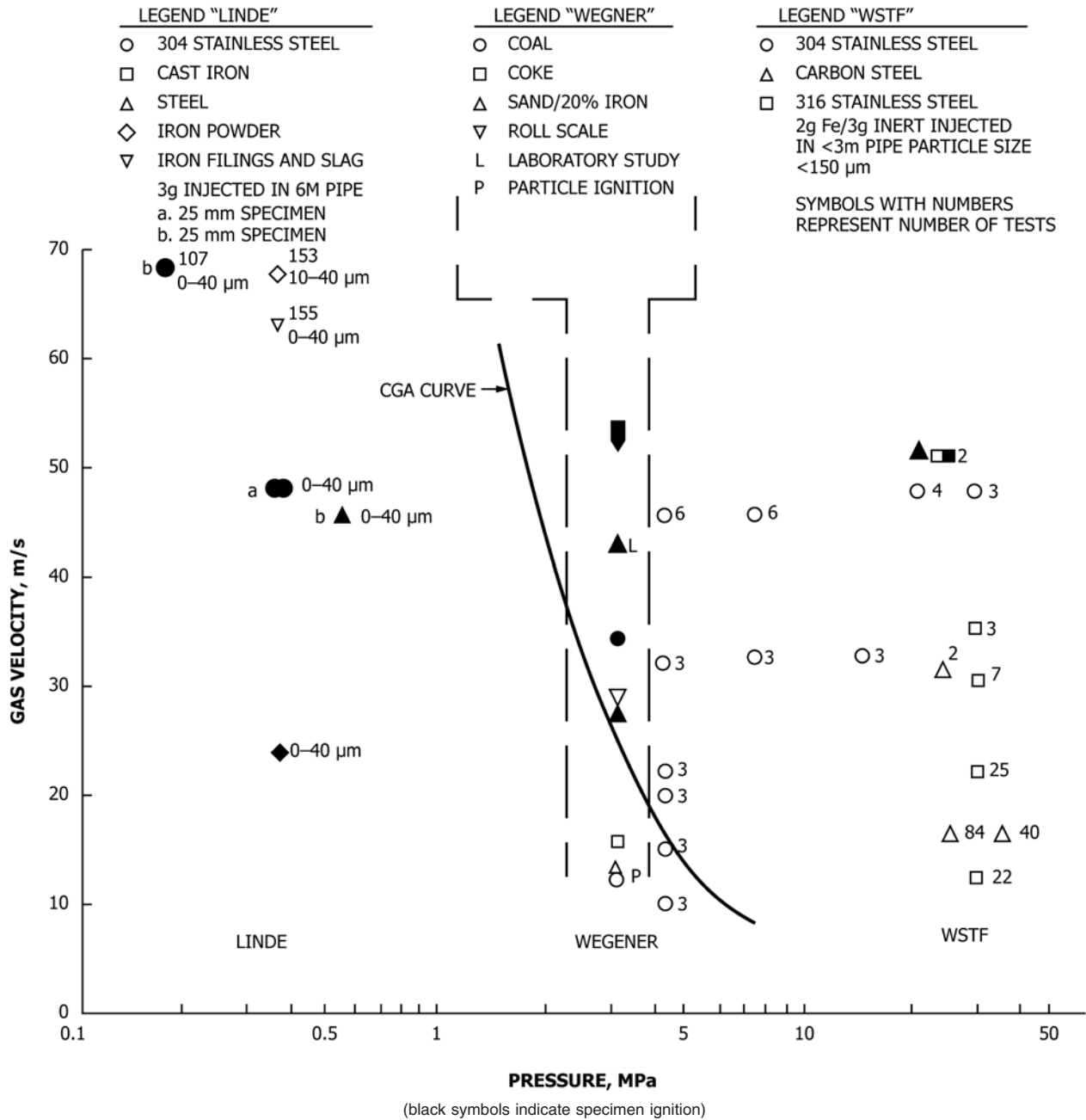
FIG. X2.5 Oxygen Velocity Limit Comparison

X2.5 *Mechanical Impact*:

X2.5.1 *Fire Tests on Centrifugal Pumps for Liquid Oxygen* (**61**)—As part of a project to test liquid oxygen pumps, drop hammer (mechanical impact) tests of several metals tested as 1 to 2 g of loose metal chips or chips pressed into pills are reported. The drop weight was 25 kg (245 N) at drop heights up to 3 m. The results are given in Table X2.10.

X2.6 *Effects of Pressure, Temperature and Fresh Metal Exposure on the Ignition and Burn Behavior of Engineering Alloys* (**62**)—The experimental program gen-

erated burn curves in oxygen over the pressure range of approximately 250 psig to 1000 psig at metal temperatures ranging from approximately 250°F to over 1000°F. Tensile fracture was used to ignite the specimens which were electrically heated. Alloys tested included: carbon steel, low alloy steel, ductile iron, 304 Stainless Steel, 410 Stainless Steel, CA15 cast Stainless Steel, Bronzes, Beryllium-Nickel, K and Monel 400, Hastelloy X, Babbitt, Aluminum, Silver and Inconel 718. The nickel and copper based alloys were the best performers; Inconel 718 was considerably less combustion resistant than the other nickel alloys.

TABLE X2.9 Ignitability of Metals in Supersonic Particle Impact Tests with 2000-µm (0.0787-in.) Aluminum Particles

Note 1—Absolute pressure at the target varied from approximately 3.6 to 4.0 MPa (520 to 580 psia).

Note 2—Temperatures given in table refer to temperature of test target prior to particle impact.

Engineering Alloy	Highest Temperature without Ignition[A] of Target[B]		Lowest Temperature with Ignition[A] of Target[C]	
	°C	°F	°C	°F
Monel K500 (heat treated)	371[D]	700[D]	...	...
Monel K500 (annealed)	371[D]	700[D]	...	...
Haynes 214	371[D]	700[D]	...	...
Monel 400	343[D]	650[D]	...	...
Incoloy MA 754	343[D]	650[D]	...	...
Yellow Brass	316[D]	600[D]	...	...
Inconel 600	316[D]	600[D]	...	...
Tin Bronze	288[D]	550[D]	...	...
Al Bronze	260	500	316	600
Inconel 625	260	500	316	600
440C SS (annealed)	177	350	204	400
Inconel 718 (annealed)	149	300	204	400
Ductile Cast Iron	149	300	204	400
Incoloy 800	121	250	204	400
Incoloy 903	93	200	121	250
Haynes 230	38d	100d	...	...
Nitronic 60	-18	0	121	250
316 SS	10	50	38	100
304 SS	-18	0	38	100
Incoloy MA 956	-46	-50	10	50
13-4 SS	none	none	10	50
14-5 PH SS	none	none	10	50
6061 Aluminum	none	none	-46	-50

[A] Ignition is defined as an event that produces a visually observed fire with obvious consumption of the target.
[B] Indicates that at least nine tests were performed between this temperature and the lowest temperature with ignition of target.
[C] Indicates that there was at least one ignition of the target at this temperature
[D] Indicates that the material did not ignite at the highest temperature at which it was tested.

TABLE X2.10 Impact Tests on Liquid Oxygen Pumps[A]

	Impact Energy, J	
	No Reaction	Reaction
Anticorodal 70 (92 Al, 7 Si, 0.4 Mg, 0.12 Ti)	190	250 (pill)
	60	130 (chips)
Silifont 5 (89 Al, 9.5 Si, 0.5 Co, 0.5 Fe, 0.3 Mg)	380	500 (pill)
	380	500 (chips)
Solder (45 tin, 55 lead)	250	380 (pill)
	60	130 (chips)

[A] The authors note the following metals failed to react to impact energies up to the maximum available of 735 J: stainless steel (4 300) X12 CrNi 8.8 [18.0 Cr, 8.5 Ni]; stainless steel (4 312) GX 15 CrNi 18.8 [18.0 Cr, 8 Ni]; nickel steel (5 662) X8 Ni9 [8.0–10.0 Ni]; bronze GBz14 [86 Cu, 14 Sn, 1.0 Pb]; copper; and hard solder (40 % Ag).

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