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ASRDI OXYGEN TECHNOLOGY SURVEY

Volume IX:

Oxygen Systems Engineering Review

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PREFACE

This compendium is one of a series of publications on oxygen by the NASA Aerospace Safety Research and Data Institute. It is the result of an oxygen system engineering and technology review which was conducted to identify the special considerations for achieving safe and reliable oxygen systems. The document identifies the major problems affecting the reliability of oxygen systems, and it summarizes the basic oxygen technology applicable for the design, fabrication, and use of oxygen systems. Included is a compilation of data that helps to define the limiting conditions of use that oxygen "compatible" materials may be expected to withstand when used in oxygen systems.

The purpose of this volume is to show how oxygen systems may be designed and used safely and reliably by applying known engineering principles and past engineering experience.

Solomon Weiss, Acting Director
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FOREWORD

The design and operation of oxygen systems has been relatively routine, but the occasional accidents that have occurred during the handling and use of liquid and gaseous oxygen indicate a need for a better understanding of the reactivity of oxygen at temperatures and pressures beyond the familiar experience.

Technically, how to handle and use oxygen is primarily a matter of understanding the circumstances that cause oxygen to become reactive with its surroundings. Liquid and gaseous oxygen in contact with or mixed with most materials will not react or ignite without an ignition source. Therefore, problems are usually not experienced when designing for and operating oxygen systems at nominal pressures and temperatures. With higher oxygen system pressures and the resulting flow velocities, the severity of the oxygen environment is increased, the resulting sensitivity to ignition sources is increased, and the compatibility of materials with oxygen is decreased. The effect is a reduction in the number of candidate materials that can be used in such systems.

The environmental limits of time, temperature, pressure, flow rate, contamination, and other physical and chemical stresses that materials can be exposed to and withstand in oxidizer systems need to be defined and known for each application. This is necessary, too, for planning the research and development for extending the state-of-the-art in oxygen utilization. If compatibility data as functions of environmental conditions are provided, the state-of-the-art can be advanced with less risk of unknown factors, and engineering groups without high pressure oxygen experience will avoid the problems inherent in these systems.

Harold W. Schmidt

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CHAPTER 1. INTRODUCTION

The commercial availability and widespread use of oxygen by the general public, industry, NASA, and other federal agencies have made the handling of oxygen commonplace and routine. However, it has been stated that, in general, oxygen is so easy to handle that it can be dangerous. When an incident occurs with oxygen it can be catastrophic in nature, and the vigorous burning of a part of the system, or an explosion, can occur. Because they are rare, these occurrences are always unexpected. Oxygen system failures are most often associated with a change from a steady-state condition. They are also associated with contamination that is sensitive to ignition with oxygen.

Accident prevention in the use of oxygen requires understanding the characteristics of the fluid being handled, recognizing the limits of compatibility of materials with oxygen, and maintaining a clean system. The purpose of this volume is to provide the physical and chemical background information which will be helpful in meeting these requirements. It is the function of the designer to reduce or eliminate the possibility of oxygen system failure by anticipating potential operating problems and selecting appropriate materials, configurations, and controls. Accordingly, the emphasis of this review is on design. However, where they are pertinent, considerations for assembly, maintenance, and operations are an integral part of the review.

The following chapters discuss many of the special considerations that should be taken into account. They also attempt to provide an understanding of the characteristics of gaseous and liquid oxygen and how to deal with them under various circumstances. Understanding the behavior of oxygen with materials under use conditions reduces the possibility of system failures. Also reduced are the potential hazards and their resulting costs and time losses.

The subject is covered in four parts: (1) oxygen characteristics, purity, and specifications (ch. 2), (2) compatibility of materials with oxygen (ch. 3), (3) fluid flow phenomena and fluid system characteristics of special concern in oxygen systems (ch. 4), and (4) engineering review of oxygen systems and components (chs. 5 to 10). The first two parts provide an insight into the nature of oxygen - its characteristic behavior with other materials and how this behavior varies with operating conditions. The last two parts deal primarily with the application of oxygen technology to fluid systems and their components.

Special effort has been made to compile and correlate data on ignition energies and burning rates of materials in various oxygen environments. Although the data came from many sources using different techniques, good correlation was obtained on the effect of oxygen pressure (and partial pressure) on burning rates and ignition temperatures.

Operating pressure ranges as they are used in this document are defined as follows:

Low pressure	0 to 500 psia
Medium pressure	500 to 2000 psia
High pressure	2000 to 7500 psia
Very high pressure	7500 to 10 000 psia
Ultra-high pressure	10 000 to 15 000+ psia

While the general design considerations for oxygen systems for both flight and ground-based hardware are essentially the same, the problems encountered in flight hardware design are often more severe. This is true because of the weight limitations and lower structural margins of safety for flight hardware and the more critical nature of the flight environment. For this reason the two classes of hardware are usually treated separately in this review.

A microfiche supplement covering the pertinent pages of the references listed is attached to the back cover for the convenience of the reader. (Commonly available handbooks and copyrighted text books are not included.) An index to the microfiche supplement is included as a part of the list of references. Definitions of terms, acronyms, and trade names are included in appendix A. Also, since the units used throughout the volume are generally those of the references, conversion factors are included as appendix B.

CHAPTER 2. CHARACTERISTICS OF OXYGEN

Oxygen occurs naturally as one of the elements and is one of the five strongest elemental oxidizers along with fluorine, chlorine, bromine, and iodine (the halogens). Under most circumstances oxygen reacts very slowly or not at all. But under other circumstances it becomes highly reactive and will react with fuels at high energy release rates. It is this reactivity which is the primary reason for special concern when designing hardware to be used in oxygen service. Under certain conditions the elemental oxidizers oxygen and fluorine and the fluorine-oxygen mixtures (FLOX) have the same characteristics and behave in the same manner:

(1) They form oxidation films on metals that inhibit further reaction.

(2) They ignite spontaneously with fuels at their respective ignition temperatures.

(3) They burn metals and most nonmetals vigorously when ignited.

Oxygen reacts with nearly all materials that are not already fully oxidized. However, oxygen is more able to mix and form explosive mixtures with gases, liquids, and solids than with either FLOX or fluorine. Fluorine is too reactive (hypergolic) to mix with most materials and instead reacts on contact at whatever rate the reactants are combined. The passive mixing characteristics of oxygen are the basis for its greatest hazard: once the oxygen-fuel mixture is ignited, the reaction may proceed violently, even explosively. The most common hazard exists when gaseous oxygen is mixed with any vaporized fuel, thus forming an easily ignited and frequently explosive mixture. Of nearly equal concern is the absorption of oxygen by porous solids such as clothing which, when ignited, may burn vigorously. Similarly, a liquid oxygen spill may soak a solid fuel material, such as asphalt paving, and form an extremely reactive or explosive mixture. Oxygen in the liquid state is also potentially hazardous due to its extremely low temperature.

Recognition of these basic characteristics of oxygen is necessary to evaluate the safety of any oxygen system and is important in preventing system failure and the resulting hazards, cost, and time loss. The more subtle characteristics, that is, its potential reactivity in fluid systems due to pressure, temperature, and flow effects, are discussed in succeeding sections of this volume.

TABLE 2-I. - FIXED POINT PROPERTIES OF OXYGEN[a]

[Values in parenthesis are estimates.]

(a) Metric units (ref. 1, p. 314); gas constant, R = 62 365.4 cm^3-mm Hg/mole-K; molecular weight, 31.9988, mole = gram mole

Properties		Conditions							
		Triple point			Normal boiling point		Critical point	Standard conditions	
		Solid	Liquid	Vapor	Liquid	Vapor		STP (0° C)	NTP (20° C)
Temperature, K		54.351			90.180[b]		154.576	273.15	293.15
Pressure, mm Hg		1.138			760		37 823	760	760
Density, $(mole/cm^3)\times10^3$		42.46	40.83	0.000336	35.65	0.1399	13.63	0.04466	0.04160
Specific volume, $(cm^3/mole)\times10^{-3}$		0.02355	0.02449	2975	0.028047	7.1501	0.07337	22.392	24.038
Compressibility factor, Z = PV/RT		-------	0.0000082	0.9986	0.00379	0.9662	0.2879	0.9990	0.9992
Heats of fusion and vaporization, J/mole		444.8	7761.4		6812.3		0	-------	-------
Specific heat, J/mole-K	At saturation, C_s	46.07	53.313	-108.7	54.14	-53.2	(Very large)	-------	-------
	At constant pressure, C_r	--------	53.27	29.13	54.28	30.77	(Very large)	29.33	29.40
	At constant volume, C_v	--------	35.65	20.81	29.64	21.28	(38.7)	20.96	21.04
Specific heat ratio, $\gamma = C_p/C_v$		--------	1.494	1.400	1.832	1.446	(Large)	1.40	1.40
Enthalpy, J/mole		-6634.4	-6189.6	1571.8	-4270.3	2542.0	1032.2	7937.8	8525.1
Internal energy, J/mole		-6634.4	-6189.6	1120.0	-4273.1	1817.5	662.3	5668.9	6089.5
Entropy, J/mole-K		58.92	67.11	209.54	94.17	169.68	134.42	202.4	204.5
Velocity of sound, m/sec		--------	1159	141	903	178	164	315	326
Viscosity, μ	$(N\text{-}sec/m^3)\times10^3$	--------	0.6194	0.003914	0.1958	0.00685	(0.031)	0.01924	0.02036
	Centipoise[c]	--------	0.6194	0.003914	0.1958	0.00685	(0.031)	0.01924	0.02036
Thermal conductivity, k, mW/cm-K		--------	1.929	0.04826	1.515	0.08544	(d)	0.2428	0.2575
Prandtl number, $N_{pr} = uC_p/k$		--------	5.344	0.7392	2.193	0.7714	----------	0.7259	0.7265
Dielectric constant, ϵ		(1.614)	1.5687	1.000004	1.4870	1.00166	0.17082	1.00053	1.00049
Index of refraction,[e] $n = \sqrt{\epsilon}$		(1.271)	1.2525	1.000002	1.219	1.00083	1.0820	1.00027	1.00025
Surface tension, $(N/m)\times10^3$		--------	22.65	--------	13.20	-------	0	-------	-------
Equivalent volume/volume liquid at NBT		0.8397	0.8732	106 068	1	254.9	2.616	798.4	857.1

(b) English units (ref. 1, p. 414); gas constant, $R = 0.335385\ ft^3\text{-psi/lb-}^oR$

Properties		Conditions							
		Triple point			Normal boiling point		Critical point	Standard conditions	
		Solid	Liquid	Vapor	Liquid	Vapor		STP (32° F)	NTP (68° F)
Temperature, ^oF		-361.84			-297.35[b]		-181.43	32.0	68.0
Pressure, psia		0.0220			14.696		731.4	14.696	14.696
Density, lb/ft^3		84.82	81.57	0.0006715	71.23	0.2794	27.23	0.0892	0.0831
Specific volume, ft^3/lb		0.01179	0.01226	1489.2	0.01404	3.5793	0.03673	11.21	12.03
Compressibility factor, $Z = PV/RT$		-------	0.0000082	0.9985	0.00379	0.9662	0.2879	0.9990	0.9992
Heats of fusion and vaporization, Btu/lb		5.967	104.348		91.588		0	-------	-------
Specific heat, Btu/lb-^oR	At saturation, C_s	0.345	0.398	-0.812	0.404	-0.397	(Very large)	-------	-------
	At constant pressure, C_p	-------	0.398	0.218	0.405	0.230	(Very large)	0.219	0.220
	At constant volume, C_v	-------	0.266	0.155	0.221	0.159	(0.289)	0.157	0.157
Specific heat ratio, $\gamma = C_p/C_v$		-------	1.496	1.406	1.833	1.447	(Large)	1.40	1.40
Enthalpy, Btu/lb		-89.192	-83.216	21.132	-57.412	34.176	13.88	106.72	114.62
Internal energy, Btu/lb		-89.192	-83.216	15.057	-57.450	24.435	8.90	76.22	81.875
Entropy, Btu/lb-^oR		0.4401	0.50122	1.5651	0.70339	1.2674	1.004	1.5123	1.5278
Velocity of sound, ft/sec		-------	3804	461	2963	583	537	1033	1070
Viscosity, μ	$(lb/sec\text{-}ft)\times10^5$	-------	41.62	0.263	13.16	0.460	(2.1)	1.293	1.368
	Centipoise[c]	-------	0.6194	0.003914	0.1958	0.00685	(0.031)	0.01924	0.02036
Thermal conductivity, k, Btu/hr-ft-^oR		-------	0.11156	0.00279	0.08758	0.00494	(d)	0.01404	0.01489
Prandtl number, $N_{pr} = uC_p/k$		-------	5.3437	0.7392	2.1929	0.7714	----------	0.7259	0.7265
Dielectric constant, ϵ		(1.614)	1.5687	1.000004	1.4870	1.00166	1.17082	1.00053	1.00049
Index of refraction,[e] $n = \sqrt{\epsilon}$		(1.271)	1.2525	1.000002	1.219	1.00083	1.0820	1.00027	1.00025
Surface tension, $(lb/ft)\times10^3$		-------	1.552	---------	0.9046	-------	0	-------	-------
Equivalent volume/volume liquid at NBT		0.8397	0.8732	106 068	1	254.9	2.616	798.4	857.1

[a]For basic data sources the reader is referred in ref. 1.

[b]Based on the NBS-1955 temperature scale using 90.180 K as a fixed point for the normal boiling temperature of oxygen. (The IPTS-1968 temperature scale used 90.188 K as the normal boiling temperature of oxygen but the reported data used in these tables has not yet been converted to the new temperature scale.) $273.15\ K = 0^o\ C = 32^o\ F = 491.67^o\ R$

[c]Units for poise, g/cm-sec.

[d]Anomalously large.

[e]Long wavelengths.

2.1 PROPERTIES OF OXYGEN

Fixed point properties of oxygen are included in table 2-I(a) (Metric Units) and 2-I(b) (U.S. Customary Units). More precise tabular data are presented in reference 1 (pp. 145-420).

2.2 OXYGEN CONTAMINATION

One cause of failure in oxygen systems is contamination. Contamination may be introduced during the manufacture of the oxygen or, subsequently, during the handling or final use. In liquid oxygen, dissolved contaminants are primarily hydrocarbons although other materials such as carbon dioxide (CO_2) are slightly soluble. Solid contaminants in both liquid and gaseous oxygen include particulates such as wear particles or dislodged oxides. In liquid oxygen, moisture and frozen undissolved contaminants, such as CO_2 or acetylene, may accumulate in the system.

Hydrocarbons are present in atmospheric air from which oxygen is generated. These are partially removed during oxygen production. The heavier (high molecular weight) hydrocarbons are removed to insignificant concentrations during initial distillation but light (low molecular weight) hydrocarbons such as methane, acetylene, ethane, ethylene, propane, and butane may remain with the oxygen. These are further decreased by further distillation and subsequently reduced to acceptable levels with silica gel absorbers.

Hydrocarbon contamination may be reintroduced through various means during subsequent handling and transfer. Since most of the common contaminants are less volatile than liquid oxygen they tend to increase in concentration during handling and storage. The normal (atmospheric) boiling points and freezing points of some air contaminants are given in table 2-II (ref. 2).

Whenever a hydrocarbon is present in LOX in quantities greater than its solubility limit it separates out as a liquid or a solid depending on the freezing point. It may also accumulate in the system. Solid hydrocarbons in liquid oxygen could be explosive if subjected to an ignition source such as friction, shock wave, or impact. Severe damage from explosion and fire could result. Subsequent warming of the system can vaporize the liquid oxygen and the contaminant which could result in an explosive mixture. In fact, the low molecular weight hydrocarbons (i.e., methane, ethane, and propane) have a solubility limit which exceeds their respective lower flammability limits when vaporized.

Tables 2-III and 2-IV (refs. 2 and 3) give solubility limits in liquid oxygen (at normal boiling point) and flammability limits in gaseous oxygen for some of the more common contaminants. Solubilities as a function of temperature are given in appendix C while table 2-V (ref. 4) lists the detonability limits of some fuels in gaseous oxygen.

TABLE 2-II. - PROPERTIES OF SOME AIR CONTAMINANTS[a]

Name	Density at -297.3° F, g/cm³	Normal boiling point		Freezing point	
		°F	°C	°F	°C
Helium	-----	-452.0	-268.89	[b]-455.8	-271.11
Hydrogen	-----	-423.0	-252.78	-434.5	-259.11
Neon	-----	-410.6	-245.99	-415.6	-248.57
Nitrogen	-----	-320.4	-195.75	-345.7	-209.75
Carbon monoxide	-----	-310.0	-190.00	-340.6	-206.95
Argon	-----	-302.3	-185.70	-308.7	-189.34
Oxygen	1.15	-297.3	-182.88	-361.1	-218.34
Methane	-----	-258.7	-161.53	-299.2	-183.99
Krypton	-----	-243.2	-152.98	-249.9	-156.57
Nitric oxide	-----	-241.2	-151.87	-262.5	-163.56
Ozone	-----	-169.4	-111.67	-313.8	-192.02
Xenon	-----	-160.8	-107.02	-169.6	-111.94
Ethylene	.727	-155.0	-103.89	-272.9	-169.34
Ethane	-----	-126.9	-88.23	-277.6	-171.97
Nitrous oxide	-----	-127.3	-88.53	-152.3	-102.42
Acetylene	.625	[c]-118.5	-83.51	-115.2	-81.87
Carbon dioxide	1.58	[c]-109.3	-78.53	-69.9 (5.2 atm)	-56.57
Hydrogen sulfide	-----	-79.2	-61.87	-117.2	-82.98
Carbonyl sulfide	1.65	-54.4	-47.98	-216.4	-137.98
Propylene	.775	-52.6	-46.97	-301.4	-185.25
Propane	-----	-43.9	-42.12	-309.8	-189.84
Ammonia	1.01	-28.0	-33.33	-107.9	-77.68
Formaldehyde	-----	-5.8	-20.91	-133.6	-91.97
iso-Butane	-----	10.4	-11.92	-229.0	-145.00
iso-Butylene	-----	21.2	-5.96	-220.5	-140.28
1-Butene	-----	23.0	-5.00	-202.0	-130.00
1,3-Butadiene	-----	26.7	-3.03	-164	-108.89
n-Butane	.770	31.1	-.49	-211.0	-135.00
2-Butene	-----	33.8 (cis)	1.01	-218	-138.89
Ethylene oxide	-----	51.3	10.76	-168.3	-111.31
Acetaldehyde	-----	69.8	21.01	-190.3	-123.53
Nitrogen dioxide	-----	70.3	21.31	15.3	-9.24
n-Pentane	-----	97.2	36.21	-204.7	-131.45
Acetone	-----	133.7	56.47	-139.0	-95.00
Methanol	.815	148.4	64.68	-144.0	-97.78
Hexane	.795	156.2	68.99	-137.7	-94.04
Benzene	-----	176.2	80.16	41.9	5.51
Water	-----	212.0	100.00	32.0	0.00
n-Decane	-----	345.2	173.99	-23.8	-30.91

[a]Ref. 2, p. 48.
[b]Lambda point.
[c]Sublimes.

TABLE 2-III. - SOLUBILITY LIMIT[a] OF HYDROCARBONS IN LIQUID OXYGEN[b]

Solubility at -297.3° F (-183° C).

Gas	Solubility	
	ppm - methane equivalent	ppm - moles
Methane	980 000.0	980 000.0
Ethane	430 000.0	215 000.0
Propane	150 000.0	50 000.0
Ethylene	55 000.0	27 500.0
Propylene	20 100.0	700.0
i-Butane	7 640.0	1 910.0
Butene-1	4 000.0	1 000.0
n-Butane	3 440.0	860.0
i-Butylene	530.0	135.0
n-Pentane	[c]100.0	[c]20.0
Acetylene	10.0	5.0 ([c]1.7)
n-Hexane	[c]12.0	[c]2.0
n-Decane	[c]6.0	[c].6
Acetone	[c]4.5	[c]1.5
Methanol	[c]12.0	[c]12.0
Ethanol	[c]30.0	[c]15.0
Carbon dioxide	[c]4.2	[c]4.2

[a]Solubility limits as function of oxygen temperature are presented graphically in appendix D.
[b]Ref. 2, p. 55.
[c]Ref. 3, p. 113-M.

TABLE 2-IV. - LOWER FLAMMABILITY LIMIT OF HYDROCARBONS SOLUBLE IN LIQUID OXYGEN[a]

Gas	Flammability units	
	ppm - methane equivalent	ppm - moles
Methane	50 000	50 000
Ethane	60 000	30 000
Propane	63 600	21 200
Ethylene	55 000	27 500
Propylene	60 000	20 000
i-Butane	72 000	18 000
Butene-1	64 000	16 000
n-Butane	74 400	18 600
i-Butylene	72 000	18 000
n-Pentane	70 000	14 000
Acetylene	50 000	25 000
n-Hexane	70 800	11 800
n-Decane	77 000	7 700

[a]Refs. 2 (p. 55) and 3 (p. 117-M).

TABLE 2-V. - DETONABILITY LIMITS OF GAS-OXYGEN MIXTURES, DETERMINED USING 400 J HIGH EXPLOSIVE DETONATOR FOR INITIATION[a]

Gas	Lower detonability limit[b] (volume percent gas)	Upper detonability limit[c] (volume percent gas)
Acetaldehyde	12 to 14	46 to 50
Acetylene	6.5 to 7	67 to 69
Carbon disulfide	12 to 13	[d]>46
Cyclopropane	6.5 to 7	38 to 40
Diethyl ether	4.5 to 5	28 to 30
Ethane	10 to 12	38 to 40
Ethylene	9 to 9.5	50 to 52
Ethylene oxide	8 to 9	64 to 66
Ethyl nitrite	4 to 4.5	58 to 62
Methylacetylene	5.5 to 6	48 to 50
Methyl vinyl ether	5 to 5.5	44 to 46
Propadiene	5 to 5.5	48 to 50
Propane	6.5 to 7.5	30 to 32
Propylene	6.5 to 7	36 to 38
Vinyl fluoride	11 to 12	54 to 56

[a]Ref. 4, p. 384.

[b]Detonation was observed at the higher gas concentration but was not observed at the lower gas concentration.

[c]Detonation was observed at the lower gas concentration but was not observed at the higher concentration.

[d]Experiments at higher gas concentration not possible due to vapor pressure limitations.

Note the very low solubility of acetylene in table 2-V. It is less dense than liquid oxygen and can readily accumulate in liquid oxygen systems. Also, acetylene is a highly unsaturated hydrocarbon (with a triple bond) which makes it unstable and highly reactive (shock and heat sensitive) in oxygen to a greater degree than the other hydrocarbons. Therefore, acetylene is highly undesirable as a contaminant and its presence in oxygen is generally limited to 0.05 ppm or less. Because of these characteristics it is generally measured separately from the rest of the hydrocarbons which are measured as a group and reported as an equivalent amount of methane based on carbon atom content.

Solid contaminants, in addition to the fire and explosion hazard, present the added hazards of mechanical malfunction and plugging or the restriction of flow. System fail-

ures due to these hazards can be minimized by controlling the purity of the oxygen and maintaining adequate system cleanliness. Most solid hydrocarbon impurities are lighter than LOX. (See contaminant densities in table 2-II.) They tend to float and accumulate at liquid level surfaces. This may be observed by examining the walls in a LOX storage tank. If impurities have been present, there may be a ring in the tank near the usual liquid level.

In general, the contamination of oxygen will increase as it is handled or stored. As liquid oxygen is lost by vaporization, contaminant concentration increases. Whenever a system is opened for repair or even for transfer line connect and disconnect operations contamination may enter the system. Long term wear and deterioration of mechanical components may contribute to particulates. Even residue from solvents used for cleaning may be a source of added contamination. These are the reasons why it is important to maintain rigid cleanliness practices and provide filters in stategic locations in some oxygen systems. (See chapter 10 on FILTERS.)

It is evident that control of the various sources of contamination mentioned previously is critical to the safe operation of oxygen systems. While specific control procedures are a function of system complexity and product end use, many techniques for such control have evolved. Contamination control procedures and specifications and oxygen quality control tests and test methods are listed in references 2 (appendix 3), 5 (sec. 4), 6, and 7 (secs. 2 and 3). Cleaning procedures and verification techniques are discussed in reference 8.

2.3 OXYGEN PURITY REQUIREMENTS

Oxygen purity-level requirements are dictated by the effect the contaminants have on the end use item. For example, fuel cells are sensitive to some impurities that would be acceptable for life support systems. The requirement for extremely high purity oxygen for fuel cells is necessitated to avoid contamination of the diffusion membranes. Toxic contaminants such as nitrous oxide and the chlorinated hydrocarbons are of concern for breathing oxygen.

The purity requirements for oxygen purchased by NASA for launch vehicle and spacecraft use are contained in MSFC (Marshall Space Flight Center) Specification 399A (ref. 6). Table 2-VI from this specification is a summary of those requirements including permissible specific contaminant levels. Procedures for purity verification are also included in reference 6. Oxygen systems cleanliness requirements and cleaning procedures are discussed in section 4.4.

TABLE 2-VI. - OXYGEN PURITY REQUIREMENTS[a]

[For grade A oxygen - all other impurities including inert gases and nitrogen, 30 ppm.]

Requirement	Grade A for fuel cells	Grade B for breathing	Grade C for propellant
Purity	99.995	99.60	99.60
Methane and ethane	Methane, 10 ppm Ethane, 2.0 ppm	Methane, 25.0 ppm Ethane, 2.0 ppm	No requirement
Propane and higher hydrocarbons	1.0 ppm as propane	1.0 ppm as propane	No requirement
Alkyne and acetylene hydrocarbons	0.05 ppm as acetylene	0.05 ppm as acetylene	0.25 ppm as acetylene
Total hydrocarbons	14.0 ppm as methane	29.0 ppm as methane	50.0 ppm as methane
Moisture	3.0 ppm	3.0 ppm	3.0 ppm
Nitrous oxide	1.0 ppm	1.0 ppm	No requirement
Halogenated hydrocarbons	1.0 ppm	1.0 ppm	No requirement
Odor	No odor	No odor	No requirement
CO and CO_2	1.0 ppm total	5.0 ppm carbon monoxide 5.0 ppm carbon dioxide	No requirement
Particulate	1.0 mg/liter max. (liquid only)	1.0 mg/liter max. (liquid only)	1.0 mg/liter max. (liquid only)

[a]Ref. 6, p. 2.

CHAPTER 3. MATERIALS SELECTION CRITERIA AND DATA

The reactivity of materials with oxygen depends on their conditions of exposure to oxygen and their physical and chemical properties. Except for most oxides and inert gases, most materials can react with oxygen. The reaction of oxygen with these materials may occur very slowly, such as the rusting of iron or oxidation of an aluminum surface, at a high rate, commonly observed as combustion or burning, or explosively, where the rate of reaction is nearly instantaneous. However, most materials will not burn when exposed to liquid or gaseous oxygen because their ignition temperatures are generally much higher than normal exposure temperatures. Oxygen system failures that occur during routine operations with oxygen are frequently characterized by an unexpected ignition of a part of the system from a localized energy source - the energy added being sufficient to reach the ignition temperature of the material involved.

If the energy input rate (power input) as converted to heat is greater than the rate of heat dissipation, and if it is continued for a sufficient time to reach the ignition temperature, ignition and combustion will occur. Sources of energy input per unit time (power) that may provide sufficient heat flux to cause ignition temperatures may include one or more of the following: mechanical impact, abrasion, rubbing friction, puncture, or rupture; surface shock from explosions, water hammer, pressure spikes, and shock waves; erosive fluid flow; electrical sparks or arcing; chemical reaction from sudden exposure of unoxidized surface or pockets of contamination; and heat transfer from an external source. Therefore, an understanding of the quantitative energy sources and energy release rates capable of causing combustion or explosion of a material is very important. If ignition temperature and burning rate data are considered, proper design and operational considerations can help eliminate potential ignition energy sources or accommodate them through the selection of proper materials. Existing data have been generated mainly by independent investigations to resolve the immediate problems of selecting the proper materials. Accordingly, because of varying techniques, procedures, specimen selection, and purpose, the data sometime appear to be scattered and incomplete. However, when all the data are used together, sufficient ignition temperature and burning rate data exist to evaluate the materials selected for given applications; these data are presented in the following sections. Although the burning rate of a material is an important factor when selecting materials for oxygen use (in the event an ignition would occur),

the ignition temperature is the most important parameter in preventing ignition and a possible fire hazard. To avoid ignition and fire with oxygen, it is desirable to use materials with ignition temperatures as high as possible. In addition, it is desirable to use materials and design criteria that would provide for maximum possible heat dissipation by thermal conduction. This would tend to require a greater power input to reach the ignition temperature. And finally, where possible, materials with the lowest heat of reaction with oxygen would contribute less energy to sustain combustion. The closer the initial temperature of the system is to the ignition temperature of the material the easier ignition becomes because less energy is required. The apparent ignition temperature may vary depending on exposure conditions such as the presence of an oxide film; the pressure, temperature, phase, and concentration of oxygen; and the rate of mechanical, electrical, or chemical energy input.

Therefore, it is desirable to provide engineering designs for fluid systems which preclude excessive energy releases, and it is necessary to provide a valid factor of safety by choosing materials to meet all possible environmental conditions. To do this, two things must be known: (1) the ignition temperature (or ignition energy requirements) of the material, and (2) the energy sources and energy release rates to which the material may be exposed under worst case combinations of power input. The selection of materials for use in oxygen systems has, up to the present time, been based largely on use experience and standardized impact and flammability tests. These tests are described in section 3.6. However, the final selection of a material for oxidizer applications is a trade-off between the chemical compatibility, the ignition and combustion characteristics, and the physical properties of the material. Material selection is based only on use experience, and precedence is acceptable if the use conditions are the same and ignition and burning rate data are not available. However, it is always better to review the possible ignition factors carefully to be sure the precedent is applicable.

The many trade-off factors to be considered when selecting materials are discussed in succeeding sections.

3.1 OXIDE FILM FORMATION ON METALS

Solid or quiescent liquid metals will form surface oxide films when exposed to oxygen environments. For a given metal the instantaneous rate of oxide film formation is primarily a function of temperature and pressure and of oxide film thickness. This is illustrated schematically in figure 3-1. The higher the initial surface temperature, the higher the rate of reaction and, thus, of initial oxide film growth. However, the oxide film tends to prevent the oxygen from contacting the base metal; for further reaction the oxygen must diffuse through the oxide film. Therefore, the reaction becomes diffusion rate limited, and the film growth reaction rate decreases and approaches zero with time.

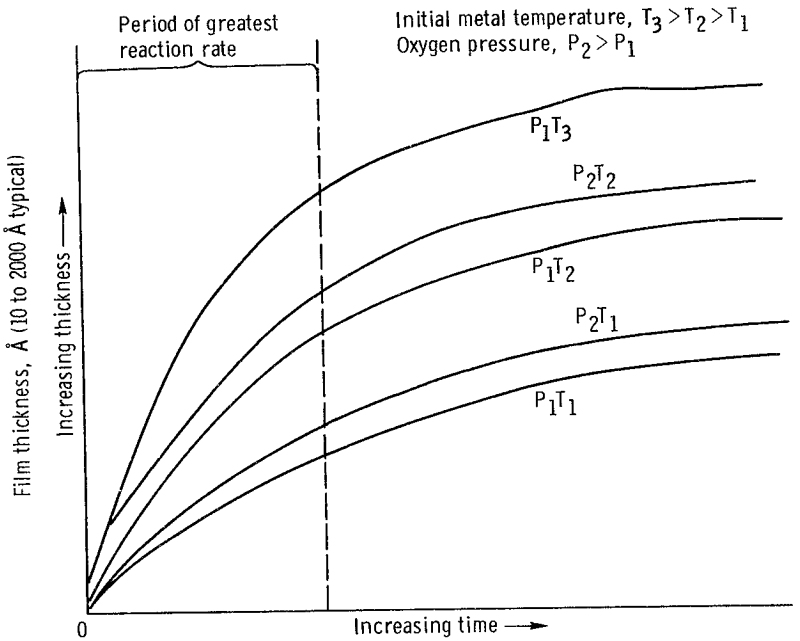


Figure 3-1. - Typical oxide film formation on metal surfaces.

The resulting film forms a protective barrier which inhibits further reaction. Increasing the oxygen partial pressure can increase the reaction rate by increasing the diffusion rate, but the protective film formed, although thicker than before, will continue to approach zero growth with time and provide protection from the higher pressure conditions.

Studies of oxide film growth on various materials indicate the rate of growth may be linear, parabolic, cubic, or logarithmic when the film thickness is plotted against time. For some materials and conditions the rate may follow a combination of all four profiles. Film formation on most metal surfaces approaches maximum thickness within a few minutes to several hours, depending on the materials and temperature.

Since the process of film formation is a chemical reaction, the heat of reaction may become significant in some cases. For example, powdered metals with a very high surface area to mass ratio may ignite when exposed to oxygen, or even air at room temperature, because the heat of reaction from film formation is sufficient to raise the metal particles to their ignition temperature. Similarly, if a bulk metal is exposed to a temperature near enough to its ignition temperature, sudden exposure of an unoxidized surface (such as from rupture or puncture) and subsequent heat of reaction may be sufficient to initiate combustion. The rate of film growth or oxidation, as illustrated in figures 3-2 and 3-3 (refs. 9 and 10), indicates an increase in reaction rate as the temperature is increased. Figure 3-3 illustrates a linear film growth rate which is typical of magnesium above the critical temperature (approximately 425° C). Note that the very high rate of oxide formation on magnesium is 550° to 575° C. The ignition temperature is only 625° C.

As illustrated by the data in figures 3-2 and 3-3, when the temperature of the materials exposed to oxygen approaches (but does not reach) the ignition temperature of the

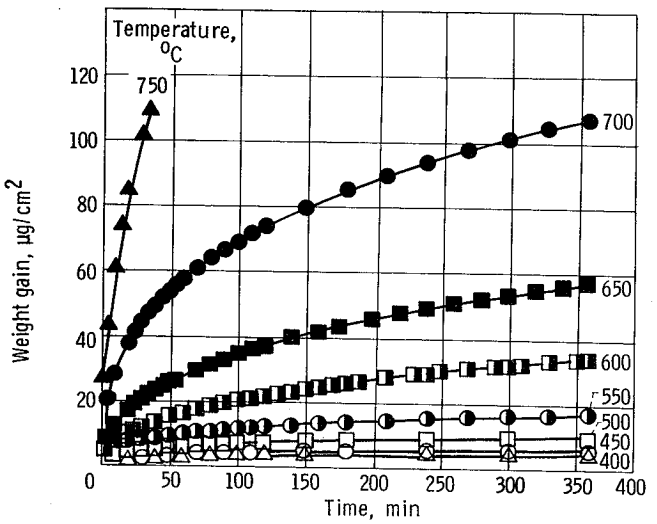


Figure 3-2. - Film growth on nickel as function of time and temperature (ref. 9, p. 492).

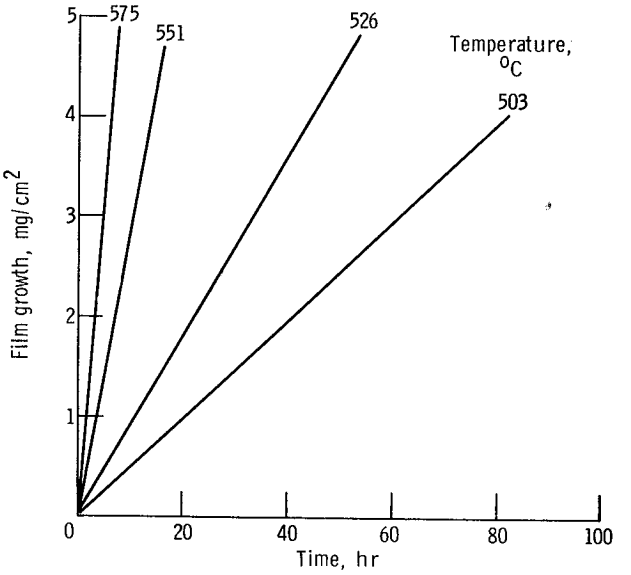


Figure 3-3. - Oxidation of pure magnesium in oxygen at various temperatures (ref. 10, p. 46). Ignition temperature, 625° C.

materials, the film formation rate may become catastrophic; that is, the film loses its protective capability and a continuous surface deterioration occurs. The rate of deterioration depends on the diffusion rate of the reactants through the oxide film.

A noncombustive, catastrophic reaction or film formation can occur when any of the following conditions exist:

(1) A metal or alloy is exposed to oxygen at a temperature approaching the ignition temperature of the alloy or one of its constituents[1].

(2) The material forms an oxide with a melting point below the exposure temperature[1].

(3) The exposure temperature exceeds the melting point of the base metal[1].

(4) A metal or alloy forms a relatively volatile oxide at the exposure temperature.

(5) The specific volume of the oxide formed is less than the specific volume of the base material, which would not permit complete coverage of the surface at any given time.

For example, the oxidation of iron alloy 15Mo-75Fe-10Cr exposed to oxygen at 910° and 1000° C is catastrophic (fig. 3-4 (ref. 11)). The oxides formed on the surface of this material are as follows:

---

[1]Ignition temperatures and melting points of selected metals and their oxides are given in the table on p. 17.

Oxide	Melting point, °C
Chromium oxide (Cr_2O_3)	2435
Iron oxide (Fe_2O_3)	1565
Molybdenum oxides:	
MoO_3	795
MoO_2	778
MoO_3 eutectic	778

In this case, the melting points of the oxide of one constituent (MoO_3) and its eutectic are below the test temperature. The MoO_3 formed can diffuse to the base metal and aid in oxidizing the surface. Not only does the MoO_3 formed aid in oxidizing the base metal, but, since it melts at the test temperature, it leaves the surface unprotected. At temperatures below the critical temperature (778° to 795° C) catastrophic oxidation does not occur. Above the critical temperature (910° to 1000° C), however, the rate of catastrophic oxidation increases very rapidly as shown in the example given in figure 3-4.

Another effect is the volatility of the oxide contributing to catastrophic oxidation as shown in figure 3-5 (ref. 12). Normal film formation occurs when tungsten is exposed to

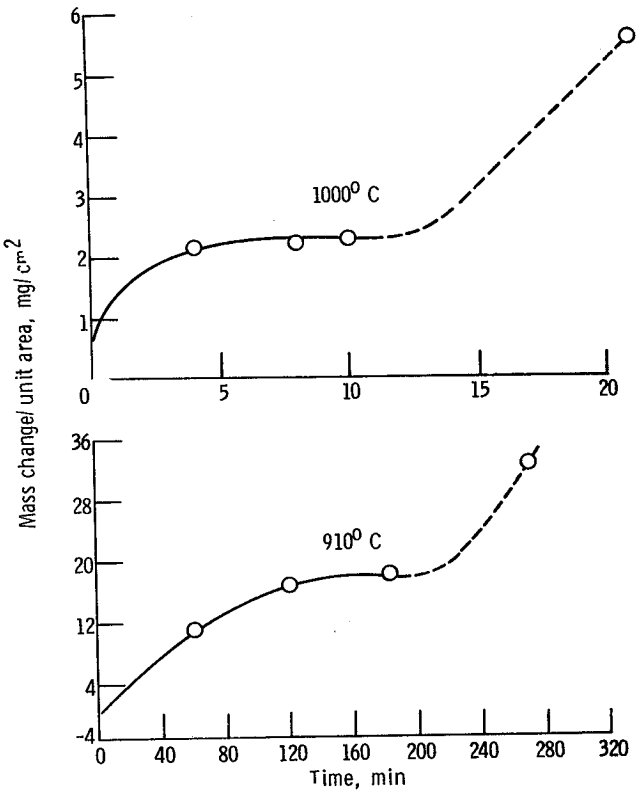


Figure 3-4. - Oxidation of 15Mo-75Fe-10Cr alloy (ref. 11, p. 18).

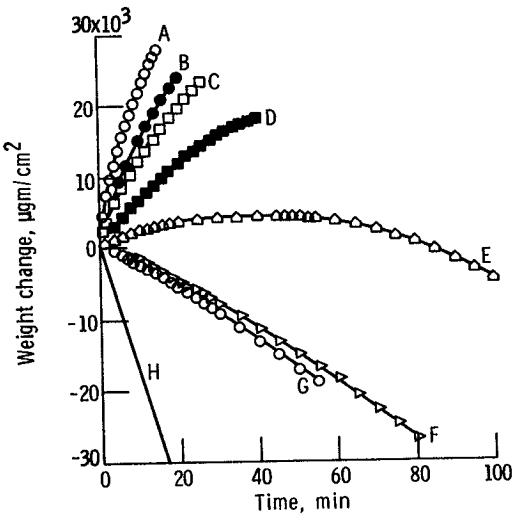


Figure 3-5. - Oxidation of tungsten at 1050° C. Effects of pressure: A, 0.1 atmosphere; B, 0.0512 atmosphere; C, 0.0263 atmosphere; D, 0.0112 atmosphere; E, 0.0066 atmosphere; F, 0.0033 atmosphere; G, 0.00131 atmosphere; H, volatility WO_3 (ref. 12, p. 623).

oxygen at 950° to 1050° C. The melting point of the oxide formed WO_3 is 1473° C; when the pressure is reduced as indicated, WO_3 is sufficiently volatile to sublime, and rapid weight loss is indicated.

For an additional discussion of surface oxidation phenomena and experimental test results see chapter 4 of reference 13.

3.2 CORROSION

The term corrosion is used to describe three surface reactions: stress corrosion, chemical corrosion, and galvanic corrosion. These could be classed as catastrophic. The phenomena should not be confused with film formation. As previously emphasized, film formation is a regressive, protective process; corrosion, on the other hand, is a progressive, destructive process that continues as long as both reactants are in contact.

3.2.1 Chemical Corrosion

The chemical corrosion is a straightforward chemical reaction of a fluid with the metal surface like the attack of salt solution on metal automobile bodies. The rate of attack or corrosion is determined by the temperature at the reaction zone and the type and concentration of the reactants. Although oxygen in a pure state is noncorrosive, the film formation phenomenon which is normally self-limiting can become propagating if the normal protective oxide film is compromised. For example, the presence of impurities such as moisture or other contaminants in the oxygen (or air) can result in serious chemical corrosion. Moisture is especially corrosive because the oxides are partially soluble in water which permits ionization: Consequently, an accelerated reaction results. For this reason oxygen systems must be kept clean and dry and their external surfaces protected from corrosion where necessary.

3.2.2 Galvanic Corrosion

Galvanic corrosion occurs where dissimilar metals are in contact in the presence of an electrolyte. Any fluid or substance that can conduct an electric current will do so by transferring ions from the cathode to the anode; in the process, the anode surface is destroyed. The presence of moisture or contaminants accelerates the corrosion of the dissimilar metal junction.

If metals are arranged in the order according to their electromotive potential, the more widely they are separated the greater the electromotive potential between them.

TABLE 3-I. - METAL COUPLES[a]

Group	Metallurgical category	Electromotive force, V	Permissible couples[b]
1	Gold, solid and plated; gold-platinum alloys; wrought platinum	0.15	
2	Rhodium, graphite	0.05	
3	Silver, solid or plated; high silver alloys	0	
4	Nickel, solid or plated; Monel metal, high nickel-copper alloys, titanium	-0.15	
5	Copper, solid or plated; low brasses or bronzes; silver solder; German silver; high copper-nickel alloys; nickel-chromium alloys; austenitic stainless steels	-0.20	
6	Commercial yellow brasses and bronzes	-0.25	
7	High brasses and bronzes; Naval brass; Muntz metal	-0.30	
8	18 Percent chromium type corrosion-resistant steels	-0.35	
9	Chromium, plated; tin, plated; 12 percent chromium type corrosion-resistant steels	-0.45	
10	Tin-plate; terneplate; tin-lead solders	-0.50	
11	Lead, solid or plated; high lead alloys	-0.55	
12	Aluminum, wrought alloys of Duralumin type	-0.60	
13	Iron, wrought, gray, or malleable; plain carbon and low alloy steels, Armco iron	-0.70	
14	Aluminum, wrought alloys other than Duralumin type; aluminum, cast alloys of the silicon type	-0.75	
15	Aluminum, cast alloys other than silicon type; cadmium, plated and chromated	-0.80	
16	Hot-dip-zinc plate; galvanized steel	-1.05	
17	Zinc, wrought; zinc-base die-casting alloys; zinc, plated	-1.10	
18	Magnesium and magnesium-base alloys cast or wrought[c]	-1.60	

[a]Ref. 14, Std 63.

[b]Members of groups connected by lines are considered to form permissible couples. These permissible couples should not be construed to be totally devoid of galvanic action, but rather to represent an acceptably low galvanic effect. The ○ indicates the most cathodic member of the series, ● an anodic member, and the arrows the anodic direction.

[c]Aluminum alloys 5052, 5056, 5356, 6061, and 6063 are considered to form permissible couples with magnesium alloys.

Galvanic corrosion rates are a function of this potential. Therefore, metals with the lowest potential difference are preferred to minimize galvanic corrosion. A NASA table of preferred metal couples is given in table 3-I (ref. 14). Where dissimilar metals must be in contact, they should be insulated with gaskets, plating, or coatings. For additional detail, see reference 15.

3.2.3 Stress Corrosion

Stress corrosion, the phenomenon of crack formation and propagation that occurs in some metal alloys, is generally caused by intergranular corrosion at points of localized strain from high stress levels.

The occurrence of intergranular attack requires exposing the strained surface to an electrolytically active fluid such as moist oxygen, moist air, or water. The electrochemical potentials that exist across grain boundaries when the electrolyte is present cause the progressive attack. Since the reaction is chemical and the cause is stress, the rate of stress corrosion is determined by the amplitude and frequency of the strain, the temperature at the reaction zone, and the type and concentration of the reactant.

One problem is that the rate of attack or even the occurrence of stress corrosion varies in a specific alloy depending on the heat treatment. Therefore, care must be taken when selecting alloys and their heat treatments for any application where high localized stress can occur in the presence of an electrolytic fluid. Since the exterior of nearly all oxygen system components are exposed to moist air, an electrolyte is nearly always present on the outside of the system. Another related problem is the phenomenon of oxide film formation under stress. The strain resulting from the critical stress level permits the oxygen to undermine the surface film and thus allow bare metal oxidation rates. The critical stress is generally the stress required to exceed the elastic limit of the oxide film and, according to reference 16 (p. 17), corresponds to a strain of approximately 1 percent in 100 hours. The effect is very similar to catastrophic oxidation.

3.3 CRACK PROPAGATION AND FATIGUE LIFE REDUCTION

The presence of oxygen affects the rate of fatigue crack growth in metals as illustrated by the examples of stainless steel and nickel in figures 3-6 and 3-7 (refs. 17 and 18). In each case, as the oxygen pressure is increased, the fatigue life is reduced. Note that this phenomenon occurs at very low oxygen pressures. The significance of this is that an oxygen environment has a serious effect on fatigue life when compared to an inert gas environment. In the example given for stainless steel, the crack growth was almost negligible for 10^5 cycles at an oxygen pressure of 1×10^{-6} torr. When the oxygen

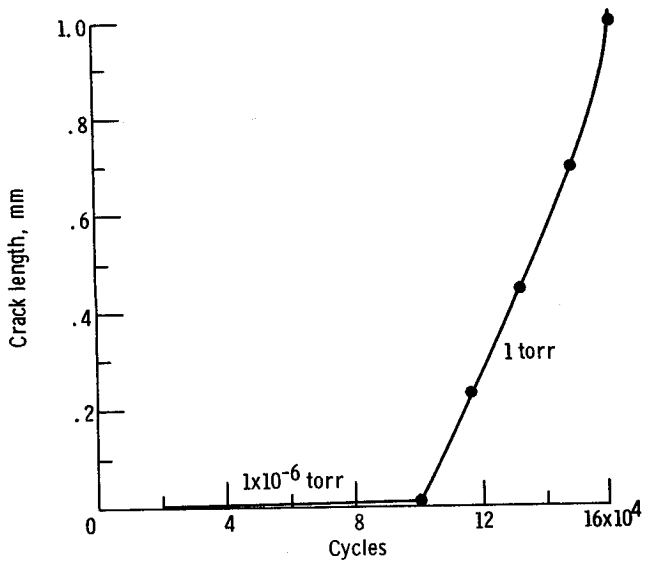


Figure 3-6. - Increase in rate of fatigue crack growth in 316 stainless steel upon introduction of 1 torr oxygen during fatigue at 800° C with 0.062 percent strain (ref. 17, p. 950).

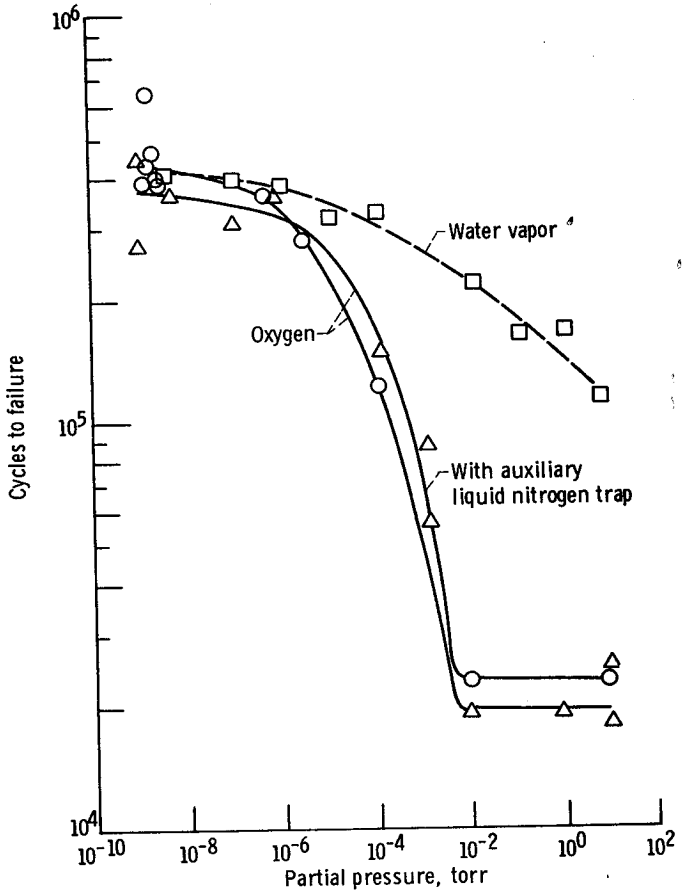


Figure 3-7. - Effect of oxygen and water-vapor pressure on fatigue life of nickel at 300° C at a plastic bending strain of 0.17 percent (ref. 18, p. 223).

pressure was increased to 1 torr, the crack growth increased abruptly. In the case of nickel, at oxygen pressures in the range of 10^{-6} torr or less, there was very little effect, but when oxygen was present at pressures of 10^{-3} torr or greater, the cycles to failure were reduced an order of magnitude.

The reaction of oxygen at crack boundaries, where fresh surface metal is exposed during stress cycles, weakens the metal and thus causes the cracks to grow faster. Metals which are more reactive with oxygen show this effect whereas the noble metals are not significantly affected (ref. 19, p. 170).

The presence of water vapor generally accelerates the effect of oxygen, and fatigue crack growth from the presence of both water and oxygen is greater than either alone. The failure of a D7AC alloy steel tank being tested under water was attributed to this phenomenon. (See section 5.1.4.)

Although the examples given in figures 3-6 and 3-7 were of results at elevated temperature, it is important to recognize that component metal parts subject to high stress cycles in moist oxygen or air environments may have a lower cycle life than would be ex-

pected. When cycle life is an important consideration, testing under exact environmental exposure may be indicated.

3.4 IGNITION OF MATERIALS

Ignition is defined by various researchers in slightly different ways, and there is even some controversy as to whether a particular material has a precise ignition temperature which is completely independent of all other parameters. In order to avoid this controversy, this document will employ the apparent or measured ignition temperature of materials.

The apparent ignition temperature of a given material is affected by its heat capacity, thermal conductivity, and heat of reaction and the rate of heat input, the method of temperature measurement, and measurement techniques. Other parameters affecting the ignition temperature include the thickness of the protective oxide film present before additional exposure and the surface to mass ratio of the exposed material (i.e., powdered material, surface finish, configuration, etc.). In addition, variables such as oxygen concentration, pressure, and temperature as well as exposure conditions (static or dynamic) affect measured ignition temperatures. Also, most materials often have localized imperfections such as contaminant inclusions (commonly found in both metals and nonmetals) as well as variations in polymeric chain endings and molecular irregularities (nonmetals). Such local imperfections may have much lower ignition temperatures than the bulk material and may serve as an igniter; this condition naturally causes variations in the measured ignition temperature.

The ignition temperature and ignition energy data presented in this chapter and in appendixes D and E are useful in selecting the most compatible material to meet the physical requirements for specific applications.

A summary of melting points, ignition temperatures, and thermal diffusivity and heat of combustion data for selected materials are presented in table 3-II (refs. 20 to 22).

The thermal diffusivity parameters, (i.e., thermal conductivity, density, and specific heat) may be used to calculate energy input rate or power input to reach the ignition temperature of the material. As the thermal conductivity, density, and heat capacity increase, the rate of energy (power) input to reach an ignition temperature increases. Also, if the heat of reaction is relatively high, the material, once ignited, burns with greater heat release which tends to propagate combustion more readily.

The melting points of the base metal and its oxide are important parameters since the protective effects of the oxide film are destroyed if the metal or its oxide melts.

These are some of the factors which must be considered in an engineering trade-off for selecting materials. The most advantageous of the previous factors for achieving an

TABLE 3-II. - IGNITION PARAMETERS FOR SELECTED METALS

Metal	Metal melting point (a)		Thermal conductivity at 20° C, (cal)(cm)/(sec)(cm²)(°C) (b)	Density at 20° C, g/cm³ (c)	Specific heat at 20° C cal/(g)(°C) (a)	Ignition temperature range at 1 atm oxygen, °C (d)	Heat of reaction (heat of oxide (formation), kcal/(g)(mole) (e)	Product (oxide)	Product melting point (f)	
	°C	°F							°C	°F
Aluminum	660	1220	0.53	2.699	0.215	>1000	-399.09	Al_2O_3	2015	3659
Antimony	631	1167	.045	6.62	.049	650	-166.5	Sb_2O_3	656	1213
Beryllium	1277	2332	.35	1.848	.45	1260 to 2500	-146	BeO	----	----
Chromium	1875	3407	.16	7.19	.11	1998	-269.7	Cr_2O_3	2435	4415
Copper	1083	1981	.941	8.96	.092	1083	-37.1	CuO	1326	2419
Iron	1537	2798	[g].18	7.87	.11	1310	-196.5	Fe_2O_3	1565	2849
Lead	327	621	[g].083	11.36	[g].0309	850 to 871	-52.07	PbO	888	1630
Magnesium	650	1202	.367	1.74	.245	625 to 640	-143.84	MgO	2800	5072
Manganese	1245	2273	----	7.43	[f].115	----------	-92	MnO	535	995
Molybdenum	2610	4730	.34	10.22	.066	745 to 780	-130	MoO_2	----	----
Nickel	1453	2647	[h].22	[h]8.902	.105	----------	-58.4	NiO	1990	3614
Platinum	1769	3217	[i].165	21.45	[g].0314	----------	--------	PtO	[j]550	1022
Silver	961	1762	[g]1.0	10.49	[g].0559	950	-7.306	Ag_2O	[j]300	572
Tantalum	2996	5425	.130	16.6	[h].034	1245 to 1270	-499.9	Ta_2O_5	1800	3272
Thorium	1750	3182	[k].090	[l]11.72	.034	500	-292	ThO_2	3050	5522
Tin	232	450	[g].15	[m]7.3	.054	865 to 970	-138.8	SnO_2	1127	2061
Titanium	1668	3035	[n].0372	4.507	.124	1310 to 1600	-218	TiO_2	1830 to 1850	3326 to 3362
Tungsten	3410	6170	[g].397	19.3	.033	1270 to 1300	-200.84	WO_3	1473	2683
Zinc	419	787	[h].27	[h]7.133	.0915	900 to 940	-83.17	ZnO	1975	3587

[a]Ref. 20, pp. 46 and 47.
[b]Ref. 20, pp. 48 and 49.
[c]Ref. 20, pp. 44 and 45.
[d]For additional data, see appendix D.
[e]Ref. 21, pp. 8 to 535.
[f]Ref. 22, pp. B-149 to B-242.
[g]At 0° C.
[h]At 25° C.
[i]At 17° C.
[j]Decomposes.
[k]At 100° C.
[l]Bomb-reduced
[m]Beta.
[n]At -240° C.

optimum chemical compatibility must be balanced against the required structural properties of materials.

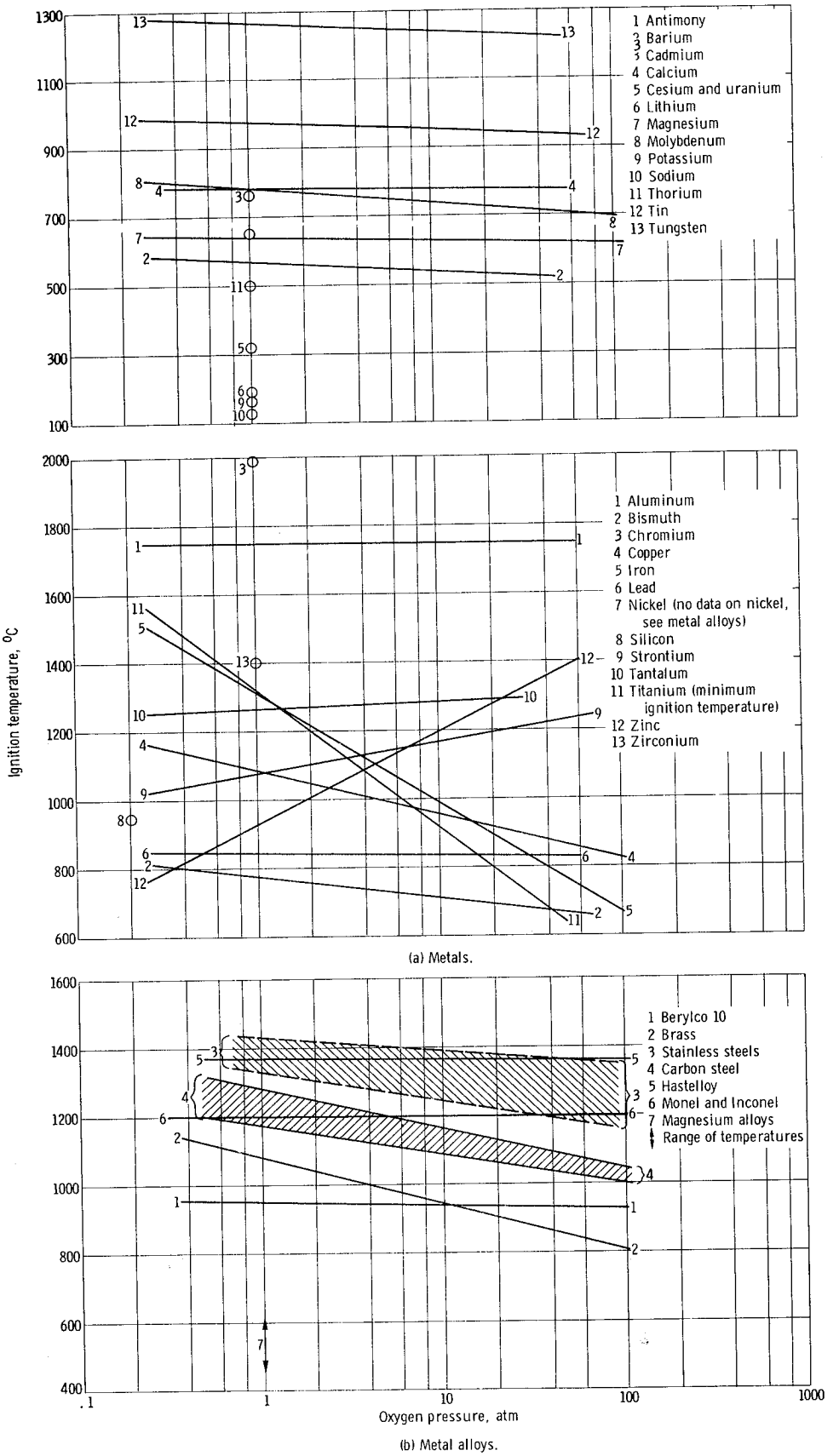
3.4.1 Ignition Temperature of Metals

For most practical purposes, the measured ignition temperature of most metals varies only slightly over a wide range of pressures. For example, the ignition temperature of materials (both metal and nonmetal) tested at 2000 and 7500 psi in oxygen gas was essentially the same (ref. 23, p. 55). However, these data together with other available ignition temperature data plotted on a semi-logarithmic scale (to cover a wide pressure range) show slightly reduced ignition temperatures at high oxygen pressures for most metals (fig. 3-8). A few exceptions show an increase in ignition temperature with pressure. These exceptions and the variations in the slope of the curves are probably due primarily to the properties of the oxide film formed. (Nonmetal materials tend to be much more consistent.) These data are based on detailed information plotted in the figures in appendix D and are a composite compilation from the sources listed. In most cases the metal sample was placed in pressurized oxygen and heated slowly until the ignition temperature was reached and combustion occurred.

These data are useful in selecting the material most resistant to ignition. The highest possible localized temperature spike that could be anticipated in a given system should be less than the ignition temperature corrected for pressure per figure 3-8 and table 3-II plus an appropriate safety factor.

The apparent ignition temperature of most particulate metallic materials, which may be present in oxygen systems as contamination, is somewhat lower than that of the same material in bulk form. This is due primarily to the high specific surface or surface to mass ratio of the particulate. If the particles are small enough, the heat of oxide film formation alone may be sufficient to raise them to ignition temperature in gaseous oxygen. In any case, the power input required to raise particulates to their ignition temperature is lower than might be anticipated if only the bulk material ignition temperature is considered. For example, the ignition temperatures of chromium and copper are approximately 2000° and 1083° C, respectively, while the apparent ignition temperatures of 44 micron powders of the same materials in air are 580° and 700° C, respectively, as reported in reference 24 (p. 4).

Liquid oxygen, because of its cooling effect, makes particle ignition less likely. However, ignition may still occur in gaseous pockets or at sites of impact or friction, particularly when accumulated quantities of incompletely reacted wear particles or other contaminants are present.



(a) Metals.

(b) Metal alloys.

Figure 3-8. - Average ignition temperature of metal and nonmetals.

3.4.2 Ignition Temperature of Selected Nonmetal Materials

The primary concern when using nonmetals in oxygen systems is their potential reactivity with oxygen. Their ignition temperatures are generally lower than those for metals and their low thermal conductivity and heat capacity make them much easier to ignite. For this reason, their use is more restricted.

The effect of oxygen pressure on the ignition temperature of polymeric materials is difficult to measure except over a wide range of pressures. As in the case of metals, when ignition temperatures of polymeric materials are plotted against pressure over a wide pressure range, a reduction in ignition temperature with increasing pressures be-

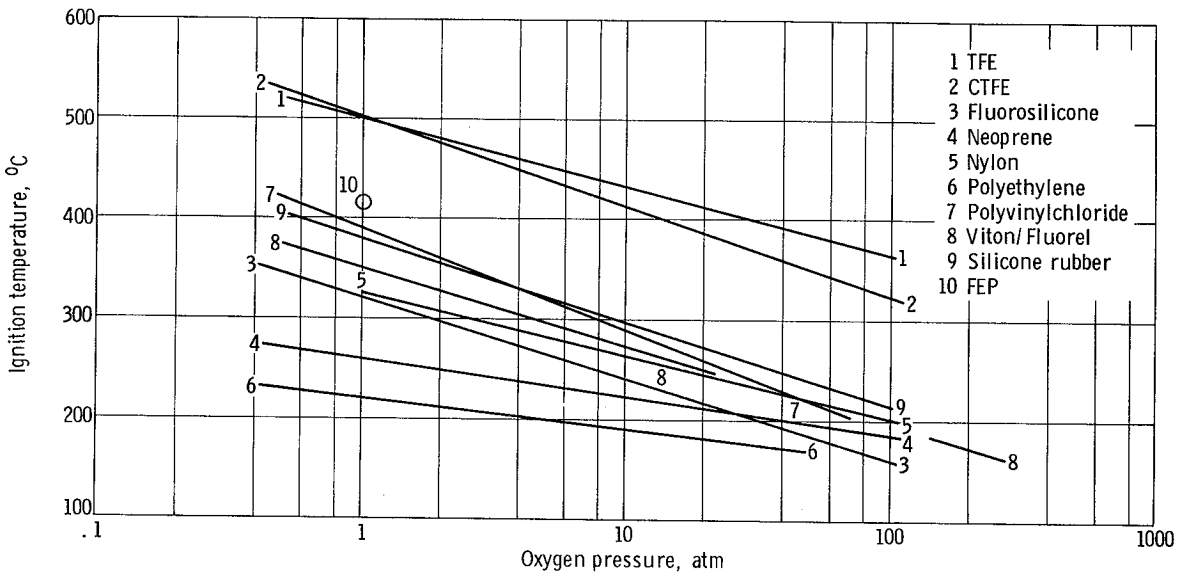


Figure 3-9. - Minimum ignition temperatures of nonmetal materials.

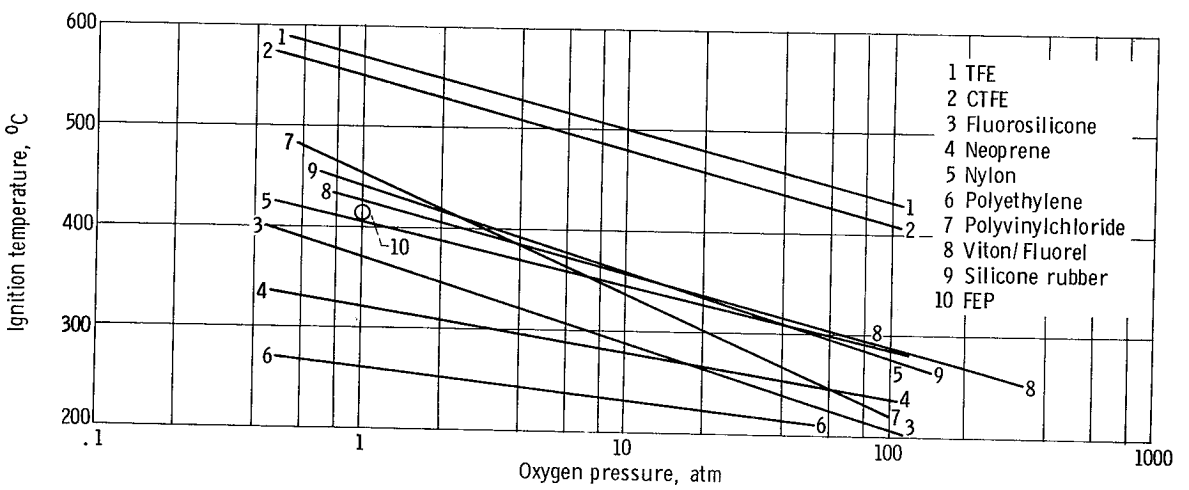


Figure 3-10. - Average ignition temperatures of nonmetal materials.

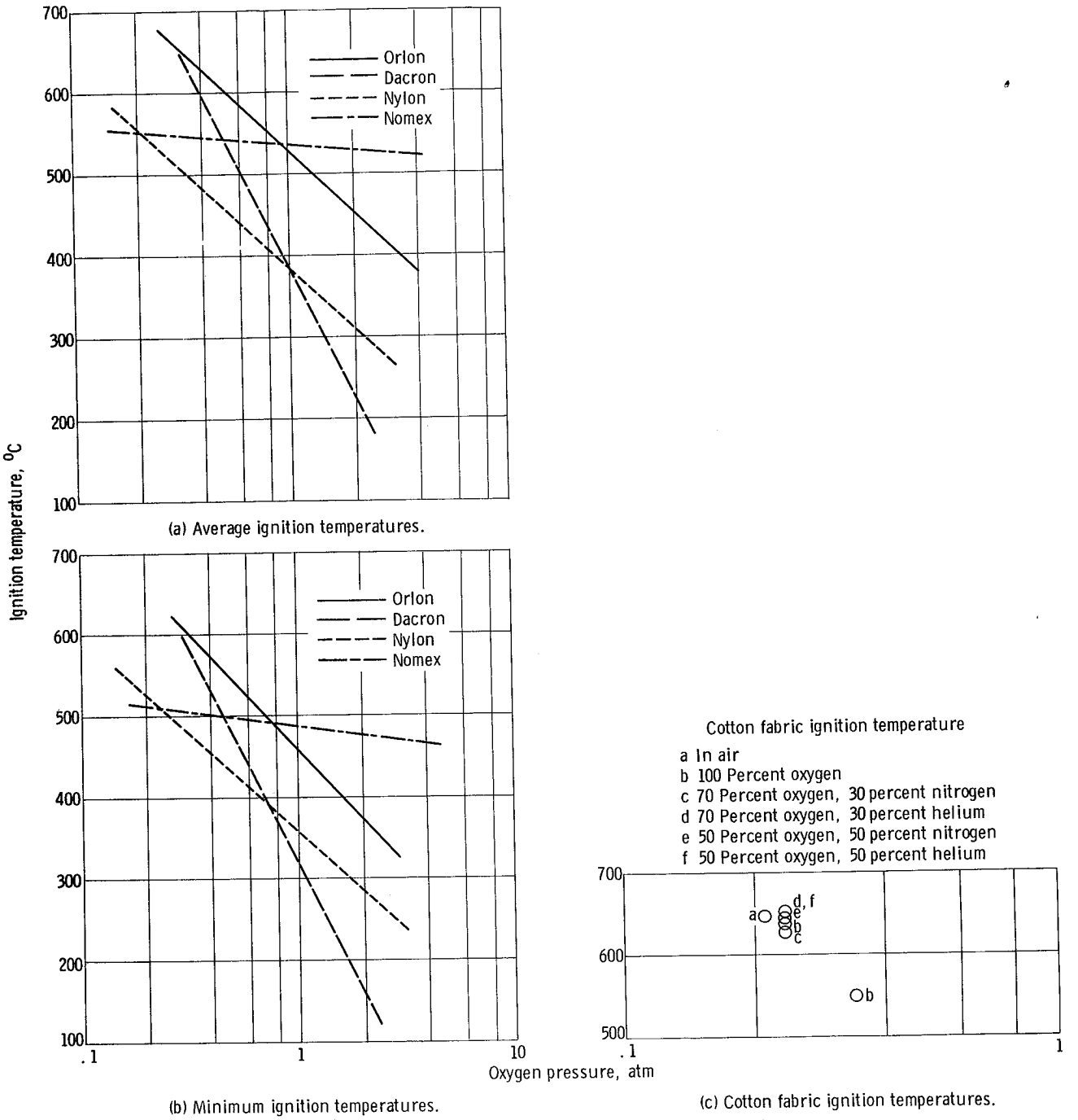


Figure 3-11. - Ignition temperatures of fabric materials.

TABLE 3-III. - MINIMUM IGNITION TEMPERATURES OF MATERIALS IN OXYGEN AT 1-ATMOSPHERE PRESSURE[a]

Material	Minimum ignition temperature, °C
Selected plastics and elastomers	
Polyimide (Vespel)	500
Chlorotrifluoroethylene (TFE)	500
Tetrafluoroethylene (TFE)	500
Duroid 5600	468
Duroid 5813	463
Duroid 5870	452
Duroid 5650	444
Rulon A	463
Rulon B	460
Rulon C	458
Graphite asbestos	460
Vinylidene fluoride/hexafluoropropylene (Viton A/Fluorel)	[b]435 (see figs. E-1(p) and E-1(q))
Polymethylmethacrylate (Plexiglas)	430
TFE (carbon filled)	420
Fluorinated ethylene propylene copolymer (FEP)	412
Polyvinylalcohol	400
Silicone rubber	390
Kel-F 5500	340 to 352
Kel-F 3700	332 to 341
Carbon	330
Fluorosilicone	320
Polyvinylidene fluoride	(see fig. E-1(m))
Polyvinylchloride	390
Nylon[c]	345
Mylar[c]	320
Selected plastics and elastomers	
Butyl rubber[c]	275
Neoprene[c]	250 to 270
Polyethylene[c]	160 to 220
Natural rubber[c]	150
Selected lubricants	
TFE lubricant	505
CTFE grease	500
Halocarbon grease 25-10	431
Halocarbon oil 13-21	427
Mano pipe and joint	422 to 430
Oxyweld 64	410
Silicone grease	370
Selected adhesives	
Fused TFE	465
Eposy (3M EC 1469)	380
Oxyseal (2)	347 to 360
Epoxy (Armstrong A-6)	310
Selected fabrics	
Nomex	490
Orlon	430
Nylon	360
Dacron	310 to 390

[a]See introduction to appendix E for qualifications applicable to the data in this table.

[b]Ref. 25 data indicate this value could be as low as 335° C. Ref. 25 data also show ignition temperature to be 308° to 318° C at 3.4 atmospheres.

[c]Not recommended for oxygen - included for comparison only.

comes evident. On the other hand, the measured ignition temperature increases as the oxygen pressure or partial pressure is reduced below atmospheric pressure until a point is reached where no spontaneous ignition can occur since combustion can not be sustained.

Ignition temperatures as a function of oxygen pressure (or partial pressure) are presented in figures 3-9 to 3-11; these figures were compiled from the detailed data plotted in the figures of appendix E. Note that figure 3-9 shows the minimum ignition temperature, and figure 3-10 provides the average ignition temperature of the same materials. Average and minimum ignition temperatures for selected fabrics are included in figure 3-11.

It should be noted that materials which are not normally recommended for use with oxygen, such as nylon and cotton, have ignition temperatures nearly as high as some of the acceptable materials. Factors such as absorption characteristics, chemical deterioration, variations in the polymer structure, and contamination could explain the failure experience of some of the materials that are not recommended for oxygen. (For a discussion of recommended materials, see section 3.7.) In any case, the minimum ignition temperature (less an appropriate safety factor) should never be exceeded.

A summary of the minimum ignition temperatures for selected materials is presented in table 3-III (selected data from ref. 25).

3.4.3 Impact Energy Test Data for Metals and Nonmetals

As previously stated, the selection of materials for use in oxygen systems has been based on use experience and impact, ignition, and flammability testing with impact testing being a major source of compatability data. A description of impact test equipment and procedures may be found in the section 3.6.1.1.

When applying impact test data it should be recognized that the test was devised as a convenient and reproducible method for choosing materials from those that could withstand a selected impact energy level under standardized environmental conditions. This provided a form of "worst case" testing which has more recently been refined to permit measurement of impact limits or threshold data.

"Go-no-go" type impact ignition data in oxygen environments obtained by this test are compiled in reference 26 (pp. 42 to 220). Using fixed impact energies does not permit a determination of the limit of impact energy a material can withstand, nor does it permit a determination of how close to the limit a given test or operational condition may be. These data are helpful because they indicate the relative compatibility of a material when compared to the others tested. However, in order to make an engineering estimate of impact compatibility, the maximum level of impact that is possible in a given system must be determined, and the impact tolerance limit of the material must be known. With both factors known, a safety factor appropriate to the application can then be applied which would provide a more quantitative approach to compatibility determinations.

TABLE 3-IV. - IMPACT ENERGY FOR IGNITION OF SELECTED MATERIALS IN OXYGEN

Material	Impact energy, ft-lb/in.^{2}	Reference
Metals		
Zinc dust	380	27, p. 98
Aluminum 6061-T6	368+	26, p. 166
Rene 41	368+	26, p. 175
18 Percent nickel maraging steel	368+	26, p. 175
Stainless steel 347	368+	28, p. 7
Iron powder	357	27, p. 98
Columbium	357	27, p. 98
Aluminum chips	306	27, p. 98
Titanium	78	29, pp. 5 and 6
Titanium Ti-6Al-4V and Ti-25Zr	78	29, pp. 5 and 6
Nonmetals		
Polytetrafluoroethylene sheet	306 to 400	27, p. 97
Polytetrafluoroethylene (20 mil, sintered)	370	30, p. 102
Polytetrafluoroethylene tape	368+	26, p. 74
Polytetrafluoroethylene (glass filled)	368+	26, pp. 156 and 157
Polytetrafluoroethylene	368	31, p. 47
Polychlorotrifluoroethylene grease	368+	26, pp. 58 and 59
Polychlorotrifluoroethylene oil	368+	26, pp. 50 and 51
Fluorinated silicone (Drilube 822, 0.050 in. thick)	368+	26, p. 47
AFD-E-124D (experimental fluoroelastomer)	368	31, p. 49

Material	Impact energy, ft-lb/in.^{2}	Reference
Nonmetals		
CTFE (polychlorotrifluoroethylene)	357	27, p. 98
CTFE (20 mil)	210	30, p. 102
CTFE (10 mil)	160	30, p. 102
Vinylidene fluoride and hexafluoropropylene (cured)	357	27, p. 98
FEP (fluorinated ehtylene propylene, shredded)	306	27, p. 98
FEP (fluorocarbon resin, 10 mil)	145	30, p. 102
TFE (40 mil)	305	↓
TFE (30 mil)	300	
TFE (10 mil, unsintered)	220	
TFE (10 mil, sintered)		
Viton A	204 to 254	31, pp. 47 and 49
Fluorosilicone	204	31, p. 47
Phenylsilicone	204	31, p. 47
Mylar	122	32, p. 37
Trifluoropropylmethyl (Siloxane)	100	27, p. 98
Polyvinylidene fluoride (10 mil)	80	30, p. 102
Polyethylene (irradiated)	78	27, p. 97
Neoprene	55	30, p. 103
Nitrile rubber	39	30, p. 103
Fluorel[a]	368+	28, p. 6
Plexiglas[a]	368+	28, p. 6

[a]Ambient temperature GOX tests.

Some impact tolerance threshold data for metals and nonmetals are given in table 3-IV (refs. 26 to 32). The materials listed include those cases where an impact energy level has been reached without reaction in successive tests. For example, if the highest no reaction impact was 200 and the lowest impact at which reaction occurred was 215, the limit value used was 200. Therefore, since some of the values are not the absolute máximum of impact tolerance, the conservative value is considered to be close to the maximum.

Because of the variations in test results caused by sample thickness, material batches, apparatus types, and physical characteristics of striker and anvil materials, the test values are only approximate. Even different operators using the same equipment may get different results. An example of the effect of sample thickness for selected materials is illustrated in table 3-V (ref. 33). There are also chemical variations in compounded and processed materials - even materials with the same name. There are wide

TABLE 3-V. - EFFECT OF SPECIMEN THICKNESS OF VARIOUS MATERIALS AT 10-kg·m IMPACT ENERGY (IN GOX)[a]

Material	Thickness, cm	Oxygen pressure, N/m^2	Percent reaction	Increase in sensitivity
Silicone rubber	0.152	34×10^4	55	---
Silicone rubber	.050	34×10^4	100	1.8
Polytetrafluoroethylene	.157	6.8×10^6	10	---
Polytetrafluoroethylene	.086	6.8×10^6	20	2
Fluorinated rubber	.229	6.8×10^6	10	---
Fluorinated rubber	.152	6.8×10^6	33.3	3.3

[a]Ref. 33, p. 29.

variations in purity, chemical content, additives, and processing agents. This can also occur with different batches of the same material from the same source. For this reason, it is a common requirement that many materials be "batch" tested for acceptance for oxygen system applications.

Despite these variations, the data in table 3-IV are helpful in choosing a material and can help in achieving a good oxygen system component with less problems, redesign, and retesting.

3.4.4 Ignition of Materials by Adiabatic Compression of Oxygen

Adiabatic compression of gaseous phase oxygen from pressure spikes due to "water hammer," fast operation of valves in high pressure systems, oscillatory flow, or other

sudden pressurization can cause localized temperature increases sufficient to ignite many materials, especially organic contaminants or fine particles. Nonmetal materials especially should be protected from direct exposure to high pressure adiabatic compression of oxygen. Theoretical temperatures that can be reached by adiabatic compression of a gas are given in figure 3-12.

Not many data exist on adiabatic ignition of materials. Existing data for some materials generally compatible with oxygen are given in table 3-VI. Obviously, the samples which were exposed to a sudden compression of over 6000 psi ignited; figure 3-12 shows

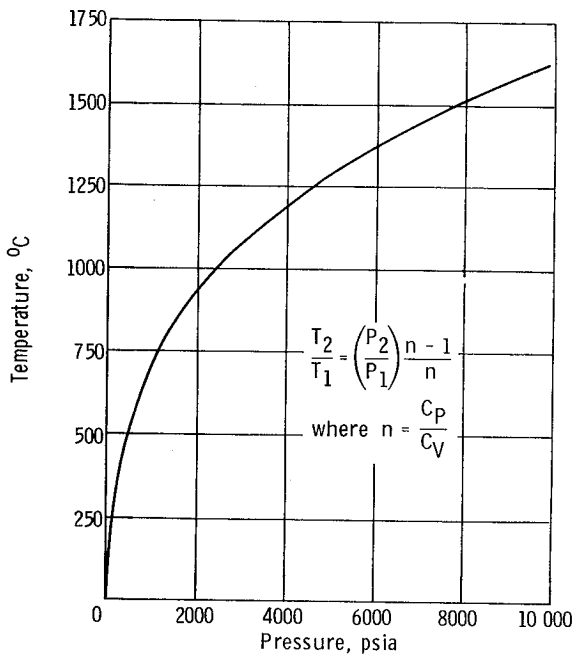


Figure 3-12. - Theoretical temperature attained by adiabatic compression (ref. 23, p. 60). Initial conditions: T_1 = 293 K (~20° C); P_1 = 14.7 psia.

TABLE 3-VI. - ADIABATIC COMPRESSION TESTS[a]

Pressure in storage vessel, psi		Sample	Weight of sample, g	Pressurization time of 51 in. length of 5/16 in. i.d. tubing and sample, sec	Remarks
Before test	Immediately after test				
7200	6900	Viton A (Virgin)	0.217	0.05	Sample ignited
7100	6700	Viton A (Virgin)	.223	↓	↓
7000	6500	Kel-F 81	.240		
6900	6300	Teflon (Virgin)	.161		

[a]Ref. 23, p. 80.

a temperature capability for that pressure approaching 1400° to 1500° C, and the ignition temperature for all these materials is less than 500° C.

Extremely high pressures (as just shown) are generally required since the material to be ignited must absorb sufficient heat from the gas to reach the ignition temperature of the material (or a contaminant on the material). To do this, the final gas temperature must be considerably higher than the ignition temperature to allow sufficient time for the ignition temperature to be reached.

3.4.5 Ignition from Rupture of Materials

When material is overstressed to cause rupture, several things occur that can result in ignition in an oxygen environment. The temperature of the material increases in the area of rupture from strain, and the highest temperature develops at the rupture interface. The ruptured surface is generally very rough and has a very high local surface area to mass ratio. In addition, the newly exposed surface is subject to immediate additional heating from oxide film formation reaction. Finally, the faster the strain occurs leading to rupture, the higher the ruptured surface temperature will be. Although most materials (metal and nonmetal) can tolerate rupture in a moderate oxygen environment, some materials with poor ignition resistance characteristics may react if ruptured in a high pressure oxygen environment at a temperature near the ignition temperature.

Occurrences which are most likely to result in massive structural deformation, and thus possible ignition, are failed turbopump impeller assembly, water hammer, excessive overpressure, excessive g-forces, and the like.

Although titanium is a bad actor in an oxygen environment, it does serve to illustrate the rupture ignition phenomenon. Figures 3-13 (ref. 34) and 3-14 (ref. 34) show the limits of initial temperature and pressure combinations for rupture ignition of titanium and one of the titanium alloys. In this case, the data are based on tensile rupture. Tearing rupture would possibly result in a shift of position or slope of the curve. Other materials (whose ignition temperatures are lower than their melting points) would react in the same way at initial temperatures near their ignition temperature. "Molecular concentration" (or density) was used rather than pressure of oxygen only to illustrate that the effect of pressure on ignition is due to the higher concentration of oxygen molecules at the site of ignition.

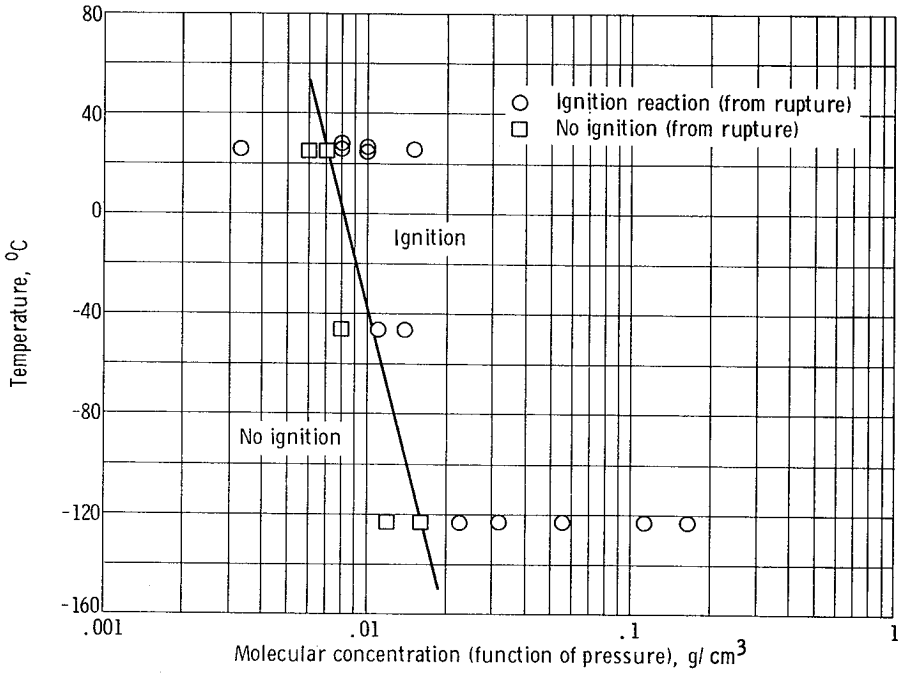


Figure 3-13. - Spontaneous ignition of titanium (Ti-75A) from rupture in oxygen (ref. 34, p. 10).

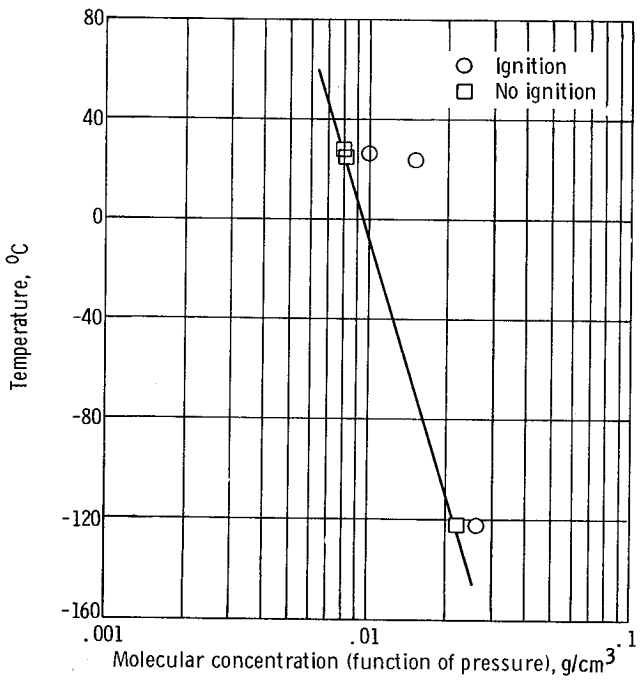


Figure 3-14. - Spontaneous ignition of titanium alloy (Ti-6Al-4V) from rupture in oxygen (ref. 34, p. 14).

3.4.6 Dynamic (Flow) Effects

Limited data and experience indicate that a high velocity flow of oxygen can effect ignition and increase the burning rates of materials. Also, solid particles entrained in a high velocity flow stream can cause surface erosion, and particle impact can cause, or be the source of, ignition.

Ignition of oxygen piping from impact and abrasion of entrained particulate matter has been a frequent occurrence in gaseous oxygen systems especially at room temperatures or higher. This is especially true where a high degree of cleanliness has not been maintained. Those organizations familiar with the problem maintain that the required cleanliness limits the flow velocity in the piping. In most cases, the oxygen flow velocity limits are set in consideration of past experience, the pipe material, and operating pressure and temperature. These vary with the organization. Typical values are listed in table 3-VII.

Actual tests (ref. 35) have confirmed what has been observed from experience: exceeding a velocity limit when entrained particulates are present results in ignition of the flow duct, and bends, valves, and other flow system obstructions or deviations are the most critical ignition sites. A summary of the actual test results is given in table 3-VIII (ref. 35).

TABLE 3-VII. - TYPICAL VELOCITY LIMITS FOR ENTRAINED PARTICULATES IN OXYGEN WITH CARBON STEEL PIPE

Pressure, atm	Temperature, °C	Maximum flow velocity	
		ft/sec	m/sec
10	175	150	46
10	150	175	53
10	120	200	61
20	175	75	23
20	150	85	26
20	120	100	30
20	65	130	40
40	120	50	15
40	100	60	18
40	65	65	20
60	100	30	9
60	65	35	10 to 11

TABLE 3-VIII. - IGNITION VELOCITIES OF ENTRAINED PARTICLES IN OXYGEN (STEEL PIPE)[a]

Pipe line configuration	Entrained material	No ignition velocity, m/sec	Ignition velocity, m/sec
Straight	Rust	[b]84	--
Straight	Sand	[b]84	--
Straight	Steel scale	28	52
Straight	Weld slag	[c]44	--
Curved	Weld slag	[d]53	--
Straight	Coke	30	--
Curved	Coke	17	53
Curved	Carbon	---	34
Straight	Carbon	---	13
Straight	80 Percent sand, 20 percent iron powder	13	31

[a]Ref. 35, pp. 13 to 16.
[b]Maximum test velocity attainable.
[c]Particles began to glow at this velocity.
[d]Some sparks at this velocity.

Although the added effect of the flow parameter on the total ignition energy may be small, especially for metals, it can become significant at higher temperatures and very high flow rates. While titanium is not normally suitable for use in oxygen, its sensitivity to oxygen makes it well suited to illustrate flow sensitivity to oxygen at relatively low pressures and flow rates. As illustrated in figure 3-15 (ref. 36), the reaction of titanium occurred at lower pressures and oxygen concentration under dynamic conditions than under static conditions. In this work (ref. 36, pp. 1 to 17) the static reaction data were obtained by tensile rupture of the specimen in a pressure vessel while dynamic reaction

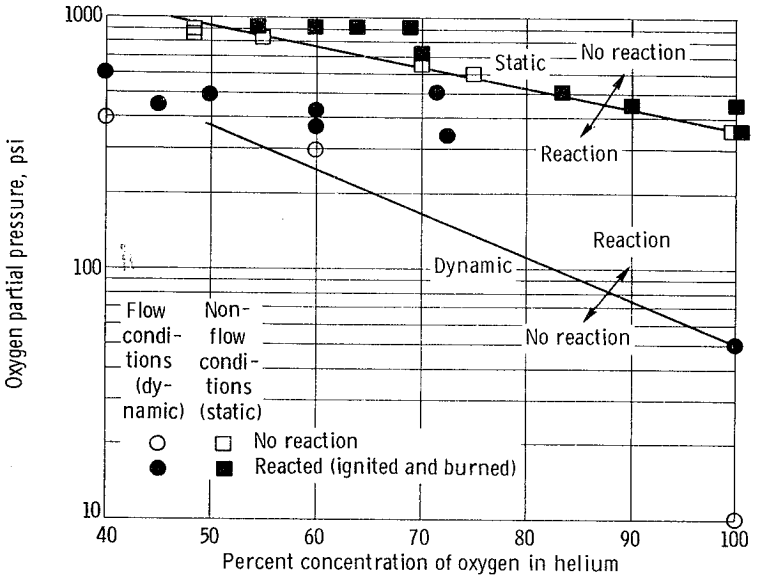


Figure 3-15. - Effect of flow and nonflow on the ignition of titanium foil as function of pressure and concentration (ref. 36, pp. 8 and 16). Tests at ambient temperature and with freshly exposed surface.

data were obtained by mechanical rupture of a diaphragm with subsequent gas flow through the rupture. This effect is also illustrated by tests with cryogenic oxidizers (oxygen-fluorine mixtures) on nonmetals (ref. 37, pp. 99 and 102). Sharp reductions in compatibility were measured, and ignition occurred as a function of flow velocities in both liquid and gaseous states. In both cases, flow conditions, in effect, added to the energy available to cause ignition or increased the sensitivity of the material to the exposure; this resulted in ignition under conditions where no ignition would occur statically.

Fluid shear forces, liquid cavitation, and sonic velocity effects in gases appear to be major causes of the sensitivity to high flow rates by various materials.

In summary, the primary source of concern under high velocity flow conditions is the entrainment of particulates and their subsequent impingement on a surface such as at bends in piping. However, the effects of extremes in flow velocity and pressure cannot

be ignored. Whether material erosion or ignition is due to entrained particulate impact and abrasion, to the erosive effects of the fluid flow, or to both, the fact remains that the effects exist and they increase with pressure and flow velocities. (See section 4.2 on erosion.)

Until a more quantitative limit can be established, the following practices are recommended:

(1) Where practicable, avoid sonic velocity in gases and cavitation in liquid oxygen; where this is impractical, use the preferred materials listed in section 3.7 and in chapters 5 to 9.

(2) If possible, avoid the use of nonmetals at locations within the system where sonic flow or cavitation can occur.

(3) Maintain fluid system cleanliness and limit entrained particulates as discussed in chapter 2, section 4.5.

3.5 FLAMMABILITY AND COMBUSTION

Despite the large volume of combustion and fire hazards research reported in the literature, very little information is directly applicable to or usable in oxygen system engineering, because most of it is the result of qualitative tests for specific applications rather than quantitative evaluation for general use.

Having standard flammability tests and procedures for testing solid materials is an important step in achieving more reliable and uniform data. This has been largely due to the needs of the Apollo program. These tests are specified in reference 38 and are summarized in section 3.6.

Gaseous phase flammability of fuels in air mixtures has been much more fully explored than solid phase reactions. Flammability limits for nearly all liquid and gaseous fuels are available in the literature. Data for selected fuels are given in table 2-V (p. 9). The data compiled in the following sections and in appendix F show fairly good quantitative correlations and indicate definite trends in the burning rate characteristics of solid materials in oxygen.

Burning rate data for selected polymeric materials are presented as a function of the oxygen pressure (or partial pressure for a mixtures with helium or nitrogen) in table 3-IX and figures F-1 to F-3 in appendix F.

The burning rate of a material varies depending on its initial temperature before ignition. If a material is uniformly heated close to its ignition temperature before ignition, its burning rate can be much higher than if it is ignited at room temperature. The entire surface may flash into flame if the material is ignited at a temperature near its ignition temperature. Therefore, it must be kept in mind that the burning rate data discussed

TABLE 3-IX. - COMBUSTION RATE OF SELECTED MATERIALS IN OXYGEN[a]

Material	Combustion rate, in./sec		
	Oxygen pressure		
	21 Percent oxygen, 1 atm	100 Percent oxygen, 0.2 atm	100 Percent oxygen, 1 atm
Cotton[b]	2.5	1.0	7.4
Dacron	.70	.90	2.30
Epoxy	----	----	.12
Neoprene	----	.10	.40
Nomex	.52	.31	.96
Nylon (fabric)	.32	.46	1.02
P.B.I.	----	.22	.40
Polyethylene	----	.06	.27
Polymethylmethacrylate (sheet)	.76	See figs F-1(k) and (l)	----
PVC	----	.30	1.0
Polyurethane	----	.56	.7
Silicone	----	.20	1.1
TFE (fabric)	----	See fig. F-1(q)	1.07
TFE (rod)	----	See fig. F-1(r)	No ignition
Viton-Fluorel	----	See fig. F-1(s)	----
Velcro	----	.24	.48

[a]See appendix F.
[b]Other than vertical burning, see fig. F-1(a).

here do not include the effect of initial temperature, since all the tests were begun at ambient temperature.

For any given oxygen partial pressure the burning rate is decreased by the presence of an inert diluent; at higher pressures the effect of the diluent increases, as indicated by the divergence of the burning rate curves in appendix F. However, the burning rate in all combustion supporting concentrations increases with pressure. For example, the partial pressure of oxygen in the normal atmosphere is about 0.2 atmosphere. From table 3-IX, in the case of Dacron, the combustion rate at 1.0 atmosphere total pressure for 20 percent oxygen (normal air) is about 0.7 inch per second and at 100 percent oxygen at the same partial pressure it is 0.9 inch per second. However, for 100 percent oxygen at 1 atmosphere it burns at 2.3 inches per second - about three times as fast. For nylon the rates are 0.32 inch per second for 20 percent oxygen at 1 atmosphere, 0.46 inch per second for 100 percent oxygen at the same partial pressure, and 1.02 inches per second for 100 percent oxygen at 1 atmosphere - over three times the normally expected burning

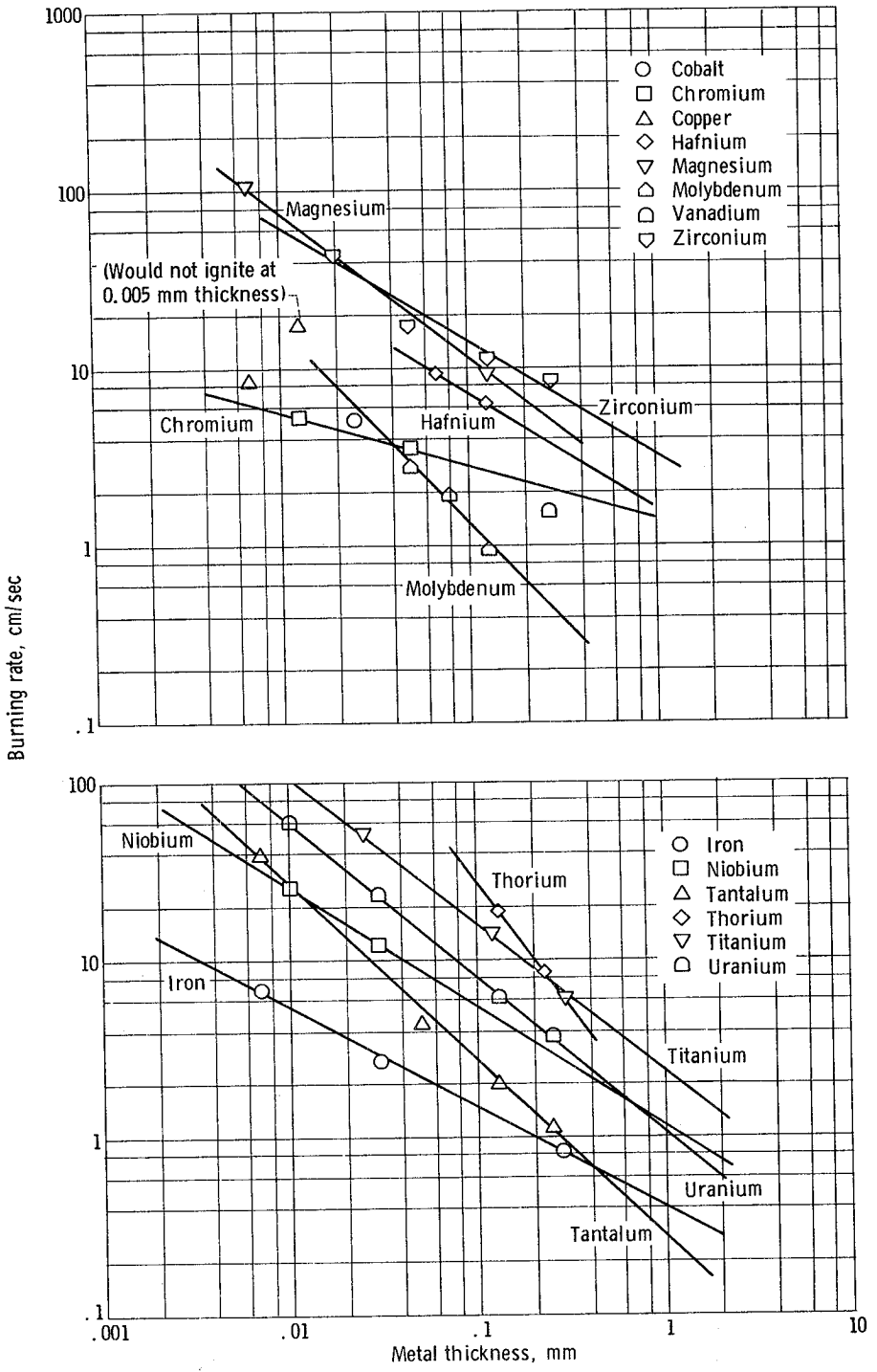


Figure 3-16. - Horizontal burning propagation rate for metals in 100 percent oxygen at pressure of 1 atmosphere (ref. 39, p. 151).

TABLE 3-X. - BURNING PROPAGATION RATE

FOR METAL RODS IN 1-ATMOSPHERE

OXYGEN PRESSURE

Material (1/16 to 3/16 in. diam)	Combustion rate, in./sec		
	Up	Down	Horizontal
Mild steel	0.3	0.5	0.435
Aluminum	10.0	-----	-----
309 Stainless steel	----	.171	.38
316 Stainless steel	.8	-----	.3
316L Stainless steel	.07	-----	-----
410 Stainless steel	.052	-----	.24
17-4PH Stainless steel	.12	-----	.3
4140 Stainless steel	.13	-----	.06
Nickel[b]	None	-----	None
Monel[b]	↓	-----	↓
Inconel[b]		-----	
Bronze[b]		-----	
Hastelloy	.06	-----	.08

[a]Ref. 40, vol. IV.

[b]These materials did not propagate combustion in oxygen at 1-atmosphere pressure.

rate. Teflon burns at 1.0 inch per second at 100 percent concentration and 1 atmosphere pressure. Nomex, a high temperature polyimide, and silicone rubber burn at about the same rate as Teflon.

An example of the effect of gravity on the burning rate is shown for cotton (fig. F-2) and Nomex (fig. F-8) in appendix F. There is a gradual increase in burning rate as the gravity level is increased; at zero gravity, the burning rate is the lowest.

In general, the burning rates of metals and nonmetals are the same order of magnitude; however, in most cases, the heat of reaction is greater for metals, resulting in a hotter fire. Burning rates for metals are shown in figure 3-16 (ref. 39) and table 3-X (ref. 40). The data in figure 3-16 show the effect of material thickness on the burning rate. Note that aluminum burned at 10 inches per second in a bottom ignition test (table 3-X) but that this burning was not propagated with the sample in the horizontal position (fig. 3-16).

A measure of the relative flammability of materials with oxygen is the oxygen index. The oxygen index value is the minimum percent concentration of oxygen in an oxygen-nitrogen mixture which will sustain combustion. Arithmetically, the oxygen index is expressed as

$$N = \frac{100 \times O_2}{O_2 + N_2} \text{ percent}$$

(The higher the number N, the greater the resistance to ignition.) The oxygen (O_2) and nitrogen (N_2) may be expressed in volume units or in moles. Table 3-XI (refs. 41 and 42) lists the oxygen index values for a number of materials. The oxygen index test is described in section 3.6.2.3.

TABLE 3-XI. - SELECTED OXYGEN INDEX FLAMABILITY TEST DATA[a]

Material	Oxygen index, N	Material	Oxygen index, N
Polyacetal, Celcon	14.9	Polypropylene (F. R.), Plaskon 1060	26.4
Polyethylene oxide, Polyox WSR-35	15.0	Nomex	26.7
Polyacetal plus 30 percent glass	15.6	Noryl SE-100	27.4
Cellulose acetate (dry = 0.1 percent water)	16.8	ABS (F. R.), Cycolac KL	27.4
Polymethyl methacrylate, Plexiglas	17.3	Noryl SE-1	28.0
Polypropylene, Profax 6505	17.4	Polypropylene (F. R.), Avisun 2356	29.2
Polyethylene[b]	17.5	Polycarbonate, Lexan 3412 plus 20 percent glass	29.8
Polystyrene, Shell 325	17.8	Polyphenylene oxide 534	30.0
Polypropylene, Profax P7401	17.8	Nylon 6-6 (saturated, about 8 percent water)	30.1
Cellulose acetate (wet = 4.9 percent water)	18.1	Polysulfone P1700	30.4
Polystyrene, Cosden 825 TV	18.2	Polyvinylchloride (PVC), Plaskon X2013	31.5
Polybutadiene[b]	18.3	ABS (F. R.), Cycovin KA	31.7
Polypropylene plus 30 percent glass	18.5	Epoxy-glass laminate, G. E. 11673FR-2	32.6
Acrylonitrile butadiene styrene (ABS), Cycolac T	18.8	Silicone rubber[b]	33.0
Cellulose butyrate (dry = 0.06 percent water)	18.8	Epoxy, Plenco 200D-B1242	38.3
Polystyrene, Dylene 8X	19.0	Polycarbonate, Lexan DL444	39.7
Cellulose butyrate (wet = 2.8 percent water)	19.9	PVC, Plaskon 2005	40.3
Arylon T-3198 natural	20.6	Alkyd resin, Plenco 1504-B6636	41.0
ABS plus 20 percent glass	21.6	Polyester, Atlac 711-050	41.5
Phenolic-paper laminate, Textolite 11571B	21.7	Polycarbonate, Lexan DL444 plus 20 percent glass	42.0
Polycarbonate, Lexan 191	22.5	Polyvinylidene fluoride	43.7
Arylon T-3198 white	22.8	PVC, Geon 101	45.0
Polypropylene (F. R.), Plaskon 1070X	23.7	Epoxy, Plenco 2000F-B6432	47.6
Polyphenylene oxide polymer, Noryl 731	24.3	Epoxy-glass laminate, G. E. 11635-FR-4	49.0
Nylon 6-6 (dry, as molded)	24.3	Phenolic (mica filled), Plenco 343-B817	52.8
Polycarbonate, Lexan 141	24.9	Porous carbon[b]	56.0
Epoxy-glass laminate, G. E. 11558G10	24.9	Polyvinylidene chloride, Saran	60.0
ABS (F. R.), Durez 2311	25.2	Polytetrafluoroethylene, Teflon	95.0
Polypropylene (F. R.), Plaskon 1050	25.6		
ABS (F. R.), Cycolac KT	25.8		

[a]Ref. 41, pp. 40 to 42.
[b]Ref. 42, p. 146.

3.6 COMPATIBILITY TESTING

There are several tests which are commonly used to obtain qualitative data pertaining to the compatibility of materials with oxygen. One of the most widely used compatibility tests is the mechanical impact test developed by the Army Ballistic Missile Agency for determining the compatibility of materials with liquid oxygen. There have been improvements in test equipment and techniques as described in reference 43. Ignition temperature determination is usually accomplished by means of some type of oxygen bomb test. Other types of tests, including flash and fire point, flow velocity, and pneumatic impact, are also employed in determining materials compatibility with gaseous oxygen. Furthermore, various flammability tests are used to determine burning characteristics of materials in oxygen environments such as spacecraft cabin atmospheres.

3.6.1 NASA Specifications for Materials Compatibility Testing

The Office of Manned Space Flight has issued a handbook (ref. 38) which establishes uniform material selection, evaluation, and control criteria for all materials that are under consideration for use in and around manned spacecraft during flight and test operations. Test specifications which were the basis for that handbook are references 44 to 46. These documents provide detailed descriptions of test equipment and procedures, some of which are summarized herein.

3.6.1.1 Mechanical impact testing. - This test is performed to determine the impact sensitivity of materials with liquid or gaseous oxygen (LOX or GOX). Tests are categorized as either ambient LOX mechanical impact or pressurized LOX or GOX mechanical impact. The basic test equipment for ambient LOX mechanical impact testing is described in reference 38 (pp. 4-60 to 4-66). For pressurized LOX or GOX testing appropriate modifications to incorporate a test chamber such as shown in reference 38 (pp. 4 to 82) must be made.

The test procedure involves dropping a 20-pound (9.04-kg) weight from known heights up to 43.3 inches (1.1 m) under near-frictionless conditions. The falling weight strikes a plunger (0.500-in. diameter) which delivers a blow to the material being tested as illustrated in figure 3-17. Complete test equipment description and procedures may be found in reference 38 (pp. 4-58 to 4-80).

Solid materials are tested in the form of 11/16-inch-diameter disks. Solid materials having up to 1/4 inch thicknesses are tested using disks in the thickness intended for actual use. Solid materials normally used in thicknesses greater than 1/4 inch are tested using disks having both 0.050 and 0.250 inch thicknesses. Greases, fluids, and other materials whose thicknesses are not dictated by conditions of use are tested as 0.050-inch layers. Paints and dry film lubricants are applied to 11/16-inch-diameter stainless

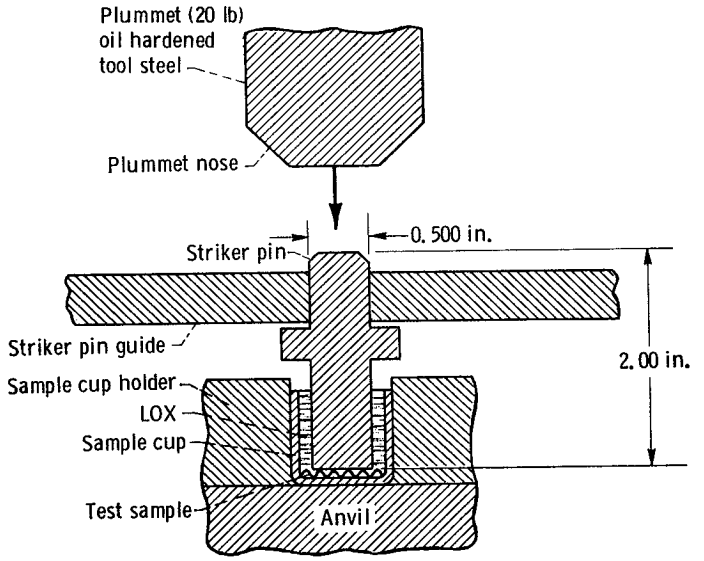


Figure 3-17. - Impact test striker assembly (ref. 45, p. 6).

steel disks in the same manner and thickness as intended for hardware application for testing. Leak check compounds, dyes, and dye penetrant systems are tested after application to 11/16-inch-diameter 6061-T6 aluminum disks which are unsealed and sulfuric acid anodized.

A material under test is subjected to twenty successive impacts at 72 foot-pounds (10 kg-m). More than one reaction in twenty impacts is cause for rejection. If one reaction occurs, the material is subjected to forty additional impacts. One reaction in the forty drops is cause for rejection. A reaction is defined as any of the following:

(1) Audible explosion

(2) Flash (electronically or visually detected)

(3) Evidence of burning (obvious charring)

(4) Major discoloration

A material proposed for use in liquid oxygen systems or subject to direct contact with liquid oxygen must be tested in a LOX environment and must meet the previous requirements. Materials proposed for use in high pressure (20 psia or above) LOX/GOX systems must meet the same requirements as a minimum. In addition, materials for use at 20 psia or above must meet mechanical impact acceptance requirements at the actual thickness (or thinner than actual) intended for use and at maximum use pressure and temperature. Material for use in high pressure environments (such as pressurized air) where the oxygen partial pressure is 20 psia or greater must meet pressurized LOX/GOX mechanical impact requirements.

A material which does not meet acceptance criteria for high pressure LOX/GOX systems is evaluated by determining its impact threshold level at maximum use pressure and temperature as outlined in reference 38 (p. 4-77). Based on this evaluation, the pro-

curing activity may approve the use of the material.

3.6.1.2 GOX pneumatic impact testing. - This test is used to determine the sensitivity and compatibility of materials with pure GOX when subjected to pneumatic impact. It is used in conjunction with mechanical impact threshold determination to verify acceptability for a specific application of a material which may be subjected to pneumatic impact loading (ref. 38, p. 2-5).

The material to be tested is placed in a sample chamber cavity where it is subjected to cyclic high pressure oxygen. This is accomplished by opening a quick acting supply valve, pressurizing the sample chamber cavity, equalizing the pressure at the test level, and then opening a chamber bleed valve. Standard impact frequency is 5 cycles within 60 seconds (automatically timed).

Materials are tested in an atmosphere of 95 (plus 5, minus 0 percent) GOX at pressures and temperatures equal to use pressures and temperatures. Standard tests are conducted at a temperature of $70^{\circ} \pm 10^{\circ}$ F. A detailed description of equipment and procedures may be found in reference 38 (pp. 4-83 to 4-87).

3.6.1.3 Upward propagation rate testing. - This test is intended to determine the flammability characteristics of materials when exposed along the bottom edge to an energized ignition source. The test is conducted at the highest pressure and oxygen concentration to which the material will be exposed.

The test is conducted in a chamber having sufficient volume to assure complete combustion of the test samples (minimum volume is 98 liters) and with pressure instrumentation and a viewing port. The test sample is supported within the chamber leaving an area 2 inches by 12 inches of the sample exposed. Ignition is accomplished by means of a standard silicone igniter (or equivalent) which is described in reference 38 (p. 4-3). Materials such as primers, paints, and coatings are applied on 3-mil-thick aluminum foil or the substrate material intended for use. Greases and fluids are applied to a substrate of 5-millimeter-thick fiberglass cloth for testing.

Materials are tested in a vertical position and exposed to an energized ignition source placed at the bottom of the sample for a period of 30 +20 or -10 seconds. Materials which fail to ignite or are self-extinguishing before 6 inches of the sample are consumed, with no sparking, sputtering, or dripping of flaming particles, are considered acceptable under this test. Flame propagation rates are measured and recorded on film. This test is described in detail in reference 38 (pp. 4-1 to 4-7).

3.6.1.4 Downward propagation rate testing. - This test is for determining the downward burning propagation rate of materials and their relative rankings. The test is similar to the upward propagation test except that the igniter is applied at the top edge of the test sample. The propagation rate is measured either by thermocouples or motion pictures (ref. 38, pp. 4-8 to 4-9).

3.6.1.5 Flash and fire point testing. - Flash and fire point testing is accomplished to evaluate the spark ignition characteristics of nonmetallic materials which have been

selected for application in and around manned spacecraft. Materials are normally considered acceptable if they exhibit a flash point above 400° F and a fire point above 450° F.

This test is conducted in a test chamber pressurized to at least 50 psia. A 0.5-gram sample is heated at a rate of 25 fahrenheit degrees per minute. A 2-millisecond, 50±20 millijoule spark is discharged between electrodes positioned 0.75 inch above the sample once for each 10 seconds.

Flash and fire occurrences are monitored visually through a glass viewport and electronically by a photoelectric cell detector. Flash point is defined as the lowest temperature at which the test specimen gives off sufficient flammable vapors that, when mixed with the test atmosphere and exposed to the spark ignition source, provides a non-self-sustaining flash or flame. The fire point is defined as that temperature at which the vapors continue to burn after ignition. As pressures are increased these temperatures tend to converge.

Data obtained from test rigs operating at pressures up to 50 psia when compared to those obtained at higher pressures are not identical. This anomaly is attributed to differences in spark generators because a higher spark voltage is required to obtain spark propagation at the higher pressures. While at low pressures the spark energy can be readily measured, at higher pressures even an approximate measurement is difficult (ref. 25, pp. 43 and 52). Accordingly, there is no assurance that test parameters are the same between high and low pressure setups. For a given pressure, however, the energy inputs appear repeatable which means that data for different materials under the same test pressure are consistent and permit ranking the materials. A description of test equipment and procedures may be found in reference 38 (pp. 4-10 to 4-16).

3.6.1.6 Electrical wire insulation testing. - This test is used to screen flammable wire insulation and electrical accessory materials such as wire bundle sleeving, heat shrinkable tubing, solder sleeves, bundle ties, cable clamps, and identification tags. The test is performed at use pressure and gas mixture conditions. Materials are considered acceptable if determined noncombustible in the test atmosphere during current overloads up to the melting point of the wire. The materials must also meet the requirements of the upward propagation test.

Testing is accomplished in a test chamber similar to the one used for the upward propagation test. Wires are assembled either in use configuration or in a bundle of seven insulated wires. Current is applied through one wire on the exterior of the bundle. Test current is increased in 5-ampere steps until either wire failure or ignition occurs. If the wire fails, voltage is maintained until it is positively established that current does not flow by bridging the gap to adjacent conductors. Equipment and procedures are described in reference 38 (pp. 4-17 to 4-20).

3.6.1.7 Connector potting flammability testing. - This test is intended to provide an evaluation of flammability characteristics of potting and coating compounds in a specific gas atmosphere environment. It simulates a short circuit or dielectric breakdown of

current carrying wires within a potting compound used to seal electrical connectors. Materials determined to be noncombustible under test conditions are considered acceptable.

The test is conducted at the highest pressure and oxygen concentration conditions for the intended use. The test chamber used is similar to the one used for the upward propagation test. Current is applied to one lead through a test connector potted with the test material. Current is increased until ignition of the potting compound occurs or the wire fails. If the wire fails, the voltage is maintained for 1 minute to establish that current does not flow by bridging the gap to adjacent conductors. For a description of procedures and equipment see reference 38 (pp. 4-21 to 4-29).

3.6.1.8 Other NASA compatibility testing. - Additional flammability tests are also required to determine combustion characteristics of materials in sealed and unsealed (vented) containers (ref. 38, pp. 4-42 to 4-48). Configuration testing to determine combustion characteristics, particularly propagation rates of materials as they are assembled in functional assemblies are also required (ref. 38, pp. 4-49 to 4-54). Such tests include simulated panel and assembly flammability tests and simulated crew bay configuration flammability verification tests.

In addition to the previously described tests, NASA also requires testing to verify compatibility with personnel, including odor and off-gassing products and carbon monoxide tests. These tests are to verify that, when heated, the materials do not give off products which will be toxic or objectional to crew members (ref. 38, pp. 4-30 to 4-36).

3.6.2 Tests Not Required by NASA

There are tests not necessarily required by NASA which are also of value in determining the compatibility of materials with oxygen. Generally these tests are designed to evaluate the ignition characteristics of materials in oxygen or combustion supporting environments.

3.6.2.1 Oxygen bomb test. - A typical autoignition test and test equipment, as described in reference 47 (pp. 2 to 6), include a reaction chamber about 12 inches in diameter by 18 inches high enclosed in a furnace. Temperature, pressure, and oxygen (gas) flow are the controlled parameters. Test samples are placed on a stainless steel tray located just above the gas inlet mixer. The tray may be independently temperature controlled or slaved to the main reaction chamber. Specimen temperature is measured by a thermocouple in contact with its exposed upper surface. Reaction chamber temperature is also monitored. The reaction chamber is pressurized with the test gas to the test pressure. A static or a dynamic test atmosphere may then be maintained. In the latter instance, the flow rate is controlled independent of operating pressure. After pressure and flow conditions are stabilized the furnace heater is activated to provide the

desired temperature profile and testing proceeds until ignition is obtained. Preignition and postignition reaction chamber atmospheres may also be sampled and analyzed for reaction products.

3.6.2.2 Thermogravimetric analysis testing. - The thermogravimetric analysis (TGA) technique may be employed for nonmetals in conjunction with flash and fire point testing techniques. In this test the weight or weight change of the sample being subjected to flash and fire point determination is determined by means of a precise spring balance. Sample weight loss and photoelectric cell output (for flash point determination) are plotted against test chamber temperature as illustrated in figure 3-18 (ref. 48). The

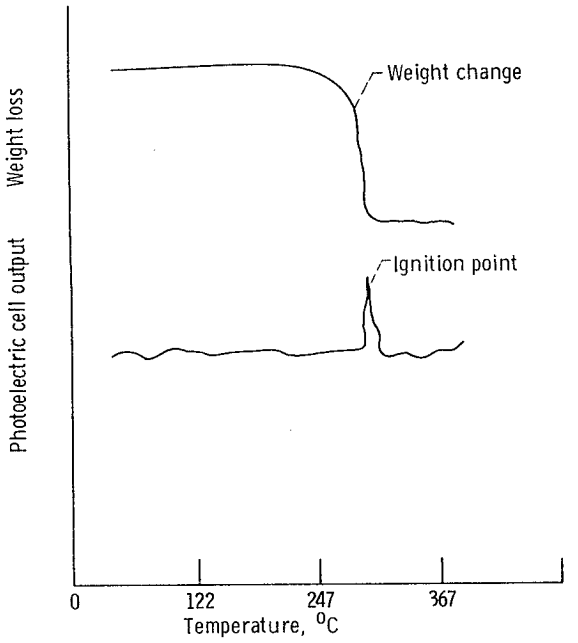


Figure 3-18. - Typical TGA ignition temperature determination (ref. 48, p. 107). Material, 85.5 milligrams polyvinyl chloride; test environment, 1.5 cubic centimeters per minute oxygen; heat rate, 24° C per minute.

temperature coincidence of an abrupt sample weight change and flash point indicator provides an ignition temperature determination. This test and associated equipment are described fully in reference 48 (pp. 101 to 104).

This test appears to provide a reproducible characterization of many nonmetal materials in oxygen atmospheres at a 1-atmosphere pressure or below.

3.6.2.3 Oxygen index testing. - The oxygen index test method is used to determine the relative flammability of materials. The test method is presently limited to physically self-supporting plastic test specimens. The oxygen index is the minimum concentration of oxygen, expressed as a volume percent, in a mixture of oxygen and nitrogen that will

just support combustion of the material under test.

Generally the test consists of igniting a specimen in a test column through which a slowly rising mixture of oxygen and nitrogen is flowing. The gas mixture is varied to determine the mixture which just supports combustion in the form of candle-like (top ignition) burning. This point is approached from both sides of the critical oxygen concentration in order to establish the oxygen index. The test and equipment are fully described in reference 49 (pp. 727 to 729). Data are tabulated in table 3-XI.

3.6.2.4 Velocity impact testing. - This test has been used by some investigators to rank materials according to their susceptibility to particle impact ignition. The test involves injecting a charge of metal particles (usually iron) into a flowing stream of oxygen. A sufficiently long flow path is provided to permit the particles to accelerate to the flowing gas velocity. At this point, the particles impinge a test specimen mounted in a cup-like holder in a combustion chamber vented to atmosphere. Ignition of a portion of the particles upon impact on the sample causes ignition of the particle cloud which then ignites the test specimen.

This test is rather limited in that there are many variables which affect the results, some of which are rather difficult to control. These include particle size and shape, distribution of particulate sizes and shapes within the flow pattern, and the thickness of the oxide film on both the particles and the sample. While test results generally confirm rankings obtained by other tests, the test is most useful as a verification test for specific applications, such as very high pressure, high velocity flow systems, where very high impact energies and possible ignition can occur. See also section 3.4.6.

3.6.2.5 Electrical arc ignition testing. - Tests to determine the susceptibility of materials to an electric arc have been conducted in a test chamber similar to the chamber used for high pressure flash and fire point testing described previously. An arc generator, electronic ignition sensing equipment, and temperature and pressure control equipment are also similar to that used for flash and fire point testing.

Test samples of varying thicknesses and a 0.500-inch diameter are prepared with a 3/32-inch hole in the center and supported between two electrodes. The electrodes are placed together through the hole. After pressure and temperature conditions are established, the electrodes are mechanically separated to initiate the arc. Ignition is monitored electronically. Tests are conducted at different arc current levels to determine current thresholds of no ignition and 100 percent ignition. The procedure for this test was developed by the White Sands Test Facility and is described in detail in reference 50.

Since actual power input to the test specimen cannot be accurately determined, this test also only provides a ranking of materials in terms of susceptibility to electric arc in proximity to the material. The power input can be accurately repeated, however, by controlling the arc current.

TABLE 3-XII. - PHYSICAL PROPERTIES OF PREFERRED POLYMERS

[Ref. 51, pp. 12.3.2-2 and 12.3.2-3.]

(a) Plastics

Common name	Fluorinated ethylene propylene	Polychlorotrifluoroethylene	Polyvinylidene fluoride	Polytetrafluoroethylene	Polyimide
Trade name	Teflon FEP[a]	Kel-F[b]	Kynar[c]	Fluorosint[d, e] Teflon TFE[a] Halon TFE[f]	Kapton H[a] Kapton F[a] Vespel[a] Polymer SP-1[a]
Physical and mechanical properties:					
Specific gravity	2.14 to 2.17	2.1 to 2.2	1.76 to 1.77	2.13 to 2.22	1.42
Tensile strength, psi	2700 to 3100	4500 to 6000	7000	2000 to 4500	[g]25 000; 10 500
Elongation, percent	250 to 330	30 to 250	100 to 300	200 to 400	[g]70; 6 to 8
Tensile modulus, psi	0.5×10^5	1.5×10^5 to 3×10^5	1.2×10^5	0.58×10^5	4.3×10^5
Compressive strength, psi	2200	32 000 to 80 000	10 000	1700	24 400
Flexural strength, psi	----------	7400 to 9300	----------	----------	14 000
Impact strength, ft-lb/in. of notch	No break	0.8 to 5.0	3.5	3.0	0.9
Rockwell hardness	R25	R110 to R115	D80 (shore)	D50 to D65 (shore)	H85 to 95
Thermal conductivity, Btu/hr/ft^2/($^\circ$F/in.)	1.75	0.9	0.9	1.75	2.2
Specific heat, Btu/lbm/$^\circ$F	0.28	0.22	0.33	0.25	0.27
Coefficient of linear expansion, in./in./$^\circ$F$\times10^{-5}$	4.7×10^{-5} to 5.8×10^{-5}	5×10^{-5} to 15×10^{-5}	6.7×10^{-5}	5.5×10^{-5}	28×10^{-5} to 35×10^{-5}
Volume resistivity, ohm-cm	$>2\times10^{18}$	1.2×10^{18}	2×10^{14}	$>10^{18}$	10^{18}
Clarity	Transparent to translucent	Transparent to translucent	Transparent to translucent	Opaque	Opaque
Processing properties:					
Molding qualities	Excellent	Excellent	Excellent	----------	----------
Injection molding temperature, $^\circ$F	625 to 760	440 to 600	450 to 550	----------	----------
Mold shrinkage, in./in.	0.03 to 0.06	0.005 to 0.010	0.030	----------	----------
Machining qualities	Excellent	Excellent	Excellent	Excellent	----------
Resistance properties:					
Mechanical abrasion and wear Tabor CS 17 wheel mg, loss/1000 cycles	----------	0.01	17.6	----------	----------
Temperature:					
Flammability	None	None	Self-extinguishing	None	----------
Low temperature brittle point, $^\circ$F	-420	-400	-80	-420	----------
Resistance to heat, $^\circ$F (continuous)	400	350 to 390	300	550	500
Deflection temperature under load, $^\circ$F	----------	258 (66 psi)	300 (66 psi), 195 (264 psi)	250 (66 psi)	----------
Chemical:					
Effect of sunlight	None	None	Slight bleaching on long exposure	None	Degrades after prolonged exposure
Effect of weak acids			None		None
Effect of strong acids			Attacked by fuming sulfuric		----------
Effect of weak alkalies			None		----------
Effect of strong alkalies			None		Attacked
Effect of organic solvents		Halogenated compounds cause slight swelling	Resists most solvents		Resistant to most organic solvents

[a]E. I. duPont de Nemours.
[b]Minnesota Mining and Manufacturing Co.
[c]Pennsalt Chemicals Corp.
[d]Polymer Corp. of Pennsylvania.
[e]Polypenco, Inc.
[f]Allied Chemical Corp.
[g]Film.

TABLE 3-XII. - Concluded. PHYSICAL PROPERTIES OF PREFERRED POLYMERS

[Ref. 51, pp. 12.3.2-2 and 12.3.2-3.]

(b) Elastomers

Elastomer types	Silicone rubber	Vinylidene fluoride hexa-fluoropropylene	Fluorosilicone	Polytrifluoro-chloroethylene
Trade name	Silastic[a] Silicone rubber[e, f]	Viton[b] Fluore[c]	Silastic LS-53[a]	Kel-F[c, d]
Physical and mechanical properties:				
Durometer range (shore A)	45 to 60	55 to 90	50 to 60	55 to 90
Specific gravity (base elastomer)	1.17 to 1.46	1.4 to 1.85	1.41 to 1.46	1.4 to 1.85
Density, lb/in.^{3} (base elastomer)	0.045	0.051 to 0.067	0.051	0.051 to 0.067
Tensile strength, psi:				
Pure gum	Under 400	>2000	1000	350 to 600
Reinforced	600 to 1500	----------	----------	----------
Elongation, percent:				
Pure gum	Under 200	>350	200	500 to 800
Reinforced	200 to 800	----------	----------	----------
Thermal conductivity, g, Btu/hr/sq ft/(^{o}F/ft)	0.13	----------	0.13	----------
Coefficient of thermal expansion, cubical, in.^{3}/in.^{3}/^{o}F	45×10^{-5}	27×10^{-5}	45×10^{-5}	----------
Electrical insulation	Excellent	Excellent	Good	Excellent
Rebound:				
Cold	Very good	Good	Very good	----------
Hot	Very good	Excellent	Very good	----------
Compression set	Good to excellent	Good to excellent	Good	Good to excellent
Resistance properties:				
Temperature:				
Tensile strength at 250° F, psi	850	300 to 800	----------	300 to 800
Tensile strength at 400° F, psi	400	150 to 300	----------	150 to 300
Elongation at 250° F, percent	350	100 to 350	----------	100 to 350
Elongation at 400° F, percent	200	50 to 160	----------	50 to 160
Low temperature brittle point, ^{o}F	-90 to -200	10 to -60	-90	10 to -60
Low temperature range of rapid stiffening, ^{o}F	-60 to -120	20 to -30	----------	-20 to -30
Drift, room temperature	Poor to excellent	Good	----------	Good
Drift, elevated temperature (158° to 212° F)	Excellent	Good to excellent	Excellent	Good to excellent
Heat aging (212° F)	Excellent	Excellent	Excellent	Excellent
Maximum recommended continuous service temperature, ^{o}F	480	450	500	400
Minimum recommended service temperature, ^{o}F	-178	-50	-90	-60
Mechanical:				
Tear resistance	Poor	Poor to good	----------	Poor to good
Abrasion resistance	Poor	Good	Poor	Good
Impact resistance (fatigue)	Poor	Poor to good	Poor	Poor to good
Chemical:				
Sunlight aging	Excellent	Excellent	Excellent	Excellent
Weather resistance	Excellent	Excellent	Excellent	↓
Oxidation	Excellent	Excellent	Excellent	↓
Acids:				
Dilute	Very good	Excellent	Excellent	↓
Concentrated	Good	Good	Very good	↓
Alkali	Fair to excellent	Poor to fair	Fair to excellent	Poor to fair
Alcohol	Good	Excellent	Poor to good	Excellent
Petroleum products, resistance	Poor to fair	Good to excellent	Excellent	Good to excellent
Coal tar derivatives, resistance	Poor	Excellent	----------	Excellent
Chlorinated solvents, resistance	Good	Good	----------	Good
Hydraulic oils:				
Silicates	Poor	Good	----------	Good
Phosphates	Good	Poor	----------	Poor
Water swell resistance	Good	Good	Excellent	Good
Permeability to gases	Good	Excellent	Fair	Excellent

[a]Dow Corning Corp.
[b]E. I. duPont de Nemours.
[c]Minnesota Mining and Manufacturing Co.
[d]CTFE compounded with vinylidine fluoride.
[e]General Electric.
[f]Union Carbon and Carbide.

3.7 PREFERRED POLYMERIC MATERIALS FOR OXYGEN SYSTEMS

Of the three general classes of materials (metals, cermets, and polymers), the polymeric materials as a class are the most sensitive to possible ignition in oxygen. Metals have a significantly higher ignition temperature than polymeric materials and they have the advantage of the protective oxide film coating. Because these advantages are highly variable, depending on the circumstances, preferred metals are discussed in context with their application in chapters 5 to 10. The cermets (fused metal oxides) and fiberglass (a silicate) are already oxidized so they will not "burn" in oxygen.

All polymers will burn in oxygen and some of them will ignite very easily compared to most metals (see section 3.4). However, a few of the polymeric materials have relatively high ignition temperatures (up to 500° C) and are highly resistant to ignition and chemical deterioration in oxygen. Polymeric materials that are most resistant to reaction with oxygen are the fluorocarbon plastics and elastomers. Next in resistance to oxygen are the silicone elastomers and the polyimide and epoxy resins. Nearly all plastics and elastomers can be exposed to oxygen with no apparent reaction. They may even be highly resistant to deterioration or reaction for short exposure times. But, care must be taken that materials considered for use in oxygen systems have the necessary resistance to oxygen attack and degradation for long term exposure.

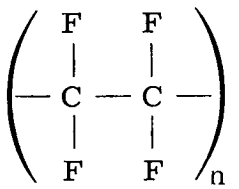
Selected physical properties of the preferred polymers are given in table 3-XII (ref. 51). For additional information see references 30, 52, and 53 (chs. 10, 11 and 12).

Although fiberglass is not a polymeric material, it is included in this discussion because of its special physical characteristics and its chemical inertness to oxygen.

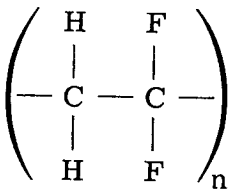
3.7.1 Fluorocarbon Polymers

The fluorocarbon polymers are the most stable polymeric materials because the fluorine atom has the highest oxidation potential of any other oxidizer, and, therefore, the fluorocarbon structure cannot be broken by a weaker oxidizer under normal conditions. The higher the degree of substitution of fluorine for hydrogen in the polymer structure, the more resistant the polymer is to further oxidation.

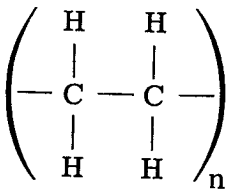
A fully substituted fluorinated polymer, such as polytetrafluoroethylene,



can only be reacted further by thermochemical degradation of the polymer which breaks the carbon-carbon bond. A partially substituted polymer, such as vinylidene fluoride,



is less resistant to attack, and regular polyethylene



is more readily attacked by strong oxidizers. The substitution for the fluorine atom in the polymer, especially with hydrogen, results in a significant decrease in chemical inertness and causes thermal degradation at a lower temperature.

The physical properties of fluorocarbon polymers are highly variable depending on the specific material, the average molecular weight, and its degree of crystallinity. The higher the average molecular weight, the greater the viscosity, hardness, and toughness. Material of thin cross section can be quickly quenched to yield low crystallinity, some increase in chemical stability and density, and a decrease in the permeability to gases. The effects of crystallinity on physical properties of some fluorocarbon resins are shown in table 3-XIII and the effects of crystallinity on creep are discussed in section 9.3.2.

Polytetrafluoroethylene (TFE) has a crystalline structure below 327° C. If heated above 327° C it becomes amorphous, translucent, and plastic and begins to soften significantly. TFE begins to pyrolyze above 400° C; when heated above 650° C it decomposes into the monomer (C_2F_4), elemental fluorine (F_2), carbon tetrafluoride (CF_4), and other fragments. If oxygen is present, some COF_2 may be formed. Oxygen, fluorine, and hydrogen all react with polytetrafluoroethylene at the decomposition temperature (approximately 650° or 1202° F). The basic reactions are as follows:

$$(-CF_2-)_n \longrightarrow C_2F_4 + (F_2 + CF_4 + C)$$
$$(-CF_2-)_n + O_2 \longrightarrow COF_2$$
$$(-CF_2-)_n + H_2 \longrightarrow HF + C$$
$$(-CF_2-)_n + F_2 \longrightarrow CF_4$$

These reactions are typical of the fluorocarbon polymers. TFE is also prone to stress crazing when exposed to halogenated solvents and cleaning agents. When used as seals,

TABLE 3-XIII. - PHYSICAL PROPERTIES OF FLUOROCARBON RESINS OF VARYING CRYSTALLINITIES

[Values were obtained by reading data points from the original data curves. Values in parentheses ( ) were obtained by interpolation. No actual data were obtained with liquid-oxygen temperatures in the original study. Change in crystallinity indicated by asterisk.]

Mechanical property	Temperature, °F	Fluorocarbon resins											
		Kel-F				FEP Teflon			TFE Teflon				
		Crystallinity, percent											
		40	55	60	70	44	49	51	47	49	52.5	66.2	71
Notched Izod impact strength, ft-lb/in.	-423	---	---	1.4	1.2	---	1.95	1.7	---	---	1.25	---	1.55
	-320	---	---	1.3	1.1	---	1.9	1.5	---	---	1.17	---	1.35
	(-297)	---	---	(1.25)	(1.07)	---	(1.9)	(1.5)	---	---	(1.15)	---	(1.39)
Modulus of rigidity, psi×10^3	-423	262	222	---	230	935	---	695	267	---	275	377	---
	-320	232	197	---	203	305	---	305	224	---	190	200	---
	(-297)	(229)	(192)	---	(195)	(275)	---	(275)	(216)	---	(175)	(175)	---
Tensile yield strength, psi×10^3	-423	28.5	20.5	---	18.0	23.8	23.5	---	---	20.0	19.0	15.6	---
	-320	24.9	17.5	---	15.3	19.1	18.8	---	---	16.0	15.4	10.6	---
	(-297)	(24.4)	(17.0)	---	(15.0)	(17.9)	(17.6)	---	---	(14.2)	(14.1)	(9.0)	---
Ultimate tensile strength, psi×10^3	-423	29.0	22.5	---	17.95	24.0	23.6	---	---	20.05	19.0	15.7	---
	-320	24.9	17.6	---	15.8	18.1	17.9	---	---	17.9	15.4	11.8	---
	(-297)	(24.1)	(17.5)	---	(15.3)	(17.0)	(16.8)	---	---	16.0	14.2	11.0	---
Tensile modulus, psi×10^6	-423	1.26	0.975	---	0.830	0.825	0.620	---	---	0.600	0.645	0.625	---
	-320	1.11	0.802	---	0.760	0.700	0.450	---	---	0.500	0.520	0.435	---
	(-297)	(1.08)	(0.800)	---	(0.750)	(0.652)	(0.430)	---	---	(0.465)	(0.480)	(0.400)	---
Elongation, percent	-423	ca 2	ca 1	---	<1	ca 5	ca 5	---	---	ca 4	ca 3	ca 2	---
	-320	ca 4	2.5	---	ca 1	ca 7	ca 7	---	---	ca 9	ca 8	ca 4	---
	(-297)	(ca 4.5)	(3)	---	(ca 1)	(ca 8)	(ca 7)	---	---	(9)	(8)	(ca 5)	---
Flexural strength, psi×10^3	-423	74.0	55.5	---	50.5	35.9	39.6	---	---	33.8	25.7	22.8	---
	-320	58.0	42.7	---	37.0	25.7	27.7	---	---	30.0	24.0	21.5	---
	(-297)	(53.5)	(41.0)	---	(35.0)	(24.0)	(25.5)	---	---	(28.0)	(23.0)	(20.5)	---
Flexural modulus, psi×10^6	-423	2.09	1.94	---	1.84	0.78	0.75	---	---	0.778	0.72	0.695	---
	-320	1.83	1.70	---	1.64	0.68	0.68	---	---	0.720	0.70	0.64	---
	(-297)	(1.70)	(1.64)	---	(1.59)	(0.67)	(0.66)	---	---	(0.690)	(0.64)	(0.61)	---
		50*	55	60	70	44	49	51	47	50*	56*	68*	71
Compressive strength, psi×10^3	-423	42.5	---	44.5	28.8	36.3	35.2	---	---	30.4	32.5	33.2	---
	-320	35.0	---	37.5	38.8	30.0	30.0	---	---	20.0	21.2	22.0	---
	(-297)	(34.0)	---	(36.0)	(38.8)	(28.5)	(28.5)	---	---	(18.5)	(20.0)	(21.5)	---
Compressive modulus, psi×10^6	-423	1.67	---	1.76	1.48	1.01	1.04	---	---	0.81	0.90	0.97	---
	-320	1.48	---	1.52	1.65	0.91	0.91	---	---	0.75	0.79	0.84	---
	(-297)	(1.27)	---	(1.49)	(1.65)	(0.90)	(0.89)	---	---	(0.72)	(0.76)	(0.81)	---
Coefficient of thermal expansion (total contraction from 70° F), in./in.	-423	0.011	---	---	---	0.017	---	---	---	0.0214	---	---	---
	-320	0.0093	---	---	---	0.0157	---	---	---	0.0205	---	---	---
	(-297)	(0.0090)	---	---	---	(0.0154)	---	---	---	0.0201	---	---	---

[a]Ref. 30, pp. 8 and 9.

gaskets, or other components in oxygen systems and under a stressed condition, halogenated solvents should not be used where exposure time is more than a few minutes. The threshold level of stress which can cause crazing is reported to be 4.1×10^6 to 5.5×10^6 newtons per square meter (600 to 800 psi) (ref. 54, p. 22).

Fluorinated ethylene propylene copolymer (FEP) is extrudable and is readily processed by common fabricating equipment. The notched Izod impact strength indicates that FEP is more resistant to impact fracture at cryogenic temperatures than either TFE or Kel-F.

Filled TFE and FEP have better resistance to deformation and cold flow, lower thermal coefficient of expansion, and better wear resistance than the unfilled Teflons (most common filler materials are metal powders and glass fiber). In the filled materials, elongation and impact strength are reduced. The glass-fabric-reinforced TFE and FEP are very strong and are used in applications involving tensile and flexural strength, as well as compression and shear. The room temperature mechanical properties of these materials are controlled by the strength of the glass fabric rather than the resin.

Chlorotrifluoroethylene (CTFE), an opaque colorless material, is exceptionally stable (comparable to TFE), highly temperature resistant, chemically inert, and a true thermoplastic. Chlorine in the molecule contributes to the translucency and the rigidity characteristics of the polymer. CTFE has superior resistance to cold flow over TFE; however, in most applications where creep or cold flow would be a problem, a fiberglass-filled fluorocarbon polymer may be preferred. The higher fluorocarbon has improved compressive yield and cold flow characteristics to some extent. However, the tensile yield and ultimate strength are decreased.

Vinylidene fluoride and hexafluoropropylene copolymer is a linear copolymer containing about 65 percent fluorine. It has excellent resistance to oxidation. O-rings molded from commercial compounds of this material make excellent static seals at temperatures from 260° to less than -184° C even though the material may be brittle at the lower temperatures.

3.7.2 Silicone Polymers

Silicone polymers are formed from a basic structure of alternating silicon and oxygen atoms cross linked with methyl, phenyl, or vinyl groups at each silicon atom. The silicone polymers are very stable at high temperatures (over 200° C). Reference 52 (p. 2-9) states that "at 500° F (260° C) after one-half hour exposure, silicone fiberglass laminates retain approximately 40 percent of initial strength." In a vacuum at 800° C, a 13 percent weight loss was measured, and at about 1200° C a 17 percent loss was obtained (ref. 52, pp. 2-9 and 2-10). The ignition temperature of silicone rubber is only 390° C. The permeability of silicone polymers to oxygen is very low even at

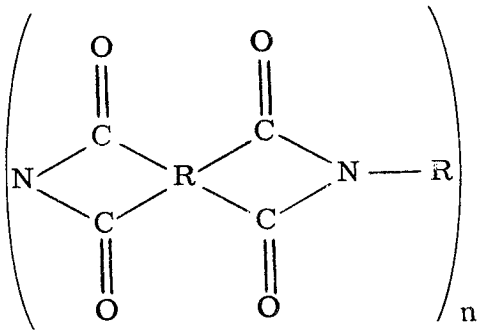
very high pressures. This is important to prevent rupture when suddenly depressurized after long periods of high pressure exposure. Experience with silicone O-rings in high pressure oxygen (over 6000 psia) has been very good in both static and dynamic seal applications. (See section 9.3.3.) However, the use of silicone rubber exposed to high velocity flow or possible high velocity particle impact is not recommended.

3.7.3 Fiberglass

Fiberglass materials are basically a mixture of oxidized silicon, metal silicates, phosphates, and borates, and because they are already oxidized, they will not burn or react with oxygen. However, processing agents and bonding materials for fiberglass laminates (such as epoxy resin) are flammable. Fiberglass is widely used as reinforcing filler in fluorocarbon materials to improve strength and reduce cold flow. Any application where fiberglass meets the physical requirements for temperature and stress may be considered for use in oxygen.

3.7.4 Polyimide Resins

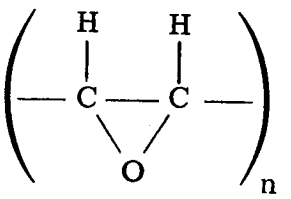
Polyimides have the basic structure



where R represents an aromatic groups which has a carboncyclic structure. Polyimides have a higher decomposition and ignition temperature than the epoxy resins and are used as wire insulation, film laminates, impregnants, and occasionally as bonding agents. They are stable at 315° C. Weight loss begins at about 370° C and reaches 40 percent at 815° C and over 90 percent when exposed to oxygen at 815° C (ref. 52, (p. 2-11).

3.7.5 Epoxy Resins

Epoxy polymers include a large family of materials having a basic epoxide structure of the form



A wide variety of curing agents and additives provide variations in physical properties useful in many applications, mainly as bonding agents. However, decomposition begins at about 300° C. Total decomposition occurs by 900° C (ref. 52, p. 2-5).

Epoxy resins will ignite in oxygen at their initial decomposition temperatures (300° to 310° C, see table 3-III) unless a flame retardant is added to increase the ignition temperature. Antimony trioxide is generally added for this purpose with some decrease in mechanical properties (ref. 52, p. 2-6). Epoxy resins are not recommended where exposure to LOX or high pressure oxygen is possible because of its limited physical and chemical compatibility.

CHAPTER 4. OXYGEN SYSTEMS ENGINEERING CONSIDERATIONS

Oxygen system failures or malfunctions result from three possible causes: insufficiently compatible materials (chemical stress), structural failure (physical stress), and system contamination, which results in solid particle interference or clogging and ignition sensitivity (physical and chemical stress). Most fluid system hardware such as valves, lines, and fittings are made of materials and have design features that are suitable for a wide variety of fluids. Much of this hardware may be used with oxygen. On the other hand, there are many subtle requirements that must be met in specific oxygen systems that can disquality a material or design feature used in the available hardware. The designer can eliminate many potential problems by design and design modifications of existing hardware that accommodate the special characteristics of oxygen. Many of these subleties for an oxygen system have been reviewed in the previous chapter with respect to chemical compatibility and physical phenomena. The following sections discuss some of the special considerations for oxygen systems engineering with respect to system design, fabrication, and use. The concerns for oxygen systems discussed in this chapter include the problems of leakage and erosion, difficulties that arise from dynamic processes, and the sensitivity of oxygen systems to contamination and cleaning requirements. Subsequent chapters discuss individual fluid system components.

4.1 FLUID SYSTEM LEAKAGE

One of the continuing problems with fluid flow systems is leakage through valves and from joints, coupling, and component interfaces and from mechanical penetrations such as rotating shafts, valve stems, and actuators. Leak rate control is especially important in spacecraft where fluid loss can be critical to the mission. Oxygen system leaks present the additional problem of fire hazard from local oxygen enrichment and possible impingement of oxygen on a combustible material. The leakage rate and the resulting hazard increases because of the erosive effect which gradually enlarges the leak path. The rate of erosion also increases with increasing pressure. Extremes in temperature, temperature cycling, vibration, and mechanical stresses also contribute to the leakage problem since they can cause a leak and affect the rate of leakage increase. Finally, seal

wear in dynamic seals or deterioration from assembly-disassembly of static seals contributes to seal failure and leakage.

The possible leakage path between two surfaces pressed together to effect a seal depends on the relative dimensions of surface asperities (texture), waviness of the contacting surfaces, and the elasticity of the seal. Under light seal loads the leakage gap will be influenced by the amount of surface texture roughness, waviness, nodules, pits, and scratches that protrude above some average plane and thus prevent full contact of the surfaces. At higher loads the asperities yield and tend to allow closer conformity of the contacting surfaces. The predominant flow path will then be through the roughness, scratches, and interconnecting pits until sufficient yielding occurs to close all leakage paths.

The prevention of leaks and leak rate control can only be affected by the proper seal configuration and a choice of seal materials that meet the physical requirements and are not affected by the fluid being sealed.

This discussion presents a brief review of seal leakage, its causes and measurement, and the main issues in effecting a good seal. The application of these principles in both static and dynamic seal design is covered in chapter 9; those for high speed rotating shaft seals for turbopumps are covered in chapter 6.

The practical definition of zero leakage is less than the smallest amount of leakage measurable or detectable by the most accurate means available for the fluid involved.

The definition of zero liquid leakage is given in reference 55 (p. 3) as "that value of liquid leak or flow rate at which the surface tension of the liquid has just overcome the pressure acting on the liquid, and no flow occurs - assuming a given pressure and leak diameter." Although zero liquid leakage may exist under these conditions, gas could evolve due to vaporization.

Reference 56 (p. 11) suggests that "no leakage" or "zero leakage" is not a practical requirement and recommends that zero leakage be defined as "a measurable quantitative value that is insignificant in the operation of the system."

Zero gas leakage does not actually exist because the transition from gaseous flow to molecular flow or diffusion varies with the type of gas and the leak path of diffusion path through the material. However, an arbitrary zero gas leakage curve (fig. 4-1) was developed by the Jet Propulsion Laboratory for use as a specification standard (ref. 55, p. 10). Leak rates above the line are considered true leakage. Leakage rates below the line are actually molecular diffusion which for high molecular weight gases can approach zero. The lower portion of the curve is based on a leakage of 1 standard cubic centimeter per year at a 1 atmosphere differential pressure. The arbitrary displacement of the curve at 10^{-7} cubic centimeter per second was considered necessary for practical considerations. A zero gas leakage definition as given in reference 57 (p. 14) is "no more than 1.4×10^{-3} standard cubic centimeter per second at 300 psig at ambient temperature." An example of a leakage specification for oxygen tank assemblies (including

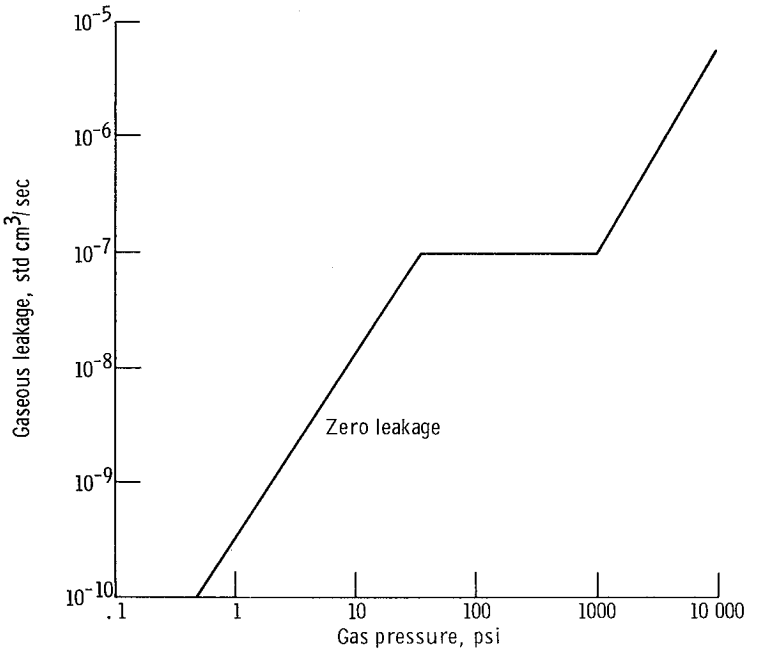


Figure 4-1. - Zero gas leakage (ref. 55, p. 10).

valve package) as used on the Skylab Orbital Workshop is 1×10^{-2} standard cubic centimeter per second helium at 3000 psig (ref. 58, p. 331).

4.1.1 Modes of Leakage

Fluid leakage can occur in four different flow modes: sonic or choked flow, turbulent flow, laminar flow, or molecular diffusion (permeation). Permeation is the diffusion of a fluid through a solid by molecular migration through the interstices of the material.

Equations for the various flow modes and flow characteristics as functions of pressure, temperature, and fluid properties are given in reference 56 (pp. 41 to 66).

Turbulent leakage flow occurs when the high velocity fluid cannot smoothly accommodate obstacles or disturbances in its natural flow path and pressure gradients are generated which tend to oppose flow. These pressure gradients cause the eddies and vortices characteristic of turbulent flow. Turbulent flow leakage generally results after erosion has enlarged the flow passage where viscosity and molecular forces are not effective and the flow passage length prevents choked flow. A Reynolds number greater than 2100 generally results in turbulent flow.

Choked flow or sonic flow in a gas occurs if the pressure drop across the leak passage or a constriction in the flow passage is greater than the ratio

$$\frac{\text{Pressure downstream}}{\text{Pressure upstream}} = \left(\frac{2}{K+1}\right)^{(K/K+1)}$$

where K is the ratio of specific heats of the fluid. The critical pressure ratio to achieve sonic flow for oxygen is in the range of 0.55 depending on the temperature of the gas.

The laminar flow equation is applicable for fluids when the Reynolds number is less than the laminar to turbulent flow transition value of approximately 1200.

The gradual transition of laminar flow to molecular flow is represented by combining the laminar flow equation and the molecular diffusion equation (ref. 59, pp. 55 to 63). However, the use of the combined equations should be limited to leaks where the flow path diameter is greater than 2×10^{-6} centimeter (ref. 59, p. 63).

Molecular flow occurs when the molecular mean free path at the average temperature is greater than the leak path diameter. When this condition exists, the average molecular motion as a result of the gas temperature and the molecular density gradient across the leak determines the flow rate.

4.1.2 Leak Path Growth

The most common characteristic of a leak is that it increases in rate with time because of erosion of the flow path and possible crack growth. The rate of leakage increase from erosion is affected by the differential pressure and type of fluid. As the pressure increases, the rate of leak path growth increases. The leak path growth is greater for turbulent liquid flow and two-phase liquid gas flow than for gaseous leakage. The erosion phenomenon is discussed in section 4.2 and crack growth from pressure stresses is discussed in section 5.1.5.

4.1.3 Leak Clogging

Very small leaks are sometimes blocked by very small particles or by liquids with a surface tension high enough to oppose the differential pressure. This blockage may be sufficient for a leak to go undiscovered.

"A phenomenon frequently observed is that if a container to be tested for leaks has at any time after manufacture been in contact with a liquid no leaks small in size (i.e., 10^{-7} atm cm^3/sec or smaller) will be found" (ref. 56, p. 74). If a liquid has entered a capillary tube, the pressure necessary to force it out of the tube is given by

$$P = \frac{4\theta}{d}$$

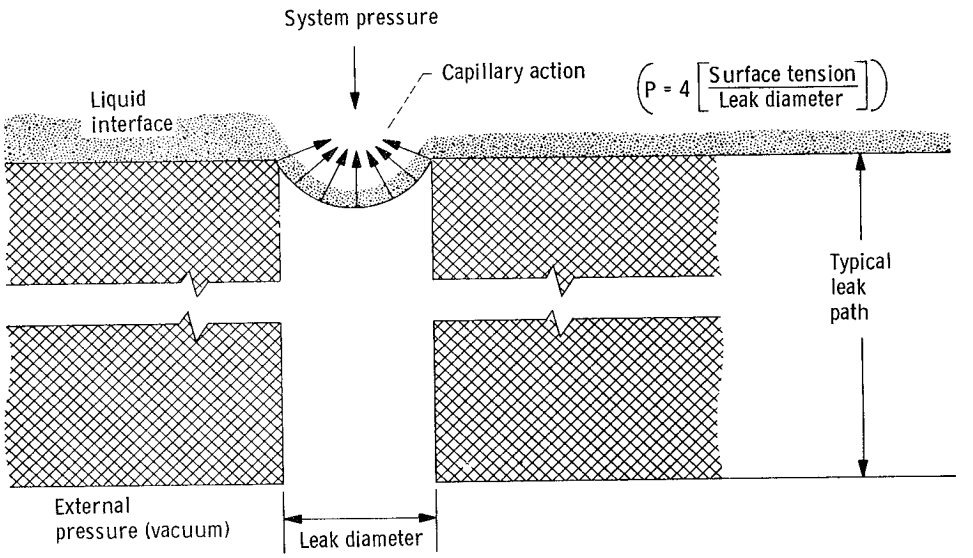


Figure 4-2. - Mechanism of clogging (ref. 55, p. 3).

(see also fig. 4-2) where θ is the surface tension of the liquid (usually expressed in dynes/cm), d the tube diameter (in cm), P the pressure (dynes/cm^2). (One atmosphere is equal to 1.01325×10^6 dynes/cm^2.) The phenomenon is of concern since water is generally used for hydrostatic testing. The differential pressure required to force water through a 1×10^{-6}-centimeter-diameter leak would be about 2.8 atmospheres (ref. 56, p. 75). However, since most leaks are not smooth round holes (they may be slits), it must be remembered that the leakage flow rate would be proportional to the cross-sectional areas. The pressure required to force the liquid through the leak is inversely proportional to the smallest cross-sectional dimension. Therefore, if the leak in the previous example were a slit with the smallest cross-sectional dimension one-tenth the diameter of the circle (of equal area), the pressure necessary to remove the water from such a slit would be approximately 28 atmospheres. For a liquid with a higher surface tension than water, the pressure could be much higher. On the other hand, the application of sufficient heat to vaporize the liquid would remove the clogged liquid and gaseous leak testing could then "discover" the leak.

4.1.4 Permeation

The permeation rate of contained gases through nonmetallic materials is an important consideration for low leakage sealing applications, since the permeability of the material may be considered a builtin leak. Permeation is measured as the volume of gas at standard temperature and pressure (STP) passing through a square centimeter of area per second per unit thickness of material per unit ΔP pressure where standard

temperature is 32° F and standard pressure is 1 atmosphere. The general formula for permeation given in reference 56 (p. 55) is

$$Q = \frac{K_p A \, \Delta P}{l}$$

where

Q flow rate, cm^3/sec

A area perpendicular to flow, cm^2

ΔP difference in partial pressure of gas across flow path, atm

l length of flow path, mm

K_p proportionality constant

(The units of K may be $(cm^3)(STP)(mm)/(sec)(cm^2)(atm)$.) Permeation rates for oxygen through selected materials are given in table 4-I (refs. 60 and 61).

TABLE 4-I. - PERMEABILITY OF POLYMERIC MATERIAL TO OXYGEN[a]

Material	Trade name or type	Permeation, P, $\frac{cm^3\ (STP)\text{-}mm}{cm^2\text{-}sec\text{-}atm}$	Temperature, °C
Vinylidene fluoride	X-500	0.0152×10^{-7}	25
chlorotrifluoroethylene	X-3700	.4150	25
Silicone rubber	RTV-502	420	23
	Silastic	448	25
	RTV-90	403	23
	RTV-501	409	23
Polyvinylidene fluoride hexafluoropropylene	Viton A	1.72	26
Polyvinyl fluoride	----------	.014	23
Polyvinyl chloride	Plasticized	.065	23
Fluorinated ethylene propylene	Teflon (FEP)	4.45	20 to 30
Polytetrafluoroethylene	Teflon (TFE)	7.6	25
Cellulose nitrate	----------	1.5	25
Polyvinylidene chloride	Saran 517	1.4	[b]25
Polychlorotrifluoroethylene	Kel-F	.023	[b]25

[a]Selected data from ref. 60.
[b]Ref. 61, p. XII-4.3.

4.2 EROSION

The phenomenon of surface damage and erosion from high velocity fluid flow is of particular concern in oxygen systems and occurs from several related flow processes. For example, erosion can be caused by

(1) Entrained liquid droplets in a high velocity gaseous flow impacting a solid

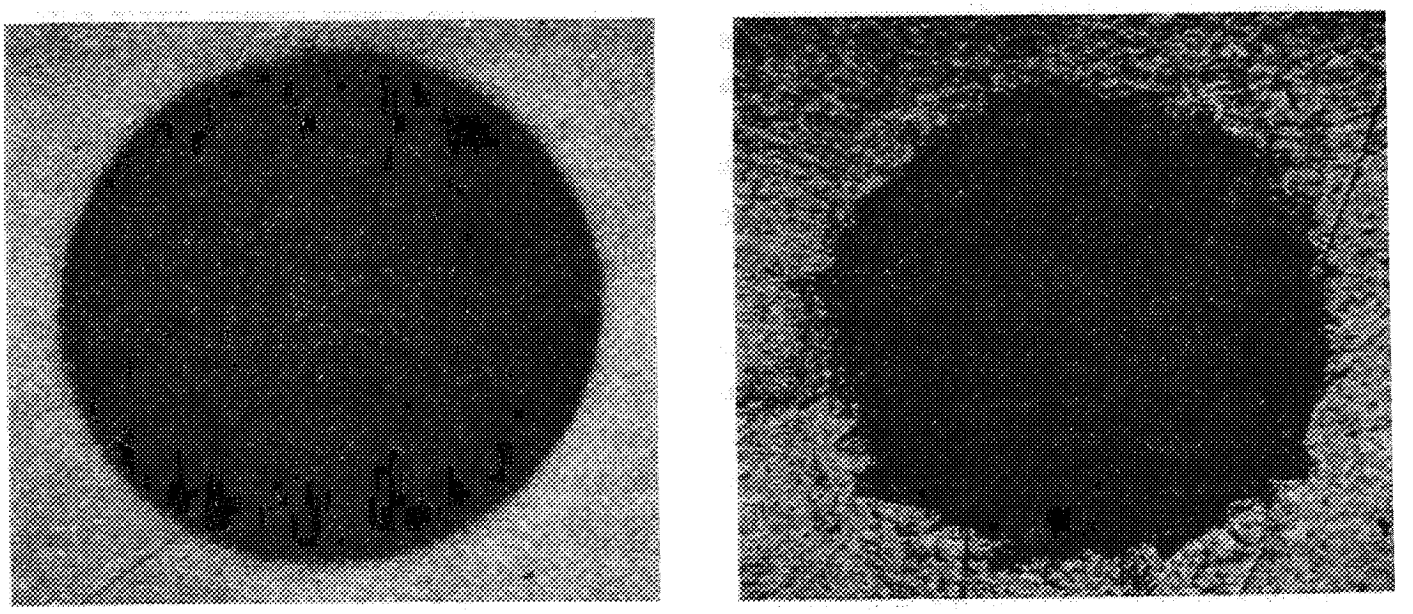
(2) Entrained bubbles or cavitation (two-phase flow) from localized reduced pressures or from excessive heat input to the fluid

(3) Entrained solid particles in a high velocity liquid or gaseous fluid

Reference 62 (pp. 239 and 240) states that "the cavitation damage process is very closely related to damage from droplet or particle impingement or conventional erosion."

Any dynamic condition that causes localized low pressure regions in the liquid that are lower than the local vapor pressure can cause cavitation. When very high relative velocities occur between the two- or three-phase fluid and the fluid handling hardware erosive impact forces are developed causing displacement of surface material.

Any example of erosion that is less common than the familiar high speed turbopump inducer cavitation was reported. It involved a high pressure fuel line in a J-57 turbojet engine. A small pin hole caused by cavitation erosion was attributed to a dent in the high pressure fuel line. In this failure the dent caused voids to form in the JP-4 (kerosene fuel) and then collapse downstream against the inner wall of the tube. The collapse of



(a) Face view before exposure.

(b) Face view after 15 minutes of flow.

Figure 4-3. - Face views of 0.006-inch-diameter Kel-F orifice (ref. 64, p. 28).

cavitation voids can produce impact pressures by implosion exceeding the yield strength of most metals. When the voids collapse, the surface of the metal is subjected to repeated local plastic deformations that result in ultimate fracture and disintegration (ref. 63, p. 18).

To demonstrate the erosive effect of high velocity flow, Kel-F orifices (0.006-in. diam) were exposed to successive oxygen "blowdowns" or venting from a pressure of approximately 12 000 psi (ref. 64, pp. 19 to 29). Figure 4-3 illustrates the erosive nature of high velocity flow resulting from these pressures. The Kel-F was exposed to 15 minutes of flow from successive blowdowns from 10 000 to 1000 psi of approximately 1 minute in duration. The amount of surface erosion that was caused by entrained particulate material and the amount resulting from fluid friction and turbulence forces are not known. However, the effect should not be unexpected even in systems where the oxygen is carefully filtered.

Consideration for possible seal leak erosion and high velocity flow erosion should not be limited to nonmetal materials as shown by the damage to the brass orifice in figure 4-4. In this test, the brass orifice (0.005-in. diam) was exposed to ultra-high pressure oxygen blowdowns and resulting high velocity flow for only 35.5 minutes.

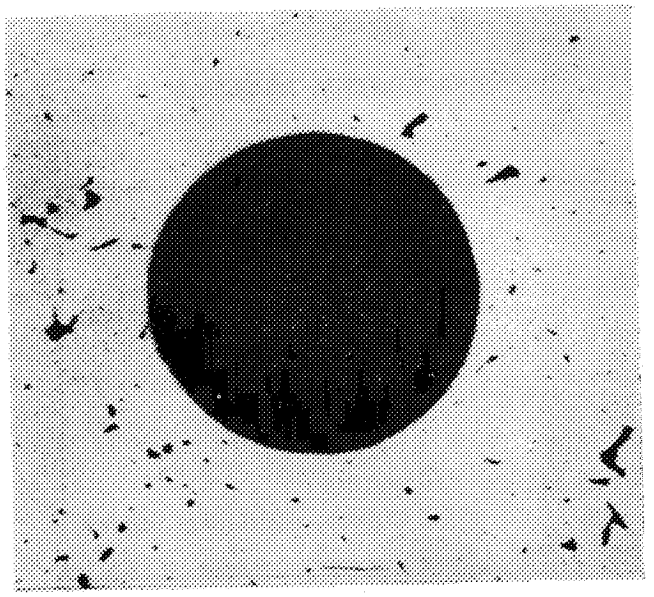
Absolute measurements of cavitation severity levels where surface deterioration begins for various materials in oxygen are not available. In general, erosion damage rates to materials in a dense liquid, such as mercury or liquid sodium, is considerably higher (3 to 20 times according to ref. 62, p. 239) than for a less dense liquid, such as water or liquid oxygen. Since liquid oxygen is less dense than water, its erosive impact on materials should be less. On the other hand, as a cryogenic fluid, liquid oxygen would tend to cavitate more readily in flowing systems since the temperature at which liquid oxygen is generally handled is near its boiling point.

Although every material has a critical velocity at which erosion will occur, this velocity is variable depending on the specific properties of the impact fluid, entrained material and its size and shape, and whether the fluid is liquid or gas. The following comparative data are helpful in confirming material selection for very high pressure applications.

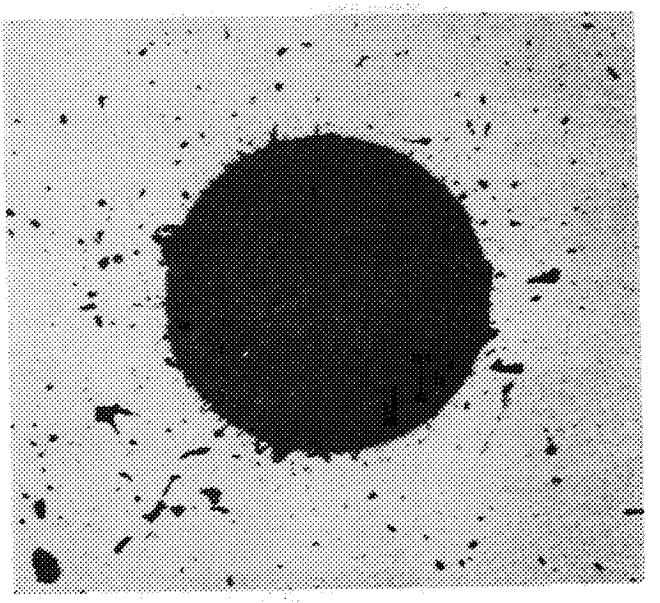
Figure 4-5 shows the rate of erosion as a function of the amplitude of energy input. This was done by vibrating the test material at 20±1 kilohertz at varying amplitudes while in contact with the erosive fluid (water in this case).

Note that in all cases the materials most resistant to cavitation are stainless steels and nickel alloys that fortunately meet most of the other selection requirements for very high pressure, high velocity oxygen systems.

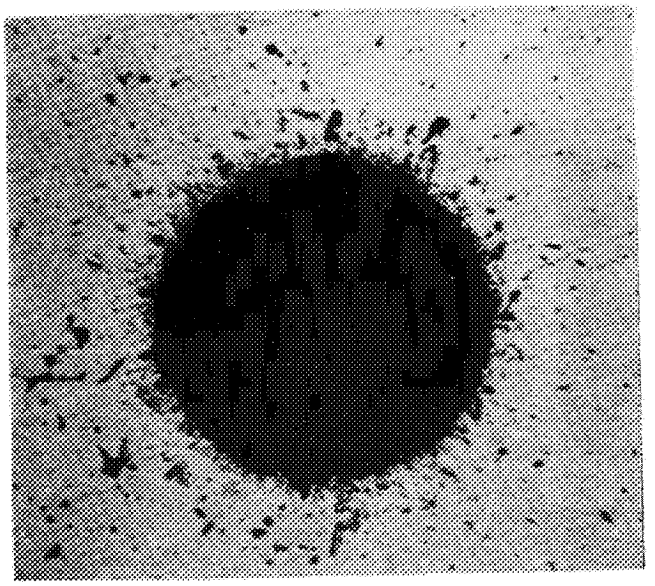
Four classes of materials in a general order of increasing resistance to erosion are glasses, plastics, cermets, and metals. A comparative listing of selected materials is given in table 4-II, which is a composite assembled from a wide range of test conditions and test fluids from reference 62.



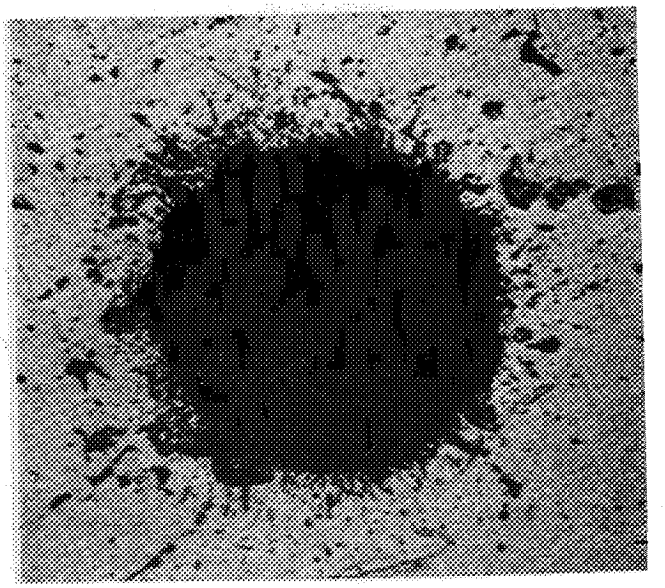
(a) Original 0.005-inch-diameter orifice.



(b) After 3 minutes and 7 seconds.



(c) After 13 minutes and 47 seconds.



(d) After 35 minutes and 29 seconds.

Figure 4-4. - Progressive erosion of 0.005-inch-diameter brass orifice exposed to high-pressure high-velocity flow (ref. 64, p. 45).

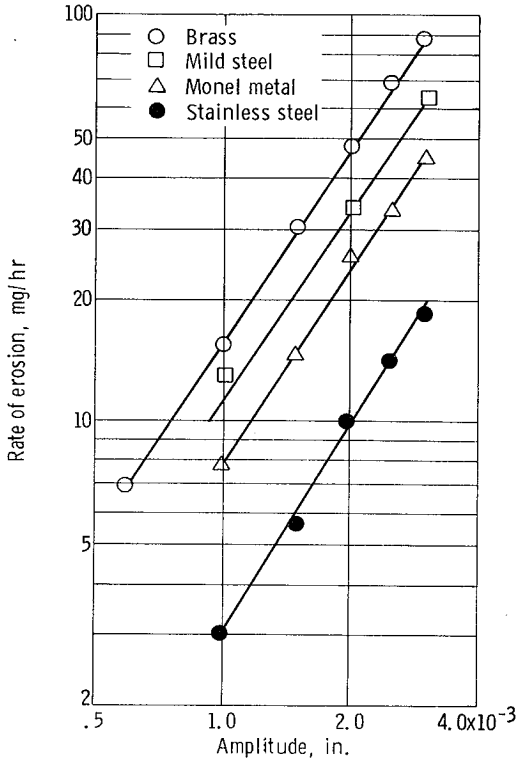


Figure 4-5. - Rate of erosion as function of amplitude (ref. 62, p. 167).

TABLE 4-II. - GENERAL ORDER OF INCREASING EROSION RESISTANCE OF SELECTED MATERIALS

Glass	Mild steel
Plexiglas	Stainless steel 400 series
Quartz	Monel
Polyethylene	Stainless steel 300 series
Aluminum 1100	Inconel 600
MgO	Steel A-286
Al_2O_3	Hastelloy X
Cast iron	Rene 41
Aluminum 2024-T4	Stellite
Bronze	Chrome plate (shot peened)
Brass	

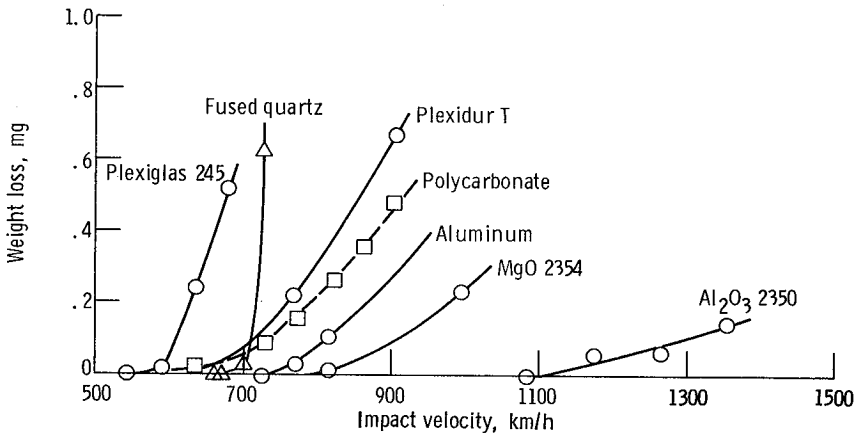


Figure 4-6. - Dependence of erosion depth on impact velocity (ref. 62, p. 46). Water droplet impact test time, 12 minutes.

The test results presented in figure 4-6 provide a relative "order of magnitude" velocity where erosion may occur from water. The nonmetals are affected between 500 and 700 kilometers per hour (455 and 638 ft/sec), and aluminum and the oxides are affected between 700 and 1100 kilometers per hour (638 and 1000 ft/sec).

The flow condition where cavitation and/or erosion begins for a given fluid temperature and ΔP is an important design consideration for oxygen systems and components.

Although cavitation as a destructive phenomenon is mainly associated with turbopumps, it may also occur any time the flow velocity is high and pressure falls below the vapor pressure of the liquid at the fluid temperature. When this occurs from throttling very high pressures (7500 to 10 000 psia) cavitation and impingement erosion may become damaging. In addition, in oxygen systems the erosion of the oxide surface and its continuous replacement would tend to accelerate the surface destructive phenomena.

Good design practice to prevent erosion damage would dictate good fluid dynamic contours, adequate filtration, materials selection most resistant to surface destructive phenomena, and assurance that the throttled pressure does not fall below the local vapor pressure when high differential pressures and flow velocities exist. This can be done by controlling the downstream minimum pressure or the downstream maximum temperature, or by decreasing the ΔP and the resulting velocity. Insulation to provide minimum heat transfer upstream of the throttling point and supercooling the liquid by jacketing are techniques to decrease the downstream vapor pressure. Filtration requirements are discussed in chapter 10.

4.3 SYSTEM DYNAMICS

Oxygen system deterioration or failure is frequently the result of dynamic forces generated within the system. These forces range from the well-known "water hammer" effect to thermal and physical stresses from cryogenic cycling and include many interacting combinations of forces. The potential damaging effect of these stresses are important enough that preventive measures should be considered at the earliest possible time in the design phase.

Failures of joints, couplings, seals, diaphragms, and bellows are most prevalent because they are the weakest part of the system. The most common causes of failure are due to over stresses from thermal expansion/contraction and water hammer. Water hammer forces in turn can cause adiabatic compression of gaseous pockets which can produce localized high temperatures. A combination of a fast acting valve closing against a column of liquid oxygen with high momentum can cause a water hammer pressure spike sufficient to force the fluid between the flange and seal. When this occurs in high pressure systems, experience has shown that autoignition sometimes occurs. Oftentimes, the metal seal between the flanges had taken a set from the strain of cryogenic to ambient temperature cycling thereby "loosening" the joint. Another form of fluid impact that can cause structural damage and possible reaction of oxygen with its container results from extremes of system size where very large masses of liquid can acquire extremely high momentum from very low pressure differentials. Very large flow systems such as the LOX fill drain system for the Saturn Booster or Shuttle at Kennedy Space Center require very long (1000+ ft) lines of large diameter. When a valve is opened allowing LOX to

flow into a line that long, the momentum of the column of liquid reaching the end can (and has) disintegrated the closure valve by a water hammer effect at the end of the line. Adiabatic compression of the gas in the line can also generate ignition temperatures. The potentially damaging momentum and resulting compression may also be generated by much smaller masses of liquid when accelerated by very high pressures. In both cases, flow rates and pressure buildups must be controlled by opening valves slowly enough or by providing a low flow rate bypass around major flow control valves.

A phenomenon which can be troublesome in the design of cryogenic systems is that of geysering. Geysering occurs when a long vertical tube with a reservoir at the top is filled with a cryogenic liquid such as oxygen. The heat transfer through the tube wall to the liquid causes gas bubbles to form. As the heating continues, the bubbles which form along the tube wall rise in the liquid and coalesce to form larger bubbles. If the tube is sufficiently long with respect to its diameter, the bubble formation and subsequent coalescence result in an expanding vapor slug which expels the liquid from the tube (almost explosively) into the reservoir above. Then, when the liquid in the reservoir drops back into the tube, a water hammer effect results which may cause structural damage to the system and the possible dumping of large quantities of liquid oxygen.

Tests were conducted (ref. 65, pp. 355 to 359) in which vertical tubes containing different fluids were heated at controlled rates to determine the predictability of geysering in order to avoid geysering by design. The geyser-nongeyser correlation shown in figure 4-7 resulted wherein the log of a parameter Z was plotted against the log of a parameter $(L/D)(D^{-0.68})$ where D is the pipe diameter, L is the heated pipe length; Z is defined as

$$Z = \frac{\frac{q}{A}L}{12\alpha(N_{pr})^{1/3}} \tag{1}$$

where A is the heat transfer area of the tube, N_{pr} the Prandtl number of the fluid, q the heat transfer rate, and α the thermal diffusivity.

While increased tank (ullage) pressure will decrease the frequency of geysering (ref. 65, p. 358), the tendency to geyser is not eliminated by the increased pressure. Therefore, it becomes feasible to design a propellant feedline in the normal manner to meet system requirements and then check the design against the correlation of figure 4-7 to determine if geysering will occur.

Having determined that for a particular design geysering will occur, there are several possibilities for eliminating the problem. First, the line diameter may be changed to take the design out of the geyser range. Second, the line may be insulated, as indicated by equation (1), to reduce the heat transfer rate in order to move the design out of

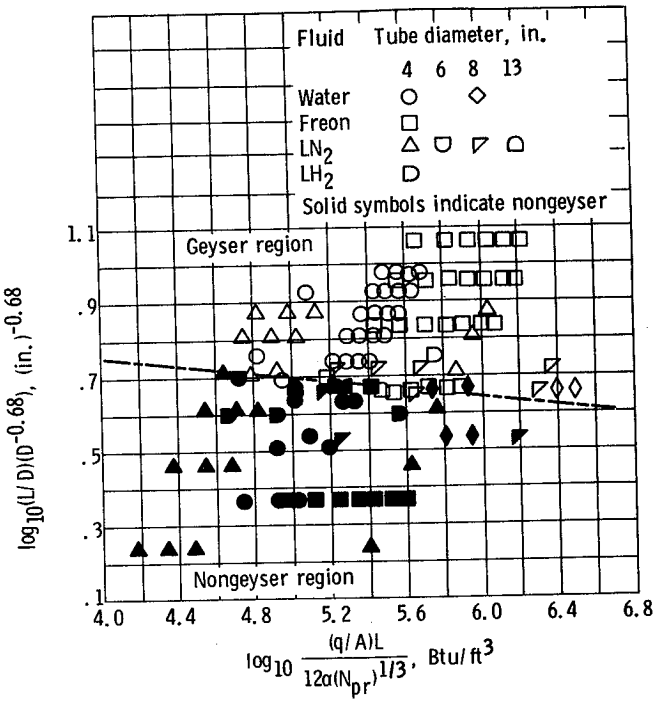


Figure 4-7. - Geyser-nongeyser correlation (ref. 65, p. 358).

the geyser range. A third method of preventing geysering is to recirculate the fluid from the reservoir through the tube at a rate high enough to prevent the fluid from reaching saturation temperature. Recirculation may be accomplished by thermal pumping, helium lift pumping, or mechanical pumping. Recirculation return lines may be added for the purpose, or if two or more feedlines from the same reservoir exist, one may serve as a return line.

4.4 GENERAL DESIGN CRITERIA

The design criteria summarized in this section are of a general nature and should be considered in the design of any oxygen system of component. They are applicable to the type of condition which is often inadvertently designed into a system but which could result in a hazardous situation or system malfunction, especially with high oxygen pressures (2000 to 7500 psi) or greater. Specific criteria applicable to various oxygen system components are reviewed in chapters 5 to 10.

The most important consideration in oxygen system design is the selection of materials which are compatible with oxygen. In addition to the compatibility and selection criteria developed in chapter 3, the design criteria and recommended practices for fluorine and fluorine-oxygen mixtures (FLOX) given in reference 37 (pp. 49 to 119) may also be used as aids in assuring a safe and reliable high pressure oxygen system. These

criteria are applicable because of the many commonalities between oxygen and the other elemental oxidizers.

When designing oxygen components or systems, every effort should be made to avoid cracks, crevices, pockets, and unnecessary cavities to prevent accumulating contamination and gas compressibility hazards. This is especially important for high pressure systems.

Contaminants caught between close clearances, accumulated in a cavity and impacted by high velocity particles, or even subjected to a gaseous compression or shock wave can ignite and burn and, in turn, ignite adjacent parts.

Filters should be installed at strategic locations to alleviate the hazard of particle impact ignition and clogging. The design and application of such filters are discussed in chapter 10.

Adiabatic compression of gaseous pockets, turbulent and erosive flow, entrained particles impinging and abrading the surfaces of the flow passage, and other local mechanical stress can all contribute to the failure and ignition of a local material. If the material is an ignition sensitive contaminant on a nonmetal component such as a gasket, ignition may occur more readily. Smooth, clean flow passages made of compatible materials preclude possible ignition. However, the maximum probable pipeline pressure spike should be such that the resulting adiabatic compression could not produce a final temperature in excess of the ignition temperature of any oxygen system component material.

Where possible, high pressure liquid oxygen systems that have gaseous oxygen pockets should be provided with liquid nitrogen jacketing. Adiabatic compression curves (see fig. 3-12 in section 3.4.4) show that the temperature of oxygen gas at atmospheric pressure and 0° C could be raised to the ignition temperature of Viton (400° C at 20 atm, fig. 3-10) at a pressure spike of 20 atmospheres or to the ignition temperature of a particulate contaminate at much lower pressure peaks. The selection of nonmetallic materials for use in gaseous pockets where pressure spikes could occur should be based on the highest possible adiabatic compression temperature and the ignition point of the material (see section 3.4.4).

When designing fittings, connections, and attachments, care must be taken with a connection interface of dissimilar metals. Metals which do not form acceptable couples (see table 3-I) should not be used in direct contact with each other when exposed to an electrolyte such as the moist atmosphere. When unacceptable couples are formed, a plating for one or both of the components may be selected from table 4-III to minimize galvanic action. Reference 66 contains specifications and criteria applicable to protective finishes (paints) and coatings and surface preparations appropriate to their application. However, the compatibility of coating materials with oxygen is not covered and must be determined by the user (see chapter 3 on materials compatibility). (Most paints and coatings should be restricted to external use in oxygen systems.)

TABLE 4-III. - SELECTED PLATING MATERIALS

Plating	Melting point, °C	Preferred base material	Application
Cadmium	321	Steels, iron, copper alloys	Widely used for bolts and fasteners to minimize corrosion and galvanic action
Chromium	1615	Steels, iron	Good for bearing surfaces and rubbing contact where resistance to wear, abrasion, and corrosion is needed; good for building up worn surfaces
Copper	1083	Ferrous alloys (improves adhesion where used as first coat for other plating)	Provides excellent undercoat base for chromium or nickel plate
Gold	1062	(a)	For maximum corrosion resistance
Nickel	1455	(a)	Optimum plating; highly corrosion resistant but low enough in cost for thick coatings, surface buildup, bearing refinishing, etc.
Platinum	1773	Copper alloys	
Silver	961	(a)	Bearing surfaces
TFE, FEP, and CTFE	(b)	(a)	Excellent chemical oxidation resistance; low friction; good for bearing surfaces and rubbing contact; sealing
Tin	232	Steels, iron	All purpose, low cost
Zinc	419		All purpose, low cost

[a]No restriction for use on oxygen compatible materials.
[b]For temperature limits see section 3.7.1.

The porosity of some materials, such as coatings, sintered materials, and some castings, may permit the absorption of gases, moisture, or other contaminants affecting their compatibility with oxygen. Whenever this possibility exists, care must be taken to assure no contamination. This can be accomplished by, first, heating the material in oxygen to the highest appropriate temperature and pressure which will oxidize the contaminant under controlled conditions, second, sealing the porosity by plating or coatings, or third, selecting an alternate material.

Many materials, especially nonmetal materials, have a variety of trade names for materials of the same or similar composition. Conversely, there are certain products

that have different chemical composition (and varying compatibility) but the same trade name. They are even similar in appearance. Worse yet, from an engineering control standpoint, materials of the same or similar composition are available in a variety of grades, purity, and quality. Some are excellent and some are poor, and their compatibility with oxygen can vary accordingly. Therefore, it is necessary that extreme care be used when selecting materials and verifying the quality of the fabrication material and the finished product. The designer and fabricator should verify the chemical composition of the materials selected by trade names, chemical names should be used for positive identification of the material, and the compatibility of the materials should be certified for use in the total environmental profile of pressure, temperature, flow rates, and exposure time to which they will be subjected.

Where the application is critical (such as with pressures over 2000 to 3000 psia or where the highest reliability is required in man-rated flight systems), the material to be used for fabrication of tanks and lines should be X-rayed to ensure quality material with freedom from unacceptable cracks and flaws.

4.5 CLEANING REQUIREMENTS AND PROCEDURES

One of the more critical aspects of engineering an oxygen system is the specification of and design for cleanliness. The appropriate level of cleaning must be specified by the designer. A detailed review of cleanliness requirements, cleaning procedures, and verification techniques is presented in volume II of this series (ref. 8). Criteria and data contained in chapter 3 of this volume may also be helpful when determining appropriate cleaning requirements. Provisions for maintenance and cleaning should be incorporated in system design.

When breaking into a system for maintenance or repair, the following must be done:

(1) Isolate, insofar as possible, the portion of the system to be entered.

(2) Verify that the system is drained and depressurized.

(3) Confirm that the entire system is at ambient temperature to avoid "breathing" contaminated air. That is particularly important if a part of the system is nitrogen jacketed. "Breathing" may also occur due to barometric pressure variations or temperature changes. A slight positive pressure or purge may be desirable to avoid "breathing."

(4) Cap or seal openings into the part of the system not being repaired as soon as possible.

(5) Purge and reclean repaired parts of the system prior to reinstallation.

It is desirable, also, to make provisions for periodic cleaning of possible contaminant traps in a system although every effort should be made to avoid such traps in the design.

4.6 COLD SHOCK CONDITIONING

All vessels and lines to be used for cryogenic service should be "cold-shocked" before final leak testing for operational use. The purpose of cold-shocking is to verify the integrity of the system for use at cryogenic temperatures. It is especially important that the expansion and contraction from ambient to cryogenic cycling does not impose excessive stresses on any component.

Components may be function tested while immersed in liquid nitrogen. Fluid systems should be conditioned with liquid nitrogen (preferably) or oxygen and function tested at operating conditions. After the system has been purged and vented and warmed to ambient temperature, all connections and threaded fittings should be retorqued.

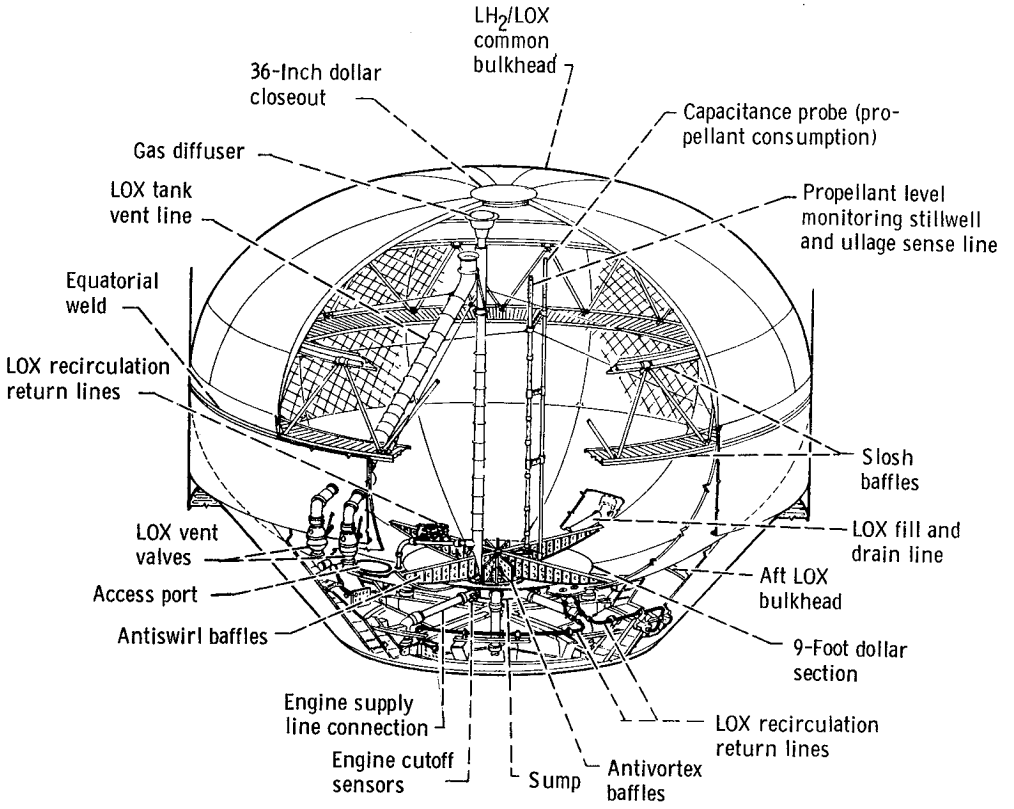
The entire system should be inspected for evidence of cracking, distortion, or other anomaly. Special attention should be given to inspection of welds. After repairs, cold-shock tests may be repeated prior to final pressure test.

CHAPTER 5. OXYGEN TANK ASSEMBLIES

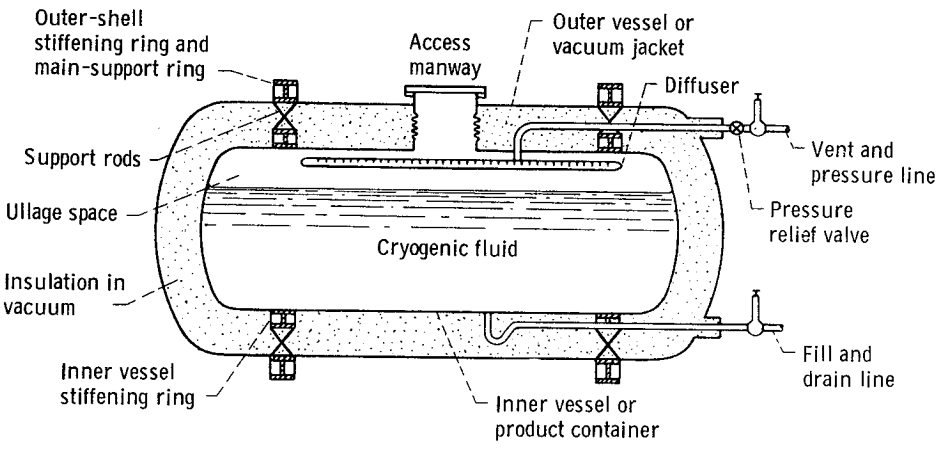
The tank assembly includes all the components necessary to contain and control the fluid. The complexity that an oxygen tank system can have is illustrated by the Saturn S-II stage flight weight liquid oxygen tank and the typical ground-based liquid oxygen tank shown in figure 5-1 (ref. 67). Failures of the tanks containing the oxygen have generally been caused by system contamination, structural failure, or incompatibility of tank components and component materials with oxygen for the conditions of use.

Accumulated system contamination can cause corrosion or can serve as a reaction initiator for ignition and combustion of the structural material with the oxygen. Structural failure of internal tank components, especially the rupture of metal components and the subsequent impact or collision of broken parts, can result in ignition and combustion of the material. Material compatibility considerations must include structural materials and component materials such as electrical conduits, insulation, and seals; these materials must be selected with consideration given to conditions that would exist for various component failure modes such as electrical shorts, overheating, rubbing, impact, and the like.

Tanks for liquid oxygen must be designed to withstand cryogenic temperatures and the slosh forces of the liquid. Tank component materials must be chemically compatible with oxygen, and appropriate cleanliness standards must be maintained. Thermal insulation requirements must be integrated with the design of any tank assembly that is to contain a cryogenic fluid. For example, the design of a tank assembly support system may be greatly influenced by the insulation requirements. Tanks for gaseous oxygen are pressure vessels so strength is a primary consideration as well as the factors of material compatibility and possible elevated operating temperatures. Weight is an important factor in flight weight tanks, whereas low cost and long life are more important than weight in ground based tanks. Therefore, design safety factors are lower for flight weight tanks than for ground-based tanks, and the probability of failure is increased unless rigid quality assurance measures are imposed.



(a) Saturn S-II stage oxygen tank (ref. 67, p. 5-4).



(b) Typical ground-based storage tank.

Figure 5-1. - Oxygen tank assemblies.

5.1 GENERAL DESIGN AND SAFETY CONSIDERATIONS

The most important factors in tank shell design and fabrication are the tank shape and method of support, material thickness control, alloy purity, weld strength, and assurance that the tank material is free of critical flaws. These factors are most critical in flight weight tanks where material thickness is minimized to keep the tank weight as low as practicable and where acceleration forces and structural stresses are generally greater.

References 52, 68, and 69 contain data on material properties applicable to tank systems. The structural design considerations and calculation methods for flight weight tanks are given in references 70 (pp. 329 to 352) and 71 (pp. 52 to 72).

Cycle life is an important consideration in the design of ground-based tanks which may be required to withstand many pressure cycles. Therefore, the design safety factors should include an allowance for the predicted cycle conditions.

Since design safety factors are generally higher for ground-based tanks, operating personnel are usually exposed to the pressurized system on a less restricted basis. Special considerations in ground-based mobile tank design include adequate load distribution in the tank suspension system to meet all road and load conditions and baffle mounting to withstand relatively high sloshing forces. A general minimum criteria used for mobile tank loadings is 2 g's vertically downward, 2 g's longitudinally, and 2 g's laterally. All tank components should be designed to meet the loads imposed plus the required safety factor. The structural design considerations for the tank shell and suspension system of ground-based storage and mobile tank systems are included in reference 72 (pp. 2-1 to 2-43).

5.1.1 Safety Standards and Specifications

Design standards and specifications have been established to assure adequate safety of ground-gased pressurized systems. These standards and specifications are generally applicable to cryogenic systems and should be considered in the design of stationary and mobile ground based liquid and gaseous oxygen tanks. They are listed here for convenience:

(1) ASME Boiler and Pressure Vessel Code, Section VIII, Division 1, 1971 (ref. 73)

(2) ASME Boiler and Pressure Vessel Code, Section VIII, Pressure Vessels, Division 2, Alternative Rules, 1971 (ref. 74)

(3) ASME Boiler and Pressure Vessel Code, Section IX, Welding Qualifications, 1971 (ref. 75)

(4) Air Force Technical Order T.O. 00-25-224, Welding High Pressure and Cryogenic Systems (ref. 76) (includes airborne and ground systems)

(5) American Petroleum Institute Standard No. 620, Design and Construction of Large, Welded, Low-Pressure Storage Tanks (ref. 77)

(6) Compressed Gas Association Tentative Specification for Insulated Tank Trucks, CGA-341 (ref. 78)

(7) Code of Federal Regulations, Title 49, Transportation Parts 100 to 199 (ref. 79)

The Code of Federal Regulations (Title 49) covers the rules and regulations governing transportation of explosives and dangerous materials by common carrier (ref. 79, section 170-179). Cargo tanks for liquid or gaseous oxygen must meet the specifications contained therein.

One of the more important considerations within the Code of Federal Regulations is the required retesting of cargo tanks every 5 years (ref. 79, section 173.33).

5.1.2 Design Safety Factors and Proof Pressures

Maximum allowable stress values for materials used for ground-based tanks are given in reference 73. The mechanical properties considered and the factors applied to establish the maximum allowable stresses are given here. At temperatures below the creep range, the maximum allowable stress value for ferrous materials and for nonferrous materials is the lowest of these:

(1) One-fourth of the specified minimum tensile strength at room temperature

(2) One-fourth of the tensile strength at operating temperature

(3) For ferrous materials, five-eighths of specified minimum yield strength at room temperature; for nonferrous materials, two-thirds of specified minimum yield strength at room temperature

(4) For ferrous materials, five-eighths of yield strength at operating temperature; for nonferrous materials, two-thirds of yield strength at operating temperature

For flight tanks, the design is optimized around the tank material strength to weight ratio parameter. Factors of safety normally used for booster tanks vary from 1.0 to 1.1 based on yield strength and 1.25 to 1.5 based on ultimate strength of the material. The higher values are applicable to manned vehicles. Table 5-I is a list of suggested safety factors for various circumstances.

In applying the safety factors listed in table 5-I, the maximum allowable working stress is computed for each safety factor pertaining to the particular circumstance or condition and the lower value is used. Proof test pressures are normally in the range of 105 to 150 percent of the maximum tank working pressure. To prevent general yielding of the tank shell during proof tests, stresses are normally limited to values equal to or less than the yield strength of the tank material or the welds. Procedures for determining an adequate proof test are outlined in reference 80 (pp. 12 to 17).

TABLE 5-I. - SUGGESTED SAFETY FACTORS FOR FLIGHT WEIGHT OXYGEN TANKS[a]

Circumstance or condition	Yield safety factor	Ultimate safety factor
No hazard to personnel or vital equipment (unmanned)	1.0	1.25
Special safety devices provided for personnel (escape system or special shielding)	1.1	1.35
Hazard to personnel or vital equipment	1.33	1.65

[a]Ref. 70, p. 334.

Some typical design and test pressures and safety factors for flight oxygen tanks are presented in table 5-II.

TABLE 5-II. - TYPICAL OXYGEN TANK DESIGN DATA FOR FLIGHT WEIGHT TANKS

System	Vessel application	Vessel dimensions, in.	Vessel material	Design pressures, psig			Ultimate safety factor
				Limit	Proof	Burst	
Atlas	Propellant	120 diameter by 480 length then taper to 48 diameter over 120 length	301 stainless steel, extra full hard	26.0	33.0	49.0	1.88
Centaur		120 diameter by 87 length ellipsoid	301 stainless steel, extra full hard	48.0	------	60.0	1.25
Saturn I-C		396 diameter by 517 length	2219 aluminum	49.3	51.8	69.1	1.4
Saturn II		396 diameter by 264 length	2014 aluminum	84.4	------	118.0	1.4
Saturn IV		130 radius segments	2014 aluminum	70.4	------	98.5	1.4
Apollo ECS	Surge tank	14 by 13	Inconel 718	1020	1356	1530	1.5
Apollo ECS	Cabin pressurization	12.62 by 6.92	Inconel 718	1210	1600	1800	
Apollo SM	Fuel cell		Inconel 718	1020	1356	1530	
Apollo LM	Descent breathing	23.522 by 21.722	D6AC carbon steel	3000	3990	4500	
Apollo LM	Ascent breathing	14.500 by 11.968	Inconel 718	1000	1330	1500	

5.1.3 Corrosion

There is no possibility of significant chemical corrosion inside the tanks filled with uncontaminated liquid or gaseous oxygen. The problem of inside corrosion begins when the tank is empty and opened to the atmosphere. Exposure to atmospheric moisture and

contaminants is a serious corrosion hazard. The use of a purge or pressurant gas containing moisture or other contaminants will also contribute to the corrosion process. Purge and pressurant gases should have a dew point lower than -50° F and should be filtered to meet system requirements (see chapter 10).

Day-night temperature cycles and atmospheric pressure variations can cause extensive corrosion damage in a relatively short time due to the breathing of moist air. The breathing of tanks and oxygen systems in a standby or stored condition must be prevented to avoid contamination. This can only be prevented with certainty by maintaining a slight positive pressure inside the system at all times. Sections that have been isolated and opened for maintenance should be purged and appropriately cleaned following the maintenance operation. For additional discussion of corrosion refer to section 3.2.

5.1.4 Stress Corrosion Cracking

The possibility of stress corrosion cracking must be reviewed during oxygen tank design especially where high internal pressures or mounting load distributions can cause high stress concentrations. The resulting strain in the presence of an electrolytic agent such as moist air or water can result in structural failure. In addition, evidence indicates that the presence of oxygen and the process of oxide film formation aggravates stress corrosion cracking (see sections 3.1 and 3.3). An example of rapid stress corrosion failure is cited in reference 81 (p. 14). A type D6AC alloy steel heat treated to 220 to 240 ksi tensile strength was used to store very high pressure gaseous oxygen in the Apollo EVA system. During hydrostatic testing of one of the tanks, an external surface flaw was exposed to water. (The tank was tested under water for safety.) The tank subsequently failed, and failure was considered to be due to stress corrosion. The corrective action was to use oil for hydrostatic testing and discontinue the water immersion procedure.

5.1.5 Cyclic Stress and Cycle Life

Tanks that are pressurized and depressurized many times during testing and/or during their life are subject to fatigue failure due to crack propagation and flaw growth at stress concentration points. Stress concentrations usually occur in zones of discontinuity such as around inspection openings, flanges for manholes, and pipe entry bosses. Residual stresses from welding the tank assembly can also cause local areas of high stress.

Much work has been done in the field of fracture control for metallic pressure vessels. Although this work has helped to clarify the causes and characteristics of fracture processes and fracture mechanics, the full clarification is only evolving. However,

fracture mechanics theory has proven itself to be a valuable design tool for pressure vessels.

Cycle fatigue failures usually start at existing cracks, structural flaws, or material blemishes in areas of high stress concentration. The maximum stress occurs at the apex of the crack where the material is parting. The rate of failure is higher and the cycle life is lower for tank materials of low ductility. Since the crack growth is dependent on the level of stress at the apex, the tank should be designed with a factor of safety applied to the local maximum stress.

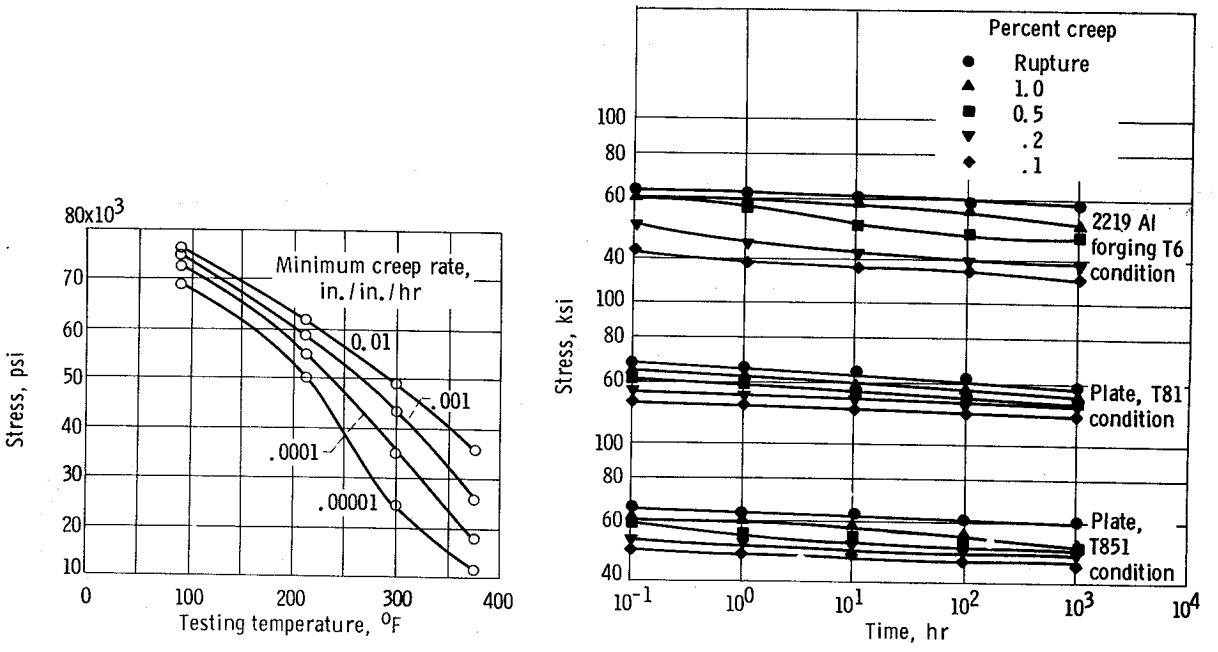
Critical flaw size and cyclic effects analysis techniques show that the size of flaws or surface cracks in the material of a finished tank may materially affect the expected tank life. The technique permits calculation of the critical flaw size and maximum crack tip stress required to cause failure at a given applied stress level. The mathematical equations and procedures for determining these limits are presented in reference 80 (pp. 5 to 10 and 23 to 25). Although these calculated stress intensity and crack growth predictions are only approximate, they provide valuable supporting information for design consideration.

Sheet stock for tanks should be screened to remove any material with visible flaws, cracks, or discontinuities greater than critical size. The remaining material is generally inspected by dye penetrants, X-ray, ultrasonic, or ferromagnetic methods as required for assurance that flaw sizes are less than the critical size.

An excellent source of practical fracture mechanics design data is reference 82. The data include state-of-the-art information on critical plane strain stress intensity factors, threshold stress intensity factors in corrosive media, sustained load crack growth rates, and fatigue crack growth rates.

5.1.6 Creep

Tanks for use at room temperatures or above may be subject to creep and should be evaluated for this possibility. Although creep in metals is usually associated with high temperatures, some materials such as aluminum exhibit a slight tendency to creep at room temperature. Therefore, if tank pressurization stresses are long in duration at stress levels near the yield stress, the possibility of significant creep exists. Creep data are usually obtained by subjecting a specimen of the material to a constant load at a specific temperature and measuring the change in length as a function of time. Typical creep and creep rupture curves are shown in figure 5-2 for selected aluminum alloys. Additional creep data are available in references 69 and 68.



(a) Creep rates as function of temperature for 7075-T6 aluminum (ref. 20, p. 949). 0.040-Inch clad sheet.

(b) Creep and creep rupture curves for 2219 aluminum. Creep as function of time and stress at room temperature (ref. 69, code 3205, p. 17).

Figure 5-2. - Typical creep and creep rupture curves.

5.1.7 Weld Joints

Good weld joint design and welding techniques are necessary for a reliable tank structure. Since the strength of the heat affected zone at a weld joint is less than that of the parent material, increased thickness must be provided in this area to achieve a strength comparable to that of the parent material. Ideally, the weld zone thickness buildup should be symmetrical to minimize bending stresses (see fig. 5-3). Mismatch between butt welded components of pressure vessels can also result in substantial local increases in stress.

Bending stresses must also be considered at curvature discontinuities and abrupt changes in thickness that occur at tank wall penetrations, reinforcements, and bosses. Abrupt wall thickness changes are avoided by providing a tapered or stepped section between the tank membrane thickness and the weld land as shown in figure 5-3. For flight weight tanks, mounting pads and penetration reinforcements are usually butt welded to the tank with a tapered transition section on the reinforcement side of the weld and a stepped weld land on the membrane side of the weld as shown in figure 5-4. Ground-based tanks normally have a reinforcement pad fillet welded to the tank to provide additional strength around penetrations as shown in figure 5-5. This is less costly and more practical for ground-based tanks where the strength margin can be accommodated without concern for weight penalty.

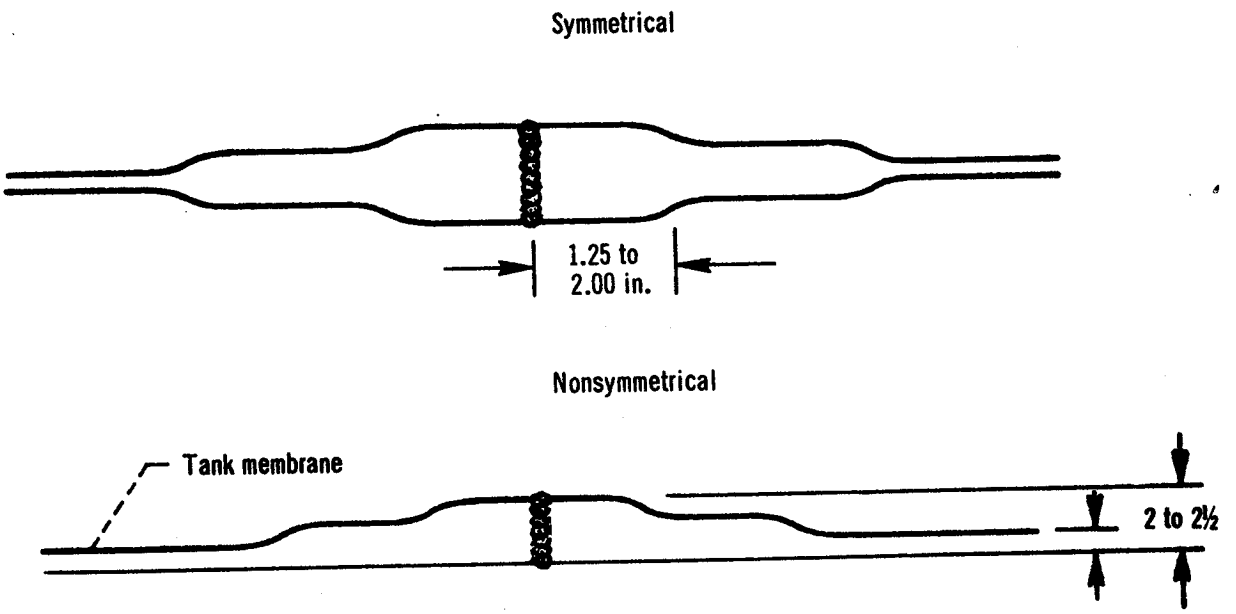


Figure 5-3. - Weld land configuration.

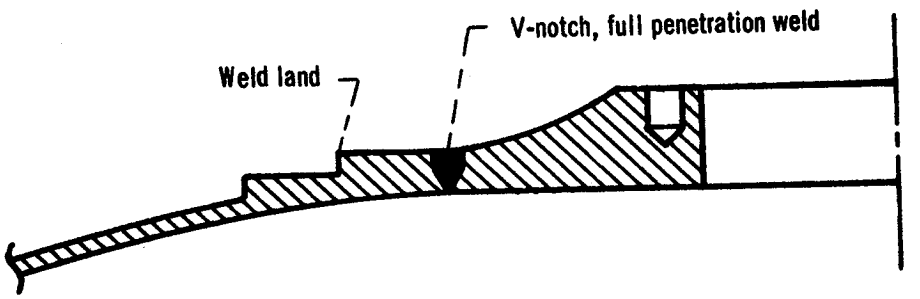


Figure 5-4. - Typical tank wall penetration for thin-walled tanks.

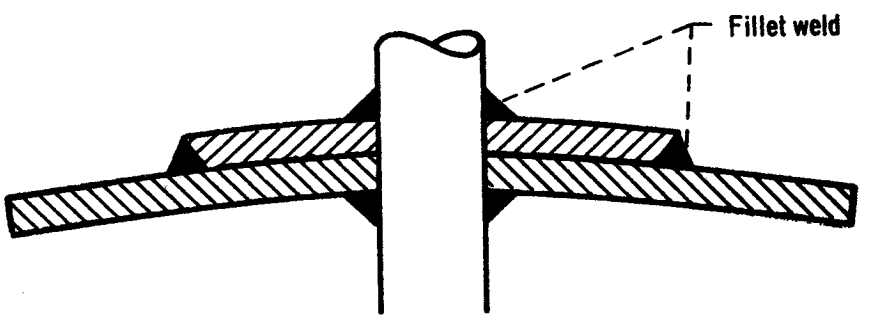


Figure 5-5. - Typical tank wall penetration for ground-based tanks.

Tank wall sheet stock and weld coupons of the material are generally tested statistically to provide a 99 percent strength reliability level for the tank material. A statistical confidence level of 95 percent is observed (ref. 71, pp. 25 to 28). Reference 83 (p. 71) provides additional statistical reliability for weld strength data by accounting for the differences in the individual weld coupon samples tested.

5.2 MATERIALS

Materials that have been used and may be considered for oxygen tanks include those listed in table 5-III. The lowest value for sheet stock gage recommended for propellant tanks is about 0.01 inch for steel alloys and 0.02 inch for aluminum alloys (ref. 70, p. 336).

TABLE 5-III. - TANK MATERIALS

Stainless steel: 301, 304, 316, 347
D6AC alloy steel[a]
Inconel 718
Monel
Mild steel (carbon steel)[b]
Magnesium: M-1, AZ31
Aluminum alloys: 6061-T-6, 6066-T-6, 2014-T-6, 2219-T-62, 2219-T-81, 2219-T-87, 5052

[a]Used for very high pressure oxygen gas storage in Apollo EVA system. See precautions against stress corrosion in section 3.2.3.

[b]Commercial gaseous oxygen cylinders (2200 psia max., -30° F min.).

5.3 INSULATION

Special concern is required when using oxygen system insulations that contain added combustible materials. These insulations can be hazardous in the event of an oxygen leak coupled with subsequent ignition. Most of the conventional insulations will not ignite readily but they will support combustion if they are ignited. All of the insulation materials listed in table 5-IV will burn in oxygen and each material will ignite in the presence of oxygen at its respective ignition temperature except those noted. The ignition temperatures and combustion rates of materials are given in chapter 3.

The use of metallic particles in combination with powdered oxide insulations for ox-

TABLE 5-IV. - TYPICAL THERMAL CONDUCTIVITY AND DENSITY DATA FOR VARIOUS INSULATIONS[a]

Insulation	Conductivity, K, $\frac{(Btu)(in.)}{(hr)(ft^2)(^oR)}$	Density, ρ, lb/ft^3	$K\rho$ factor	Insulation pressure
Multilayer aluminum foil (with glass or quartz fiber paper spacers)	0.00012 to 0.00078	7.5 2.5	0.0009 .002	10^{-4} mm Hg 10^{-4} mm Hg
Aluminized Mylar:				
24 layers/cm	0.049	2.8	.1375	
47 layers/cm	.104	5.85	.608	
Powders:				
Santocel-A[b]	.0011	6.0	.0066	10^{-4} mm Hg
Perlite[b]	.000864	8.0	.0069	10^{-4} mm Hg
Cab-O-Sil[b]	.0014	4.5	.0063	10^{-4} mm Hg
Fiberglass[b]	.01 to 0.21	4.0 4.0	.05 .84	10^{-3} mm Hg 1 atm
Foams:				
Polystyrene	.18 .056	2.88 2.88	.438 .136	1 atm 10^{-5} mm Hg
Epoxy	.229 .090	5.0 5.0	1.14 .45	1 atm 4×10^{-3} mm Hg
Polyurethane	.229 .084	5.0 to 8.74 5.0 to 8.74	1.14 to 2.0 .42 to .734	1 atm 10^{-3} mm Hg
Rubber	.25	5.0	1.25	1 atm

[a]Ref. 30, pp. 30 to 37.
[b]Nonflammable with oxygen.

ygen equipment is hazardous due to the flammability of the metals in such mixtures (see 3.4.1).

Tests have indicated that up to 20 percent aluminum powder may be used in Perlite in an oxygen atmosphere before combustion will be sustained (ref. 84, pp. 118 to 121). Since this may be affected by the particle size of the powdered metal, tests should be made of the material to determine the actual limit in each case.

Figure 5-6 illustrates the effect of gas pressure on the conductivity of a few of these insulations. Multilayer superinsulations have been developed with conductivities as low as 1×10^{-5} Btu-inch per hour-square foot-Rankine degrees (ref. 30, p. 32). However, this efficiency is extremely difficult to achieve in a practical ground-based tank application. In a 1-g environment the thermal conductivity of multilayer insulation decreases as each additional layer is added until the contact area between layers begins to increase from the added weight. Then the conductivity begins to increase. This is illustrated in figure 5-7 which shows the optimum number of layers to be between 50 and 90. Typical

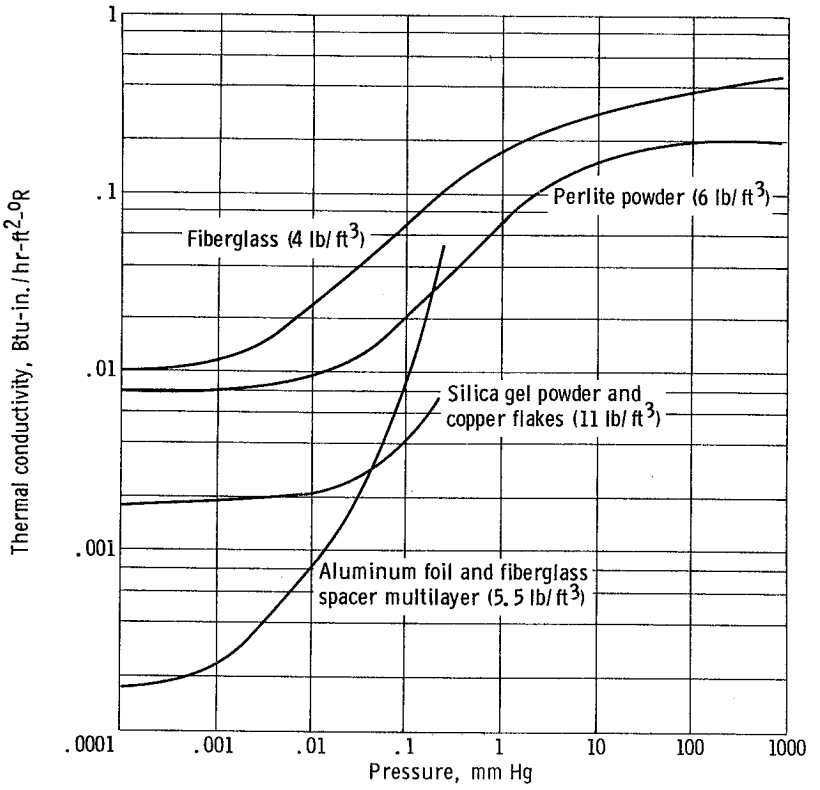


Figure 5-6. - Effect of gas pressure on thermal conductivities of various cryogenic insulations (ref. 72, pp. 2 to 9).

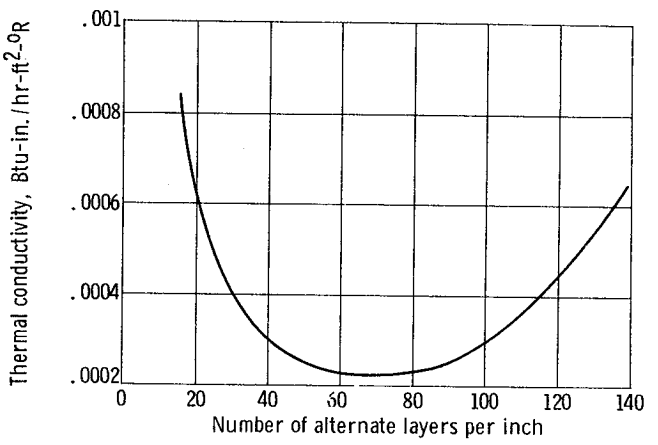


Figure 5-7. - Thermal conductivity against number of alternate layers of glass fiber paper and aluminum foil per inch thickness of insulation between 540° and 140° R (ref. 72, pp. 2 to 15).

TABLE 5-V. - MINIMUM VALUES OF EMITTANCES

FOR SELECTED METAL SURFACES[a]

Material[b]	Emittance[c]
Aluminum, 0.001-in. and 0.0015-in. household foil	0.02
Aluminum, vapor deposited on polyester film	.04
Brass, yellow 0.001-in. shim stock	.03
Cadmium, mossy plate	.03
Chromium, electroplate	.08
Copper, electrolytic, careful polish	.02
Copper, pure, carefully prepared	.01
Gold, 0.0015-in. foil	.01
Gold, vapor deposited on polyester film	.02
Lead, 0.004-in. foil	.04
Nickel, 0.004-in. foil	.02
Platinum	.02
Silver	.01
Stainless steel 302	.05
Tin, 0.001-in. foil	.01
Zinc, 0.0065-in. foil	.03
Solder, 50-50	.03

[a]Ref. 72, pp. 2 to 21.

[b]All materials solvent cleaned unless otherwise stated.

[c]For surface at 140° R from radiation source at 540° R.

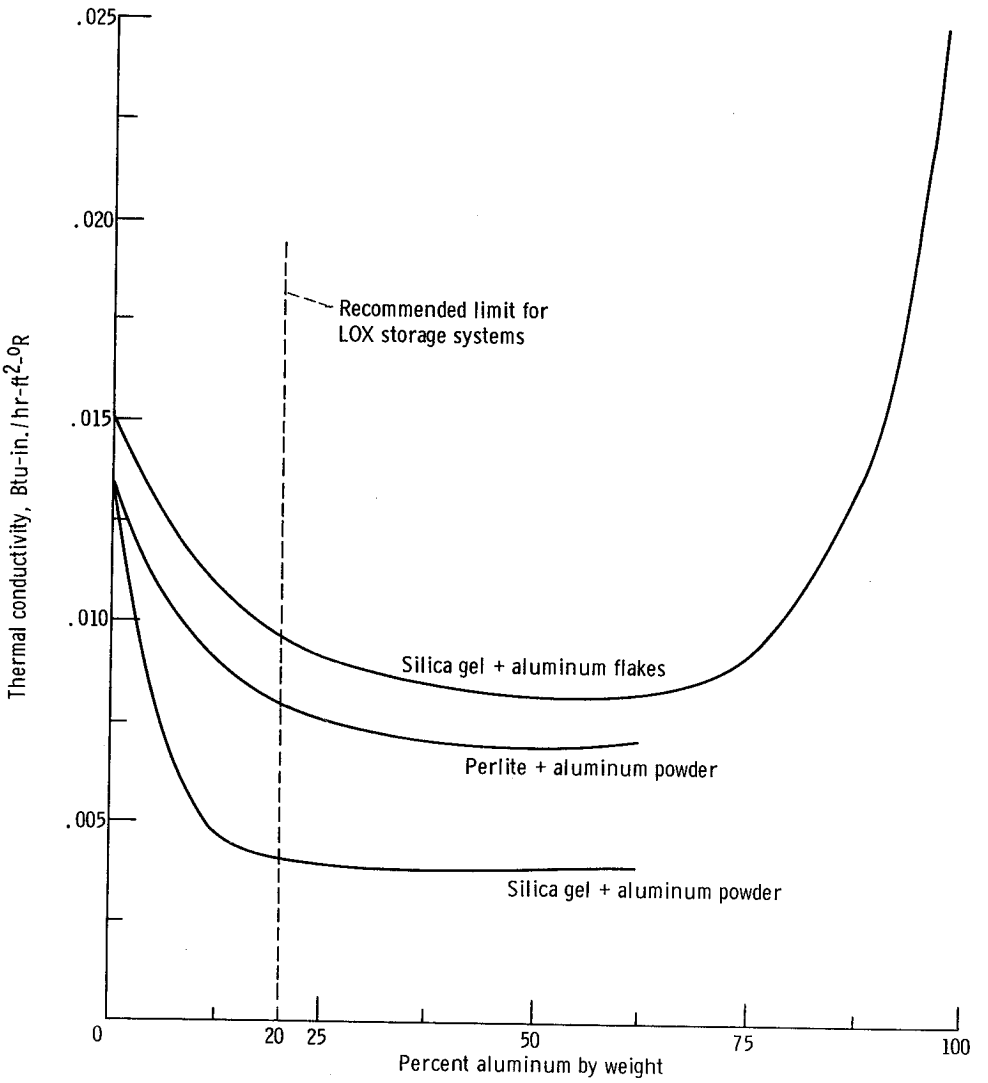


Figure 5-8. - Effect of metallic additives on apparent thermal conductivities of evacuated powder insulations between 540° and 140° R (ref. 72, pp. 2 to 11).

densities for various insulations are given in table 5-IV. The coating materials with the lowest emittance values for multilayer insulation are listed in table 5-V. The reduction of thermal conductivity of powdered insulations from the addition of metal powders is illustrated in figure 5-8. The optimum benefit results with aluminum powders in quantities of 20 to 70 percent by weight. As previously indicated, flammability is not generally sustained below 20 percent. Therefore, 20 percent appears to be an overall optimum for oxygen, but again, the actual limit would have to be determined by test in each particular case.

5.4 TANK MAINTENANCE CONTROL

In order to prevent exceeding the use limits of a tank, it is important to maintain a documentation of the tank's "life history" or "tank log." Every event in the life of the tank significant to engineering evaluation of the tank use limits should be recorded. The "log" should include the following:

(1) Original design specifications
(2) Raw materials record - source, quality test results, and processing record of the materials used to make the tank
(3) Fabrication record - record of the fabrication anomalies, weld rework, tank modifications, stress relief, and heat treat processes
(4) Test history - test data record
(5) Record of inspection anomalies
(6) Maintenance record, including cleaning and preparation
(7) Use and operation record
    (a) Cyclic use record - pressure cycles, temperature cycles, cumulative fill and drain data, cleaning, and inspection cycles
    (b) Record of use anomalies (especially accidental overpressure)

The need for these data is important in determining tank life inspection periods, cleaning, and reuse specifications. The raw materials record and fabrication record identify specific points for future inspection. Test history is important because pressurization testing can verify the tank reliability, but it can also contribute to cycle fatigue and reduced tank life. This is especially true for flight weight tanks where the margin between the working stress and yield stress is relatively small. Inspection anomalies and maintenance records aid in quality assurance. The use and operation record completes the total environmental effects profile useful in gaging the state of the tank system at any time.

5.5 TANK OVERPRESSURE HAZARD

It is difficult to predict the potential hazard that would result when a tank fails from accidental overpressure. Tanks fail by leaking local bursting or disintegrating into shrapnel. Some of the total energy is absorbed by the tank disintegration; some is absorbed to accelerate the tank parts (or shrapnel); and the rest of the energy is dissipated by a pressure wave. The amount of energy absorbed by the tank disintegration also varies with the tank wall thickness and the tank material, although this is relatively small compared to the total energy release.

The potential explosive energy equivalent of a pressurized tank is given by (ref. 85, p. 4)

$$E = 144 \left[\frac{V\left(\frac{P_1}{P_2}\right)\left(\frac{T_1}{T_2}\right)}{359} \right] RT_2 \ln \frac{P_1}{P_2}$$

where

E energy, ft-lb

P_1 tank pressure (absolute), lb/ft^2

P_2 atmospheric pressure (or ambient pressure) or zero pressure in space, lb/ft^2

R molar gas constant, 10.73 $lb\text{-}ft^3/(^oR)(in.^2)(lb)(mole)$

V tank volume, ft^3

T_1 ambient temperature, ^oR

T_2 temperature of contained gas, ^oR

This does not allow for the energy used in rupturing the tank and propelling its pieces.

The energy equivalent of TNT is 1.543×10^6 foot-pounds per pound TNT. Therefore, the TNT energy equivalent of a pressurized tank is

$$\text{lb TNT equivalent} = \frac{E}{1.543 \times 10^6}$$

An overpressure rupture of a tank in the atmosphere will cause a shock wave per distance relationship given by the Nomogram (fig. 5-9).

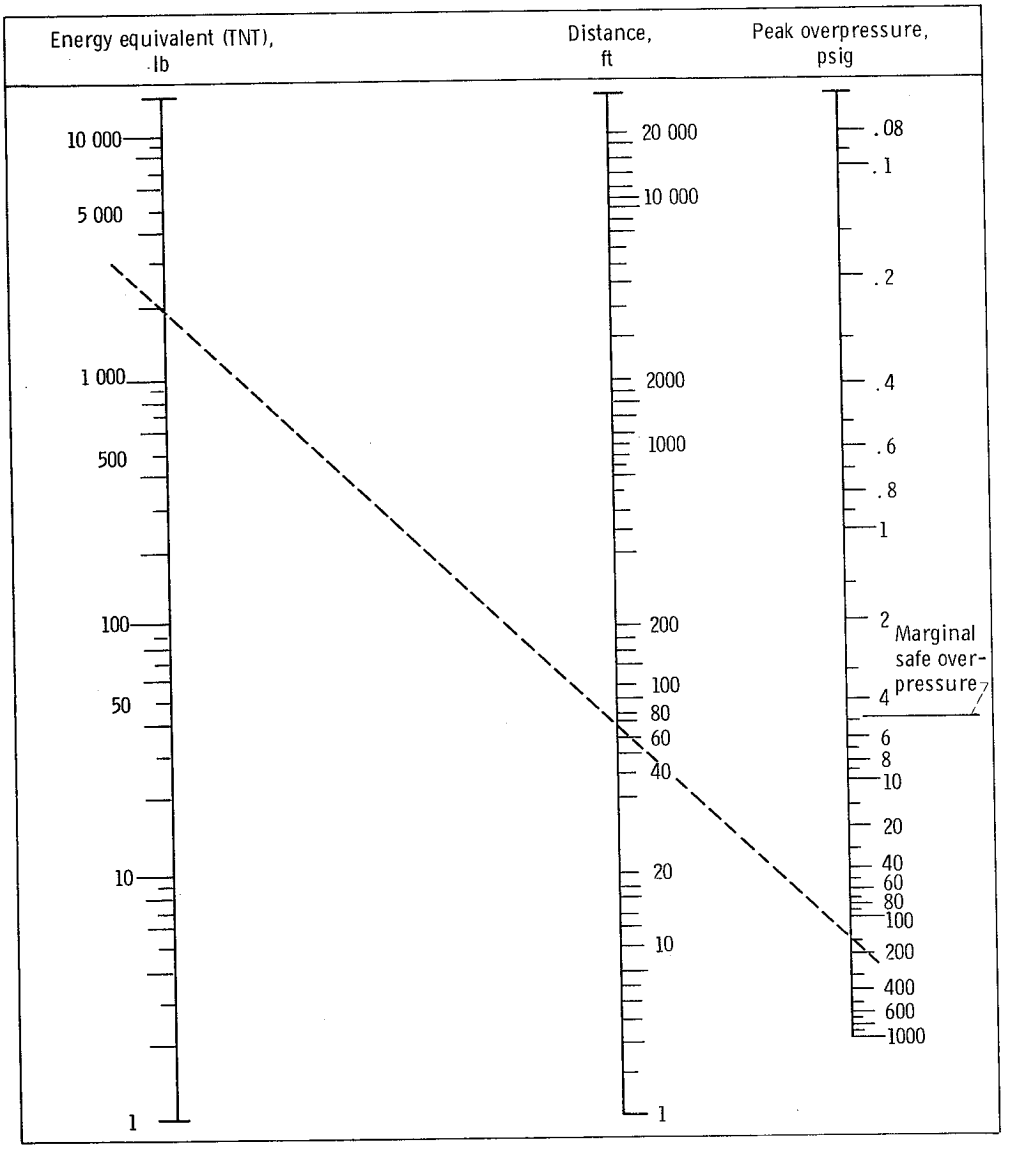


Figure 5-9. - Nomogram for magnitude of blast hazard from equivalent weights of TNT (ref. 85, p. 5). Missing factor (energy equivalent, distance, or peak overpressure) can be determined by locating two known factors on scales. Connect these points with straight line. Point of intersection of this line and third scale determines missing factor.

CHAPTER 6. OXYGEN PUMPS

The most commonly used pump for pumping liquid or gaseous oxygen is the centrifugal pump which is used almost exclusively in rocket engine systems. Centrifugal pumps are also widely used in ground applications for liquid oxygen pumping and as high flow rate gaseous oxygen compressors. Where very high pressures must be attained (usually at low flow rates), positive displacement piston-type pumps may be used; however, by means of staging, high pressures may be obtained from centrifugal pumps. Axial flow pumps tend to be impractical for pumping oxygen because of the relatively high density of the liquid and the complexity caused by bearing location and lubrication requirements for pumping gaseous oxygen. Diaphragm pumps can be designed to pump either liquid or gaseous oxygen, but practicality would generally dictate using a centrifugal or piston pump. This is because of problems such as diaphragm flexure fatigue, gaseous compression heating, and materials compatibility to meet the internal pump conditions. If for some purpose the axial or the diaphragm pump would be selected, the design criteria generated throughout this text would apply. To achieve high pressure liquid oxygen at very high flow rates, centrifugal pumps with one or more stages would be preferable. Most very high pressure oxygen requirements are for gaseous breathing oxygen storage purposes such as for life support systems. The easiest way to generate gaseous oxygen pressures up to 10 000 psi or higher is to pump liquid oxygen to that pressure through a vaporizer. Since this does not generally require high liquid flow rates, the positive displacement piston pump is the most appropriate.

Rotary pumps which may be exposed to an oxygen environment are generally used as vacuum pumps and as such are exposed to relatively low oxygen partial pressures.

6.1 CENTRIFUGAL PUMPS

Most experiences with centrifugal pump failures involve pump deterioration resulting from bearing or seal failure. Such failures often result in structural disintegration with resulting ignition and fire. The exposure of the pump materials to high-speed rubbing friction, pressure spikes, impact, and contamination is a risk in a centrifugal pump, and the sensitivity of the pump materials to these conditions in the presence of oxygen is always a potential for possible reaction.

The following sections review many of the special considerations to be given to the design, fabrication, and use of centrifugal pumps for liquid oxygen to avoid conditions that can lead to failure. Although the emphasis in this section is on turbine-driven centrifugal pumps for flight application, the principles discussed are generally applicable to ground-based pumps. Since ground-based centrifugal pumps are not weight limited, higher safety factors and long pump life can be achieved at lower cost. For example, geared electric motor drives may be used. By increasing the size and stiffness of the pump shaft, a longer impeller overhang can be tolerated thereby permitting use of conventionally lubricated rotor shaft bearings. The main drive shaft from the gear box may also support the pump impeller. This also permits the use of an integrated pump - gear box housing for greater strength.

6.1.1 Pump Housing and Rotor Assembly

The pump casing (fig. 6-1, ref. 86) which serves as the structural support of the turbopump assembly must withstand all of the torque and bending moments transmitted

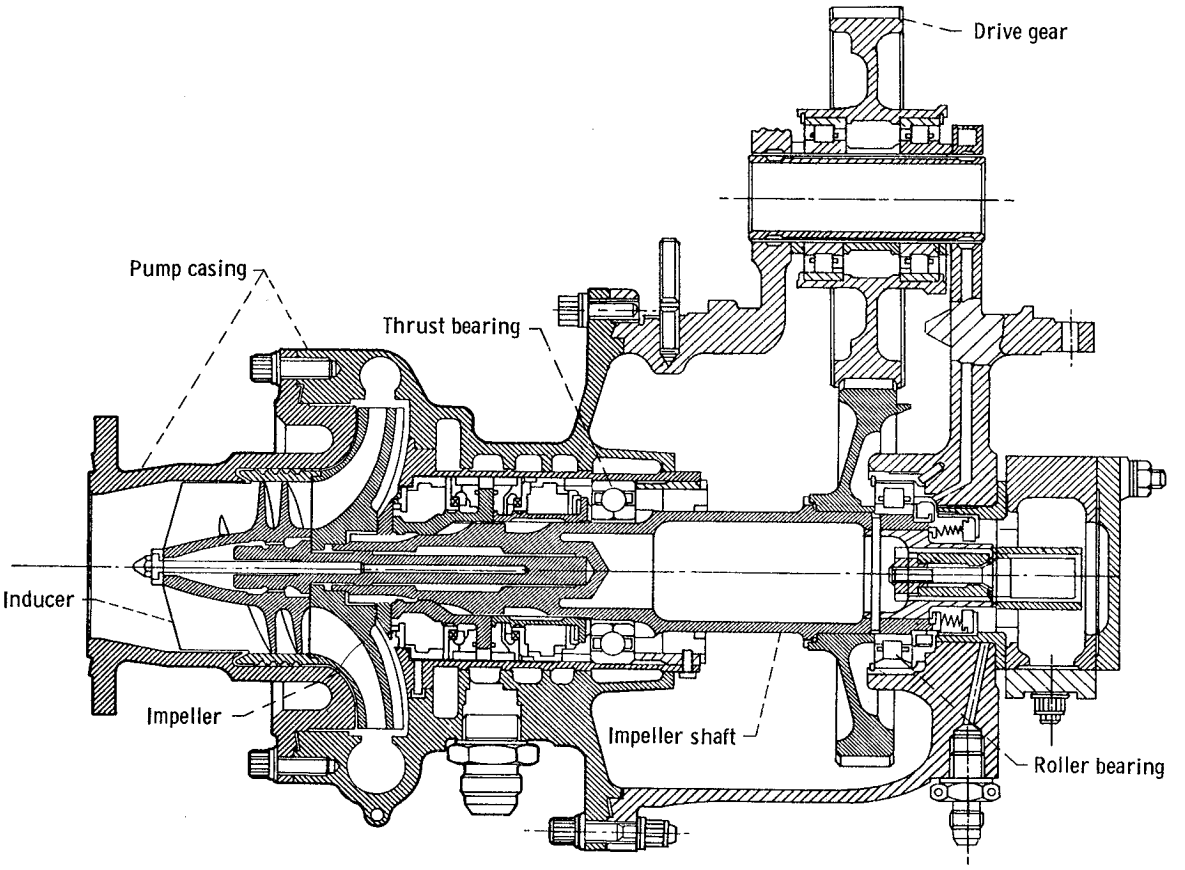


Figure 6-1. - Oxidizer pump assembly (based on ref. 86, fig. II-5).

through the structure in addition to the stresses from internal pressures. The casing must resist flexing from cyclic pressure variations, either circumferential or pulsing; otherwise, fatigue failure or excessive rotor rub could result. To avoid the large distortion associated with the resonance vibration of the pump case, the natural frequency of the pump case in any vibrational mode should be above any expected periodic driving force. Fluctuating pressure loads and perturbations in the inlet flow can be structurally damaging and should be avoided by design, operational procedures, and system monitoring.

The oxygen pump housing design is a matter of providing the strength necessary to prevent rotor contact while permitting the close clearances necessary for pump efficiency. In flight weight pumps this must be achieved without undo weight penalty. A discussion of centrifugal pump housing and rotor design is given in references 70 (pp. 219 to 225) and 87 (pp. 60 to 77 and 111 to 122). In addition, references 88 and 89 (ch. 7) are useful texts which may be consulted on design of pumps and turbomachinery.

6.1 1.1 Inducer - impeller-pump case clearance. - The practically attained minimum value for the blade tip clearance to blade length ratio for both inducers and impellers is 2.0 percent for oxygen pumps. When closer clearances are required which increase the possibility of rubbing, a "wear-in" seal or liner of polytetrafluoroethylene (TFE) or polychlorotrifluoroethylene (CTFE) liner (fig. 6-2) can be used to achieve the minimum clearance. These materials also reduce friction and abrasion should rubbing occur (ref. 90, pp. 70 and 71). The acceptance of this technique is primarily one of precedence. Therefore, the application of nonmetal rub rings and liners beyond the limit of experience should be with caution and verification testing. Initial wear-in of the seal or rub ring should be with liquid nitrogen. Although the average ignition temperature of TFE and CTFE in oxygen is between 410° and 540° C over the pressure range from 1 to 100 atmospheres (fig. 3-10) compared to 800° and 1000° C or higher for most metals and alloys, the heat sink provided by liquid oxygen and the lower coefficient of

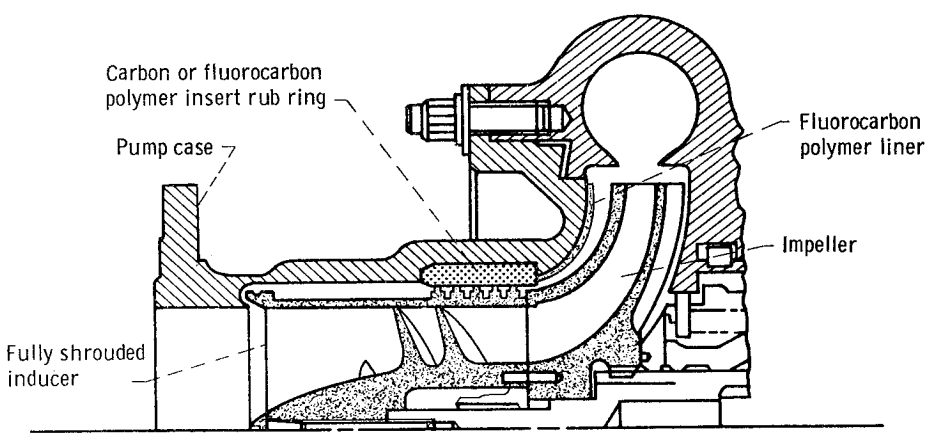


Figure 6-2. - Inducer impeller pump case lining (based on ref. 86, fig. I-1).

friction of TFE and CTFE permit their use in this application within present experience limits. A labyrinth seal is sometimes used to perform both sealing and rub liner functions. In such applications a labyrinth element is used in conjunction with a fluorocarbon polymer wear ring as illustrated in figure 6-2. The wear-in characteristics of this combination provide near optimum inducer to case clearances and reduce backflow to an acceptable level.

6.1.1.2 Turbopump shaft stability and critical speed. - Rotor stability is especially important in oxygen pumps in order to prevent rotor rub and bearing overstress while at the same time permitting the shaft diameter and weight to be minimum. With improved higher strength materials, the possibility of higher pump speeds in future pump developments increases the hazard of rubbing contact between the rotor and the pump case. The close clearances between the housing and the impeller and inducer blades must be maintained to assure pump efficiency. At current design speeds the inducer-impeller, shaft, and bearing system (rotor assembly) may pass through several critical speeds during spinup and shutdown. At critical speeds the rpm of the rotor assembly equals some multiple of the natural frequency of the rotor assembly or some forcing frequency. The shaft wobble accompanying critical speed operation may cause the impeller to rub the pump case. Accordingly, shaft radial balance and thrust balance are critical design requirements.

Although the primary driving force to shaft mount instability is rotor imbalance, other factors can induce forces which at resonant frequencies may cause the rotor to exceed its clearance envelope. Some of the factors that must be considered include variations in the bearing assembly stiffness, internal bearing friction, uneven pressure buildups in the pumped fluid around the rotor, resonant flexing of the casing, and variations in flow due to engine chugging or cyclic coupling of flow control loops. For oxygen, these factors must be anticipated as much as possible during the design stage to prevent pump failures. Initial runups of oxygen pumps should be programmed to verify a noncritical rub condition. In developmental pumps, testing should explore the complete operational profile with adequate instrumentation to determine the possibility of unacceptable impeller rub. For added safety, checkout runs may be made using liquid nitrogen.

There are two design philosophies currently applied in the design of rocket engine turbopump rotor assemblies. In one, the bearing and shaft system is designed with all of the turbopump operating speeds below rigid body, first whirling mode critical speed. To achieve this, high bearing mount spring rates are required. This requires stronger, stiffer shafts and increased shaft and bearing diameters. Roller bearings are used to provide high radial spring rates along with ball bearings for supporting axial thrust. Resonance problems are avoided, but there is a weight penalty. The second design philosophy calls for a design for pump operation above the first and second whirling mode critical speeds but below any mode where significant shaft bending occurs. This allows

smaller bearings and lighter shafts. The bearing mounting has a lower spring rate. The main advantage in this case is lower pump weight. In either design approach, a 20 percent margin is generally used between the shaft operating speed and the nearest whirling critical speed to assure rub free rotation (ref. 87, p. 11).

Because classical methods for computing rotor displacement when passing through critical speed are not accurate enough to predict rotor rub, digital computer programs for calculating the natural frequencies and amplitudes are generally used (ref. 91, pp. 31 to 48 and 82 to 88, and refs. 92 to 94). The use of such programs provides higher accuracy because more elaborate and accurate models may be used.

The rotor shaft is generally balanced initially as subcomponent and then as part of the assembled rotor on a balancing machine. The rotor assembly is then disassembled and reassembled in the turbopump. However, considerations such as pilot tolerances, runouts, and parallelism can alter the fine balance attained. In addition, fits may shift during operation due to thermal expansion differences between adjacent parts and mechanical deformations caused by centrifugal forces. Because these shifts may allow eccentric shifting of adjacent rotor parts, rotor imbalance results. For this reason, it is necessary to instrument for static and dynamic bearing loading and clearance measurements through the entire operating range as a part of the pump development testing. The assembled rotor should be balanced in the range of 50 to 100 microinches of mass eccentricity (μin.-lb out of balance/mass of rotor) (ref. 91, p. 88). When this procedure is used, actual rotor imbalance is rarely as great as the limits specified or permitted by the engineering drawings. Techniques for balancing turbomachinery are discussed in references 91 (pp. 48, 88, and 94 to 96) and 95.

Programs for computing critical speeds are given (with program description, user's manual, and FORTRAN listings) in reference 96. (Only the table of contents of this reference is included in the microfiche supplement. The text has been omitted because of its large size and small print.) Detailed discussions of shaft dynamics are presented in reference 91 (pp. 19 to 48 and 79 to 88).

6.1.1.2.1 *Torsional stability.* - Torsional vibration in turbopump shafts has not generally been a limiting or controlling design factor. But a comparison is usually made between the calculated values of torsional natural frequencies and possible forcing or coupling frequencies such as from gear teeth meshing, misalinements of couplings, or other torsional driving forces.

The calculated torsional natural frequencies are also compared with nontorsional system natural frequencies to avoid possible coupling (ref. 91, pp. 30 and 81). As in the case of whirling and bending instability, a 20 percent margin between the instability frequency and operating frequency should be provided.

6.1.1.2.2 *Axial thrust.* - Shaft axial thrust balance forces as high as 30 000 pounds per 1000 pound per second propellant flow can be required to keep the axial force on the rolling element thrust bearing to tolerable values. The impeller is generally balanced

by exposing its back face to a pressure distribution that matches that developed on the front face, as shown in figures 6-3 and 6-4. Up to 90 percent of the axial thrust load is sometimes required to be taken up by a thrust balance piston or back vanes on the pump impeller in support of a "ball" thrust bearing used to establish a fixed position for the rotor.

The pressure balancing arrangement shown in figure 6-3 incorporates a set of radial vanes on the back face of the impeller which constitutes a simple secondary centrifugal pump. The pressure field developed by this secondary pump is a rough match to the field developed on the front face of the impeller. The impeller back face vane system has been preferred from experience and is used in oxygen pumps on M-1, H-1, J-2, RL-10, and F-1 engines.

In the balance piston method (fig. 6-4) the balance chamber on the back face of the impeller is pressurized by flow communication with the pump exit. The exposed area on which this pressure acts, defined by the back wear rings and the shaft seal, is sized to provide the axial force opposing the force on the front face. For finer balancing, the piston chamber pressure is regulated by a vernier control. Techniques for determining the required balance chamber pressure level in the system shown in figure 6-4 are presented in reference 70 (pp. 223 and 224). Pressure balancing the pump impeller to support axial thrust loads using the balance piston method has caused frequent problems during turbopump development. Thrust loads could not be predicted within the desired accuracy, and small variations in impeller face pressures result in considerable variations in the magnitude of the net thrust. Because of the poor predictability of the thrust

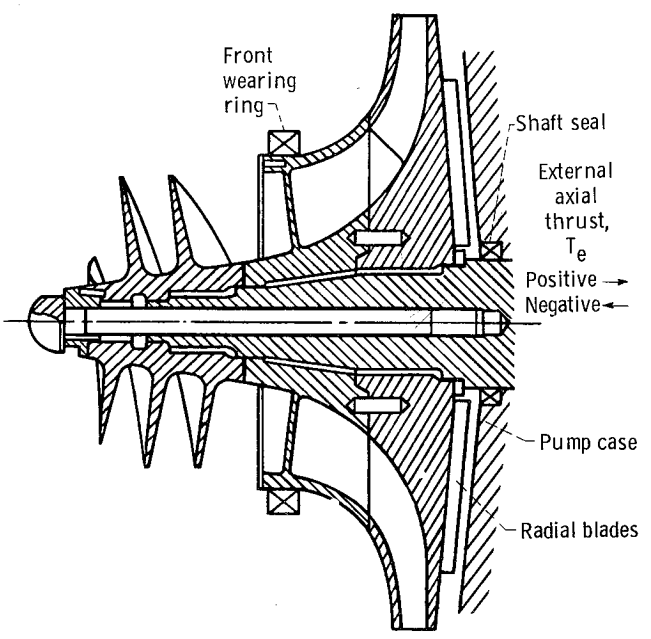


Figure 6-3. - Balancing axial thrusts of a centrifugal pump by the radial rib method (based on ref. 70, fig. 6-48).

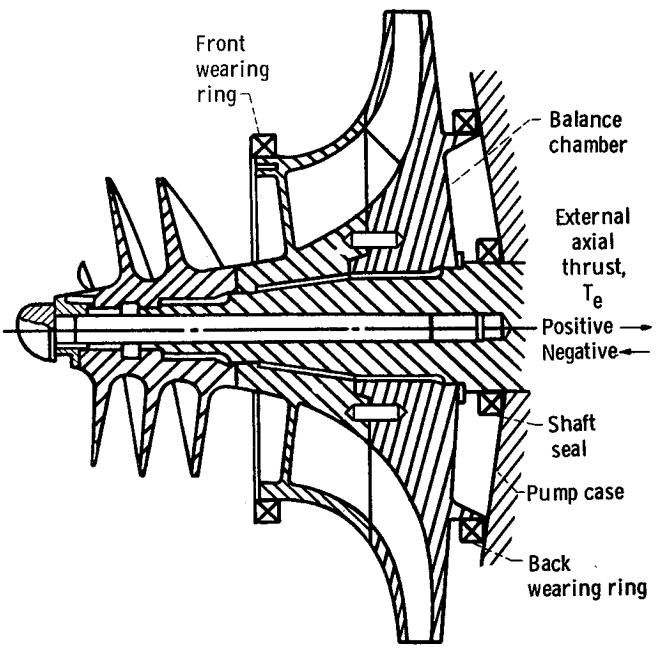


Figure 6-4. - Balancing axial thrusts of a centrifugal pump by the balance chamber method (based on ref. 70, fig. 6-47).

variations, especially during runup and stop transients, large tolerances to thrust force variations are generally provided in development models, and they are designed to be adjusted during tests. For this reason, pressure balancing with a controlled fluid back pressure has not been used in operational oxygen pumps.

Thrust balancing determinations for centrifugal pumps are discussed in references 70 (pp. 223 to 225) and 87 (pp. 82 to 89). Since experience has shown that actual and calculated thrust can vary considerably, initial runups should be done in steps with adequate instrumentation to verify thrust at operational speed.

For systems such as shown in figures 6-3 and 6-4, the balance of axial forces acting on the impeller may be approximated from equations given in reference 70 (pp. 223 to 225). A sample calculation of the axial thrust balance forces of the M-1 oxygen pump is presented in reference 97 (pp. 22 to 40).

6.1.1.3 Inlet flow dynamics. - Flow distortions and turbulence at the pump inlet introduced by valves, bellows, pipe bends, and poorly designed pipe entrance sections cause unsymmetrical hydrodynamic forces on the impeller. The unbalanced forces fluctuate with time and may cause an oscillation of the impeller-shaft system.

To avoid these unbalanced pumping forces, a straight run of pipe to the pump inlet of 5 pipe diameters is normally used (when space is available) to allow disturbances in the flow to subside before entering the pump. Valves, bellows, and elbows should be located upstream of this section. Straightening vanes are used in the inlet line if an adequate uninterrupted straight run immediately before the inlet cannot be installed. Bellows sections installed in the inlet line closer than 5 inlet line diameters should be fitted with a smooth liner to avoid the turbulence caused by the flow over the bellows convolutions. These considerations are discussed further in reference 90 (pp. 7 to 11 and 49 to 50). Problems associated with the use of convoluted sections in oxygen systems are discussed in section 8.4.

When turning vanes are used in elbows, the vane spacing to vane chord length ratio of 0.25 to 0.45 should be used for minimum pressure drop (ref. 70, p. 373). The exact value must be determined in flow tests.

6.1.1.3.1 *Inlet line cavitation.* - Cavitation in the inlet line fluid may result in a two-phase mixture of oxygen liquid and gas entering the pump. The nonuniform density of this mixture from blade to blade causes unbalanced forces on the inducer and impeller. Straightening vanes in the line do not correct this condition.

Cavitation in the line is avoided by providing a liquid oxygen tank pressure which is high enough to ensure that the static pressure at any point in the line never falls below the vapor pressure. Cavitation may also be prevented or reduced by subcooling the oxygen to reduce its vapor pressure or in some cases by reducing heat input with insulation of the pump and feedline. A boost pump may also be used to increase the inlet pressure.

In cases where the pump inlet pressure is very close to the local vapor pressure, and the feed system pressure drop is critical, filters and screens cannot be used. These would add to the pressure drop.

The relationship between the oxygen tank pressure and the maximum oxygen velocity in a loss-free inlet line is given by

$$V_{max} = \left[\frac{2g(P_t - P_v)}{\rho}\right]^{1/2} \tag{1}$$

where

P_t tank pressure, lb/ft^2

P_v oxygen vapor pressure, lb/ft^2

ρ oxygen density, lb/ft^3

g acceleration gravity, 32 ft/sec^2

To allow for pressure losses in the line and some static pressure margin for the acceleration of the flow over the pump blades without cavitation, the line cross-sectional area is taken large enough so that no more than one-third of the difference between tank pressure and vapor pressure is used to accelerate the flow in the line. The corrected line maximum velocity is computed from (ref. 90, p. 64)

$$V_m = \left[\frac{2g(P_t - P_v)}{3\rho}\right]^{1/2} \tag{2}$$

For more detail in inlet line design see references 70 (pp. 372 and 373) and 90 (pp. 7 to 11 and 64 and 65).

6.1.1.3.2 *Rotor blade cavitation.* - Two problems that can result from cavitation on inducer and impeller blades are vibration (ref. 90, pp. 39 and 40 and 76 and 77) and cavitation erosion. Although cavitation erosion is mainly a long term effect and is not normally a problem in short term turbopump operation, it could become more important in long time operation of high rpm - high discharge pressure pumps. The hazards associated with these effects in oxygen pumps are cracked or broken rotor blades from vibrations and erosion and ingested solid particles or blade parts which can fail the turbopump.

The suction surface of the impeller blade is normally the cavitation site. The pressure drop required to accelerate the flow over this surface can bring the static pressure

(4) The proof pressure for testing the case should be obtained by multiplying the pressure used in determining the limit load by a factor of 1.2 (or as established by fracture mechanics analysis). Frequently, a value of two-thirds the calculated case burst pressure is used as an alternative proof pressure.

(5) For weldments, if joint efficiency test data are not available, use 85 percent of the material tensile and shear yield stress as well as ultimate stress in computing yield and ultimate safety factors.

Although not a design factor, a limit must be placed on operating pressure when special protection for personnel such as barriers is not provided. The following pressures are recommended:

(1) One-half ultimate

(2) Three-fourths the limit pressure

Additional criteria and recommended practices are provided in reference 87 (pp. 77 and 116 to 118).

6.1.1.4.2 *Pump rotor shaft.* - Table 6-I lists some examples of safety factors for existing rotor shaft designs of lightweight flight pumps with short service life requirements. Additional criteria and recommended practices are given in reference 91 (pp. 60 to 78).

6.1.1.5 Component materials. - Materials commonly used for pump components are listed in table 6-II.

TABLE 6-I. - ROTOR SHAFT SAFETY FACTORS

Pump application	Safety factor	
	Yield[b]	Ultimate[b]
Titan I and II	1.0	1.25
M-I	1.0	1.5
Titan III-M	1.0	1.4
Rocketdyne	1.1	1.5
ARES	1.2	1.6

[a]Ref. 91, p. 10.

[b]Based on highest potential stress possible under all testing and operating conditions.

TABLE 6-II. - COMMONLY USED CONSTRUCTION MATERIALS FOR LIQUID OXYGEN CENTRIFUGAL PUMPS

Component	Materials
Housing	Monel K and KR Inconel 718 Stainless steel 304, 347 Aluminum 356 (castings) and "Tens" 50-T-6
Impeller-inducer	Monel K Bronze and brass alloys Inconel 718, Inconel X Stainless steel 304, 347, 17-4PH Aluminum 7075-T73, 7079-T6, 2024-T4, 2014-T6, 356-T6
Shaft	Inconel 718, Inconel X Monel K Stainless steel 304, 347 4340 alloy steel
Case liner	TFE (Teflon), CTFE (Kel-F)
Wear ring	TFE (Teflon), CTFE (Kel-F), carbon

there to the liquid oxygen vapor pressure and cavitation occurs. A discussion of cavitation as it affects pump performance and damage is given in references 98 (pp. 81 to 101) and 99.

Blade surface roughness is also a factor in cavitation onset. Test results comparing surface finishes of 2 microinches to finishes of 160 microinches indicated a lowering of pump efficiency by 5.9 percent with chordwise striations and 7.2 percent with spanwise striations (ref. 100, p. 209). Cavitation onset and vibrations appeared to be advanced with increased roughness. Accordingly, it has been recommended (ref. 90, p. 58) that the blades be polished to a surface finish of 25 microinches rms.

Cavitation is avoided if the pressure of the oxygen entering the pump is high enough above the oxygen vapor pressure to accommodate the acceleration pressure drop. This higher pressure at the pump inlet can be obtained with higher tank pressures, use of a separate boost pump, or use of an inducer. The inducer usually mounted on the impeller shaft (fig. 6-1) and rotated at impeller speed provides only the relatively small pressure rise required to avoid cavitation on the impeller. Because of this modest pump work requirement from the inducer, its blading can be shaped to accommodate cavitation with useful pumping efficiency and high tolerance for cavitation erosion. A detailed discussion of inducer design is given in reference 90.

If tank pressure must be too low because of design trade-offs to prevent cavitation, the use of a separately driven boost pump or inducer at the liquid oxygen tank to raise the pump inlet pressure is necessary. The design of boost pumps is discussed in reference 101 (pp. 1 to 40); additional design studies are presented in references 102 to 104.

6.1.1.4 Safety factors

6.1.1.4.1 *Pump case.* - Safety factors recommended for preliminary design estimates of pump housings are summarized in this section. Usually these factors may be used for final design calculations and proof testing; however, design considerations such as fatigue effects and fracture toughness may justify using greater safety factors. As used here, the limit load is defined as the highest probable stress which the housing is expected to experience from external forces and pressure loading, including pressure spikes due to possible chugging, impeller overspeeding, and critical speed effects. The highest possible combination of forces must be included in estimating the highest probable stress. The recommended safety factors are as follows:

(1) The ratio of yield load to limit load should be equal to or greater than 1.1.

(2) The ratio of ultimate load to limit load should be equal to or greater than 1.5.

(3) The ratio of the ultimate fatigue strength to limit load should be equal to or greater than 1.33. (The ultimate fatigue strength is the maximum stress a component will withstand for the desired number of stress cycles without fatigue failure.) It may also be based on total strain.

Oxygen compatible pump materials are normally alloys of nickel, aluminum, copper, or stainless steel. They allow a wide choice of material densities and strengths. However, allowances must be made for differences in the expansion-contraction coefficients and the dissimilar metals problem.

Monel K or Inconel 718 are preferred materials for pump rotors operating in the cavitation regime (ref. 90, p. 75). The blades can be thinner than those of aluminum and the resistance to bending and cavitation erosion is greater. Where cavitation is not severe and ease of fabrication and lower cost are desired, aluminum alloys are used. The preferred alloys are 7079-T6, 7075-T73, and 2024-T4. Alloy 7075-T73 is relatively free from stress corrosion cracking and would be preferred from that standpoint.

To improve surface hardness (and erosion resistance) the aluminum components should be anodized to a minimum depth of 70 microinches. For depths over 500 microinches, anodized surface films begin to lower the fatigue resistance of the aluminum. A practical maximum of 300 microinches is usually used.

6.1.2 Turbopump Shaft Bearings

The use of cryogenically cooled pump bearings in flight turbopumps results in an appreciable reduction in pump system complexity, weight, and cost. Use of conventional lubricants requires longer shaft overhang to isolate the bearing thermally from the cold region of the pump. Longer shaft and housing requirements can lead to excessive weight and pump critical speed problems (ref. 105, p. 309).

For ground operation where weight and efficiency are less important, ambient temperature conventional lubrication may be an advantage in achieving longer bearing life. When liquid oxygen is used to cool the bearing, a chemical reaction (i.e., surface oxidation, corrosion, ignition, and self-propagating combustion) is possible between the oxygen and the bearings, pump component material, and conventional lubricants and seals. In order to illustrate the precision and care that must be exercised in bearing design, the salient points of bearing design are reviewed briefly in the following sections. Additional detailed treatment of bearing design is given in reference 105 (chs. 6, 11, and 12); engineering design criteria and recommended practices are given in references 106 (pp. 31 to 68) and 107 (pp. 7 to 20).

6.1.2.1 Bearing materials. - Materials used successfully for bearings running in oxygen are given in table 6-III.

TFE coated or impregnated fiberglass requires greater web thickness than a metallic cage. Metallic cages are not recommended for submerged oxygen bearing. The coefficient of friction of the materials listed in table 6-III in cage applications is between 0.05 and 0.15 (ref. 106, p. 50). The web thickness to diameter ratio of 0.15 provides

TABLE 6-III. - COMMONLY USED MATERIALS FOR

BEARINGS IN LIQUID OXYGEN

Component	Material	Reference
Roller, ball, and races	440C steel 52100 steel	106, p. 19
Cages	Armalon (mandrel-wrapped glass fabric supported) (TFE) Salox-M (40 percent bronze powder filled TFE) 15 to 25 Percent glass filled TFE	106, p. 51

the best performance. Minimum web thickness should be limited to 0.15 inch for strength reasons (ref. 106, pp. 29 and 67).

The 52100 steel is sensitive to moisture corrosion and accordingly AISI 440-C corrosion resistant steel is recommended for liquid oxygen cooled bearings (ref. 105, p. 321). While no known material ideally fulfills the requirements of hardness, ductility or toughness, machinability, and availability, 440-C best meets the requirements with the fewest limitations. Grade 440-C steel is not entirely corrosion resistant, and investigations are under way to develop a substitute. Nickel-based alloys are corrosion resistant but relatively soft. Although sintered carbides are corrosion resistant and hard, they are brittle. Stellite Star-J has been investigated as a cryogenic bearing material, but testing has not produced design recommendations (ref. 106, pp. 19 and 20). Further discussion of materials choice, heat treatment, and desired hardness and maximum working stress is contained in references 105 (ch. 12) and 107 (pp. 5 to 7).

6.1.2.2 Lubrication and cooling. - Bearings which run in liquid oxygen are generally lubricated by fluorocarbon solids which are wiped from the cage by the rolling elements then transferred to the races. These solid films serve as anti-weld agents which prevent cold welding of the balls to the races. Filled TFE (usually glass fiber filled) from which the remainer is made provides the solid TFE lubricants which serve this function.

The use of fluorocarbon polymers in the bearing cage construction permits the short term high-speed operation required by most present generation rocket engines. Their use is limited, however, for extended or repeated operation because of the limited supply of fluorocarbon lubricant due to cage wear. The requirements for bearing and cage design for solid lubrication are covered in references 106 (pp. 28 to 30 and 63 to 68) and 107 (pp. 7 to 20). Cooling is provided by liquid oxygen which is circulated through the bearing as illustrated by the M-1 oxygen pump design shown in figure 6-5.

The flow on the downstream side of oxygen cooled bearings should be throttled to prevent flash vaporization of the LOX by maintaining its pressure above vapor pressure. The M-1 oxygen pump bearings used a combination of flooding and jet impingement

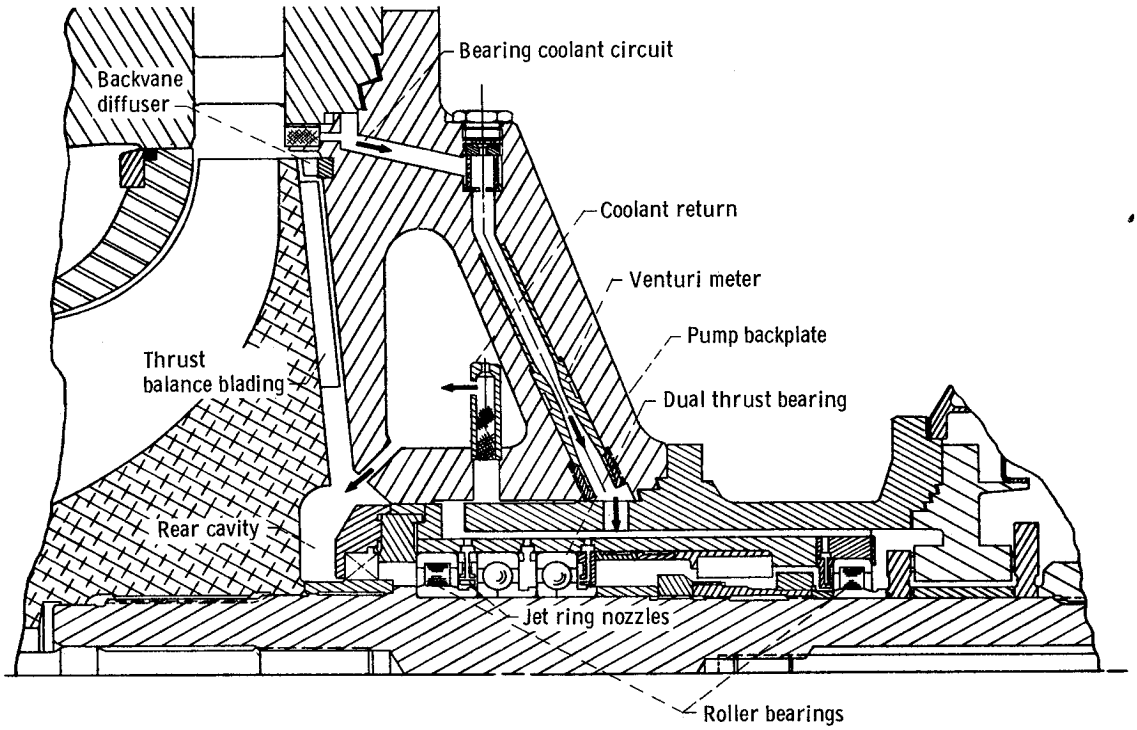


Figure 6-5. - Pump bearing cooling system (based on ref. 97, fig. 2).

(fig. 6-5). The jets were added to assure good circulation through the bearing (ref. 108, p. 1). Cooling is supplied through jet rings which direct the coolant on the rolling elements. The jet ring passage has an annular distribution channel with axial exit, cylindrical spray nozzles. For additional discussion of M-1 oxygen pump coolant system design see reference 108 (p. 12).

Typical cleanliness requirements for liquid rocket engines are given in reference 109, which gives the contamination per square foot of component as follows:

Particle size, μ	Number allowed per ft^2
175 to 700	5
700 to 2500	1
>2500	0
Nonvolatile residue	1 mg/ft^2 maximum

Since particles of the sizes permitted would have an adverse effect on bearings cooled by the LOX, filters ahead of the bearing cooling parts should screen out particles in excess of 40 microns; fluids used to clean the pump and bearings in preparation for oxygen service should be filtered through 10 micron filters (ref. 106, pp. 16 to 18 and 38 to 40).

6.1.2.3 Bearing life. - The life of an adequately lubricated bearing is limited by fatigue-induced pitting of the race and ball surfaces. Maximum stress appears at a depth of several thousandths of an inch below the surface. Fatigue failures begin as minute cracks at this depth which grow to the surface. Surface material is lost to this depth to produce a pitted surface. Once pitting occurs the rate of surface damage accelerates with each rotation cycle and the useful life of the bearing declines rapidly. However, oxygen cooled bearings are subject to an oxide film formation process where the oxide film is continually being replaced when virgin metal surface is exposed. This film promotes better boundary lubrication and helps to prevent galling and welding of the bearing surfaces.

The fatigue life of the bearing varies inversely with the ninth power of the maximum Hertz stress (ref. 105, pp. 383 to 384). For radial bearings the stress is due to preloading, impeller weight, shaft imbalance, and the centrifugal force of the balls against the outer race. Smaller balls will decrease the centrifugal force but increase the ball rotational speed. Hence, the number of fatigue inducing load cycles the ball surface will see will increase. A generally accepted life rating for ball and roller bearings is the "B-10 life," the operating life (hr) of a group of bearings at a given load and speed at which statistically 10 percent of them will have failed. Turbopump bearings are generally designed for a B-10 life of at least 10 times the required turbopump life (ref. 70, pp. 257 to 259). Figure 6-6 presents the centrifugal load DN (bearing bore in mm×rpm) limits in terms of 10 000 and 1000 hours of B-10 life for a typical ball bearing design.

Generally, rocket turbopump bearings have been successfully operated at DN values up to 1.5×10^6. Limited test information indicates possible satisfactory operation at 2.0×10^6 DN (ref. 70, p. 258). It is recommended in reference 106 (p. 31) that a DN of 3.0×10^6 should not be exceeded without prior testing. Ball sizes ranging from 3/16 to 7/8 inch in diameter and roller sizes from 1/4 to 1 inch in diameter are recommended

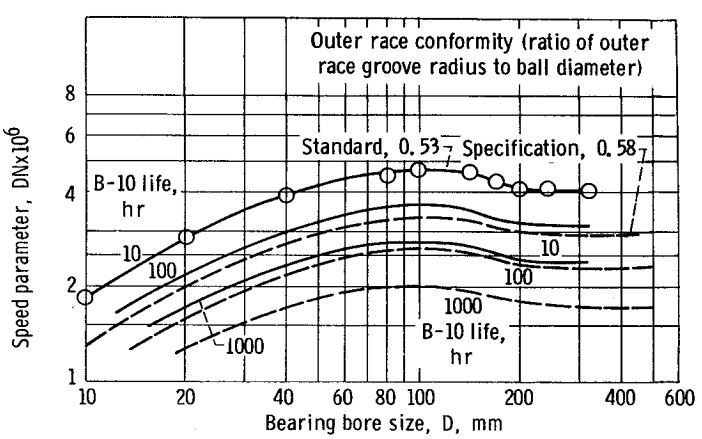


Figure 6-6. - Ball bearing centrifugal load DN limits (based on ref. 70, fig. 6-61).

(ref. 106, p. 23). Tests in liquid oxygen of the M-1 turbopump bearings reported a life expectancy of 5000+ seconds at a DN of 0.5×10^6 with ball diameters ranging from 23/32 to 3/4 inch and a bearing bore of 110 millimeters.

The maximum recommended Hertz compressive stress in balls, rollers, or races should be limited to 350 000 psi according to reference 107 (p. 7). Methods for computing the stress are discussed in reference 105 (pp. 150 to 158).

Higher bearing rotational speeds may be attainable in oxygen with unconventional designs presently under study. References 110 and 111 report recent experimental work on welded hollow and drilled hollow ball bearings. The hollow balls reduce the mass of the bearing and consequently allow higher rotational speeds before centrifugal loads become excessive.

6.1.3 Turbopump Rotating Shaft Seals

The primary concerns in oxygen pump rotating shaft seal design are the compatibility of materials with liquid oxygen in a rubbing environment and the possible seal face damage that can be caused by particulate contamination, thermal shock, and vibration.

The sliding surfaces of rotating shaft seals are subject to high thermal gradients, vibration from pump pulsations, shaft imbalance, and critical speed resonance. These vibrations can cause increased friction heating, surface breakdown, and seal failure. Therefore, the materials must be resistant to oxygen attack at high surface temperatures. The seal rubbing surfaces must have a low friction coefficient and the material should have high thermal conductivity, strength, and toughness and maintain good wear characteristics.

The contact pressure of a contact seal, as illustrated in figure 6-7, is controlled by balancing spring forces and hydraulic pressures. In this seal the spring closing force is supplied by the bellows secondary seal. Additional closing forces during pump operation are provided by pump delivery pressure being applied to the area on the high pressure side of the secondary seal and leakage pressure being applied to the low pressure side of the secondary seal. An interface pressure profile across the sealing surfaces (due to leakage flow pressure drop) tends to balance the closing forces with the resultant unbalance being the face contact load.

The seal design must not permit the maximum surface temperature to approach local ignition temperature. The oxygen pump seal integrity is of special concern because of the fire hazard from released high concentration oxygen and because of the possible ignition of the pump parts in the event of seal failure.

6.1.3.1 Seal types. - Primary seals are generally of the face contact type as illustrated in figure 6-7. While hydrostatic and hydrodynamic seals, which depend on fluid film support of the seal face, are potentially capable of extending the speed life limita-

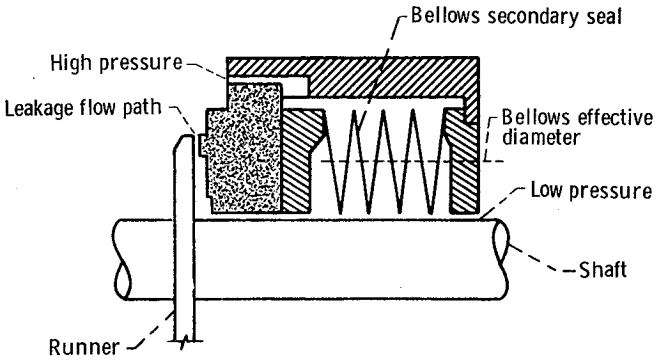


Figure 6-7. - Face contact seal.

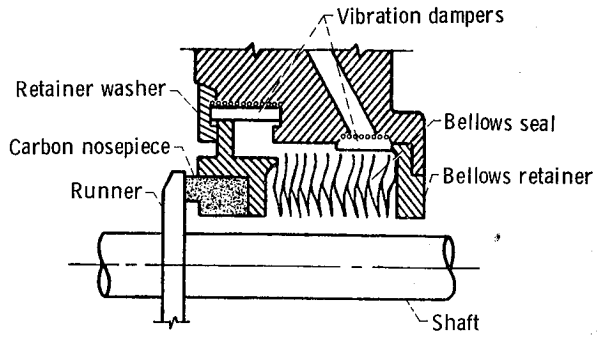


Figure 6-8. - Face contact/bellows.

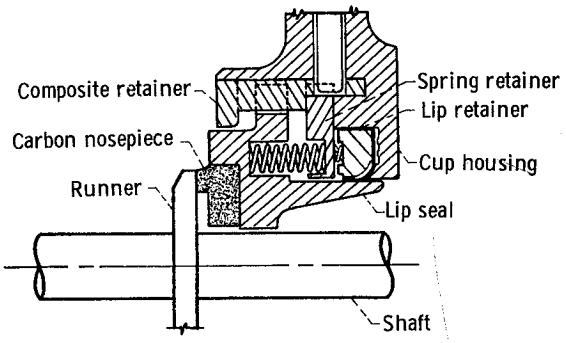


Figure 6-9. - Face contact/lip.

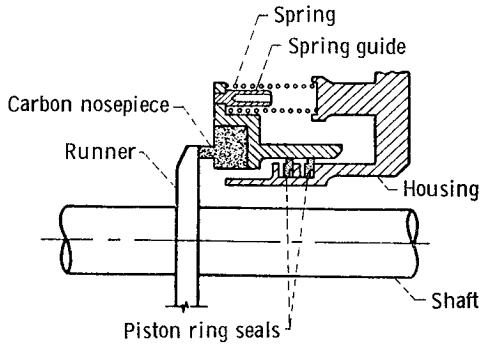


Figure 6-10. - Face contact/piston ring.

tions of seals, they have not yet been demonstrated to be suitable for oxygen service. However, the development of hydrostatic and hydrodynamic seals for oxygen service is continuing (ref. 112, pp. 15 to 18).

Secondary seal types include bellows, lip, and piston ring as illustrated in figures 6-8 to 6-10. The most common of these is the bellows seal which also provides spring and pressure loading to the primary seal. Bellows seals are subject to early fatigue failure unless damped to limit displacement under vibration. The lip seal provides good resistance to extreme vibration environments. It is, however, subject to damage and wear by accumulated contaminant particles. Piston ring seals are most resistant to oscillating pressure environments since they provide effective vibration damping. They, too, are sensitive to wear and leakage due to contaminant particles.

Labyrinth seals are not used as primary shaft seals in oxygen pumps because of the high leakage rates. This seal type is, however, often used to minimize backflow between inducer blading and pump housing. For long life seals and optimum compatibility, a back pressured purge at a controlled rate through the seal with helium or nitrogen warrants strong consideration in any oxidizer pump design.

6.1.3.2 Seal materials. - The most common nosepiece-runner materials for present generation oxygen turbopumps are graphitic (80 to 100 percent) carbon wear nose-

pieces riding on chromium-plated 4130 steel or annealed 440C stainless steel runners. Chrome plating has been shown to reduce the wear an order of magnitude. Also, 100 percent graphitic carbon has been shown to reduce wear significantly over amorphous carbon (ref. 113, p. 203). The influence of graphite content on seal wear and friction coefficient is shown in figure 6-11. The data for figure 6-11 were obtained by running carbon in sliding contact with chromium-plated 440C stainless steel in LOX at 2300 feet per minute (1000 g load with a 3/16-in. radius rider; ref. 113, p. 203). Experience with this seal combination in oxygen pumps is limited to pressures across the

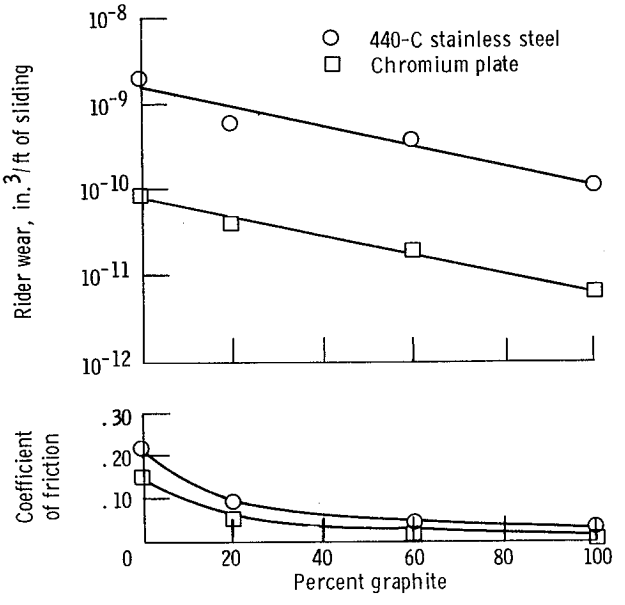


Figure 6-11. - Influence of graphite content on lubricating properties of carbon (based on ref. 113, fig. 2).

seal face of about 200 psi. If the trend toward higher pressures (and the higher pump rpm's) is considered, the continued use of carbon may be limited. Since higher pressure drops will require higher bearing forces between the graphite nosepiece and runner, the possibility exists that the ignition temperature of graphite in oxygen (about 450° C) may be reached if shaft speeds are increased over present practice.

Most failures to date have been due to cracking and breaking from thermal stress before reaching 450° C. Dense highly graphitic materials have the greatest resistance to ignition when compared to impregnated carbons. The use of impregnants must be verified by proof testing for chemical reactivity with oxygen under operating conditions (ref. 113, p. 207). The normally used materials for turbopump LOX seals are listed in table 6-IV.

Although the difference in wear rates between the various carbon face seals is

TABLE 6-IV. - LOX PUMP FACE SEAL MATERIALS

Component	Material
Nosepiece	Carbon P692, P5N, and 5AG
Runner surface coating	Chrome; tungsten chromium carbide
Runner base material	4130 steel; Inconel 750 and 1718; 440C stainless steel
Secondary seal:	
Lip seal	CTFE; Polyethylene terephthalate (Mylar)
Piston ring	CTFE; TFE
Bellows	Stainless steel 347; Inconel 750 and 718
Nosepiece base material and associated structural parts	Stainless steel 302, 303, 304, and 321; Inconel 750, 718, and 600; Invar 36; Carpenter 42
Insert adhesive (for attaching nosepiece)	Epon 901/B3; Teflon fusion

small, the best wear rates have been achieved with carbon P692. A generally preferred choice for the mating ring base material is 4130 steel (chrome plated) because of its higher thermal conductivity and lower cost. However, where pressure-velocity limits are approached (see sec. 6.1.3.3) and high temperatures and stresses are expected, Inconel 750 or Inconel 718 is preferred. These provide the higher strength and corrosion resistance for a more severe environment. The 440C stainless steel is also a suitable material. Tungsten chromium carbide (LW-5) was used in the development of the M-1 pump seal but the wear life was low (see table 6-V).

Invar 36 and Carpenter 42 have nearly the same expansion coefficient as carbon and are useful as nosepiece base materials in designs where expansion-contraction stresses would damage the carbon seal or its bond.

Of the two materials listed for bonding the carbon nosepiece to the metal base material, Epon 901/B3 is stronger but less compatible with oxygen than fused Teflon. Of the runner surface coating materials listed, chromium is the best material for wear characteristics and cost. To reduce the danger of carbon nosepiece ignition and to reduce wear rate for high pressure-velocity applications, seal combinations using aluminum oxide or calcium fluoride nosepieces operating on a nickel alloy runner have been used successfully in experimental pumps. The calcium fluoride - nickel combination also has worked well in high performance liquid fluorine pumps. Aluminum oxide, being brittle, must be properly supported on a metal substrate to avoid chipping. The use of carbon seals is discussed in reference 113. Aluminum oxide and calcium fluoride seals are covered in reference 114.

CTFE and Mylar are both used as secondary seal materials in operational pumps. Mylar is less resistant to ignition in oxygen then CTFE. Therefore, CTFE is preferable. TFE is also less likely to ignite than Mylar or other polymeric secondary seal

TABLE 6-V. - ROCKET ENGINE TURBOPUMP ROTATING SHAFT SEALS FOR LIQUID OXYGEN[a]

Program	Seal type	Materials				Seal diameter, in.	Fluid pressure, psig	Shaft speed, rpm	Rubbing speeds, ft/sec	Spring load, lb	Total load, lb	Unit load, psi	Pressure-velocity factor, (psi)(ft/sec)	Pressure balance ratio (b)	Wear life, hr	Dynamic leakage, standard ft^3/min
		Nose piece	Mating material	Secondary seal	Housing											
Thor	Fact contact welded bellows	Carbon P692	Chrome plated 4130	347 Stainless steel	304 Stainless steel	2.63	225	6 750	77	31	95	158	12.2×10^3	0.97	3	10
H-1	Face contact welded bellows	Carbon P692	Chrome plated 4130	Inconel 718	304 Stainless steel	2.63	200	6 800	78	82	106	176	13.7	.70	3	10
J-2	Face contact welded bellows	Carbon P5N	Chrome plated Inconel X	Inconel 718	321 Stainless steel	2.974	200	8 650	112	41	150	210	23.5	.85	2	15
J-25	Face contact welded bellows	Carbon P692	Chrome plated Inconel X	Inconel 718	321 Stainless steel	2.935	200	9 000	115	41	150	210	24	.85	2	15
M-1	Face contact welded bellows	Carbon P5N	LW5 (tungsten chromium carbide) on Inconel	Inconel 718	321 Stainless steel	6.902	450	4 000	120	20	471	196	23.5	.92	1.7	2.3
RL-10	Face contact welded bellows	Carbon 5AC	Chrome plated 5646 AMS	Inconel 750	5646 AMS	1.70	400	12 300	92	17	67	41	3.8	.05	---	----
F-1	Face contact lip seal (secondary)	Carbon P692	Chrome plated 4406	Mylar	303 Stainless steel	6.463	140	600	170	58	127	51	8.7	.7	3	25
Thor	Face contact lip seal (secondary)	Carbon P692	Chrome plated 4130	Kel-F	302 Stainless steel	2.65	225	6 800	78	32	82	120	10	.85	3	10
Atlas	Face contact lip seal (secondary)	Carbon P692	Chrome plated 4130	Kel-F	302 Stainless	2.63	250	10 000	115	32	86	137	15.8	.85	3	10

[a]Unpublished data obtained from Rocketdyne, Division of North American Rockwell, under NASA contract NAS3-13314.

[b]Pressure balance ratio = (closing area)/(face area).

materials, but its tendency toward cold flow and stress relaxation would require additional design innovations such as spring loading to maintain constant pressure.

The materials preferred for oxygen pump bellows seals are 347 stainless steel and Inconel. The 347 stainless steel is easy to weld and is preferable for lower pressures; where pressures (up to 500 psi) impose high stresses, Inconel 750 or 718 is used. Above 500 psi, piston ring seals are recommended.

6.1.3.3 Seal design factors. - Face contact seals have been used for oxygen pumps on the H-1, J-2, J-2S, M-1, and RL-10 engines. Seal pressures up to 500 psi were used and leakage ranged from 2.3 to 10 standard cubic feet per minute; wear life ranged from 1.7 to 3 hours with PV factors (pressure (lb/in.^{2}) × velocity (ft/sec)) up to 24 000. A state-of-the-art data summary is given in table 6-V. Seal life times of ground-based LOX pumps can be an order of magnitude greater than flight pumps since higher oxygen leakage rates are more acceptable and the designer has more flexibility for accommodation of oxygen leaks in ground-based systems.

6.1.3.3.1 *Leakage control and seal surface finish.* - Control of face contact seal leakage is achieved by carefully limiting surface waviness and roughness of nosepiece and runner. To compensate for waviness and roughness by increasing contact pressure to reduce leakage only increases the wear rate. Face seal mating surfaces are usually lapped flat to within 24 to 60 microinches in wave height; the resulting finish (surface roughness height) is approximately 10 to 20 microinches (ref. 115, p. 481). This surface finish appears to be optimum, and little or nothing is gained from a finer finish. According to references 51 (p. 6.4.3-2) and 115 (p. 481), an exceedingly smooth surface (in the range of 2 μin.) cannot support a lubricating film, and premature seal failure may occur. The lay on the mating surfaces for rotating shaft seals should be concentric circles across the seal face. As a general rule nonmetal seals (carbon or fluorocarbon polymer) will require a surface finish (roughness height) equal to 16 to 32 microinches.

6.1.3.3.2 *Seal rubbing speed, contact pressure, and wear.* - The allowable surface speed of contact seals is normally dictated by the amount of heat generation at the seal interface and the amount of cooling resulting from oxygen leakage and conduction through the structure. The temperature the seal may be allowed to attain is limited by thermal distortion, excessive wear rates, and the ignition temperature of the seal materials in oxygen. The heat generated at the seal mating surface is a direct function of the contact pressure, the coefficient of friction, and the velocity of the rubbing surfaces. Reference 116 presents a digital computer program which may be used to calculate temperature distribution in seal assemblies. These calculations are the first step in determining thermal deformation by means of the technique described in reference 117.

The face seal PV's (face pressure × velocity) for operational turbopumps are shown in table 6-V. The maximum recommended PV for a carbon seal in liquid oxygen for an expected life of 3 hours is 25 000 foot-pounds per second per square inch.

The current turbopump seal life is generally low (operating time, 2 to 3 hr) because of relatively high seal face unit loads required to meet leakage specifications. The average wear rate of the carbon nosepiece on the LOX side in the J-2 turbopump is approximately 0.010 inch per hour (unpublished data obtained from Rocketdyne, Division of North American Rockwell, under NASA contract NAS 3-13314). Allowance for high wear rate is provided by insuring that the nosepiece has sufficient height to wear away and continue to maintain seal capability during the operating life of the turbopump. Most wear and friction measurements with carbon material nosepieces indicate significantly higher wear rates and coefficients of friction during the initial seal "run-in period". During the "run-in period" a lubricating graphite film is transferred from the carbon nosepiece to the metal runner which reduces the friction and wear. The presence of stable, dense oxide film on a chromium-plated metal mating runner surface promotes adherence of the graphite transfer film.

6.1.3.3.3 *Shaft seal stability.* - Most LOX pump seals incorporate a bellows which allows the nosepiece to accommodate the face runout motions of the runner. The bellows-nosepiece combination, which constitutes a mass-spring system, is capable of vibrating in several modes, each with its characteristic natural frequency. To avoid seal leakage and rapid seal wear, resonant modes at shaft seal design speeds must be avoided. Bellows seal fatigue failures have been recorded less than 4.4 seconds after the onset of resonant vibrations (ref. 118, p. 7). If operation at or near resonance is unavoidable, vibration dampers are required. Vibration damping forces should be 5 to 10 percent of the seal spring (or bellows) load. Piston ring or lip seals used as secondary seals generally achieve enough damping forces. The subject of seal oscillations and methods for promoting seal stability are reviewed in references 112 (pp. 56 to 58 and 156) and 118.

6.1.3.3.4 *Contamination effect on seals.* - Foreign particle contamination can accumulate in the seal system cavities, and solid particle interference with sealing surfaces can cause abrasive wear of seal materials. The face contact bellows seals usually used in flight LOX turbopumps is the least sensitive to damage by particle contamination. The particles are generally too large to enter between the rubbing surfaces and usually there is very little if any damage due to seal face scoring. However, on a spring loaded face contact seal with a secondary lip seal (fig. 6-9) the tendency for particles to collect at the lip seal can cause erosive damage and excessive leakage of the lip seal. Hydrodynamic and self-energized hydrostatic type seals are also sensitive to abrasive wear from particle contamination. Particles tend to enter the face clearance gap and gouge or wear the seal face causing loss of life potential. System contamination limits specified for oxygen pump cryogenically cooled bearings (see sec. 6.1.2.2.1) also apply to face contact and lip seals for reliable operation. Contamination limits for seals are the same as those listed for oxygen cooled bearings.

6.2 POSITIVE DISPLACEMENT PUMPS

Single or multiple cylinder positive displacement pumps may be used to pump liquid oxygen to very high pressures (10 000 psi or greater). They have also been used to pump gaseous oxygen; but, because of compression heating they are generally limited to approximately a 1000 psi compression in this application. (See sec. 3.4.4 for adiabatic compression heating and secs. 3.4.1 and 3.4.2 for ignition temperatures of materials.)

The fundamental design considerations for piston pumps to be used for oxygen are the selection of materials that will function in the oxygen environment at operating conditions and the necessity of maintaining cleanliness to prevent component damage or ignition from contamination.

Positive displacement pumps are subject to most of the materials selection considerations as are centrifugal pumps. However, in centrifugal pump design, because of high speed operation, every effort is made to reduce or eliminate rubbing, while rubbing is inherent in piston-type pumps. The mitigating factor is that the rubbing in piston pumps is relatively low speed so that friction heating does not become a major problem. A schematic design drawing of a typical piston pump for liquid oxygen is shown in figure 6-12. A coolant jacketed version of the pump for gaseous oxygen compression is shown in figure 6-13 (ref. 119). In general, the pump will consist of a cylinder barrel and head, a piston with self-lubricating rings, inlet and outlet check valves, a screen filter, and a piston drive that may be any appropriate conventional power source.

The materials generally preferred for the piston pump components are given in table 6-VI.

The check valves for intake and exhaust are preferably all metal. For detailed valve design considerations see chapter 7.

Where vacuum pumps may be exposed to high concentrations of oxygen, the main concern is the possible reaction with pump lubricants.

This problem can be solved for most conventional vacuum pumps by proper cleaning and the substitution of the lubricant used to one that is resistant to oxygen. The preferred substitutes for the usual oils and greases used in vacuum pumps are one or more of the fluorocarbon lubricant oils or greases. Tricresylphosphate has also been used.

It is always good practice to review the materials used in the pump for general compatibility with oxygen and with moisture, as discussed in chapter 3.

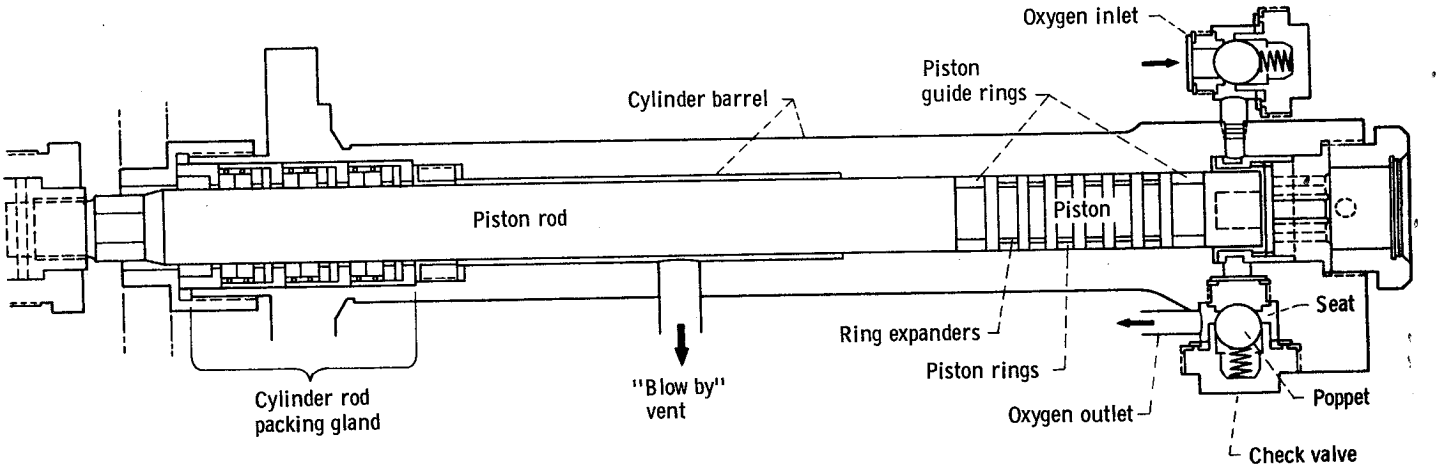


Figure 6-12. - Typical positive displacement piston pump for oxygen.

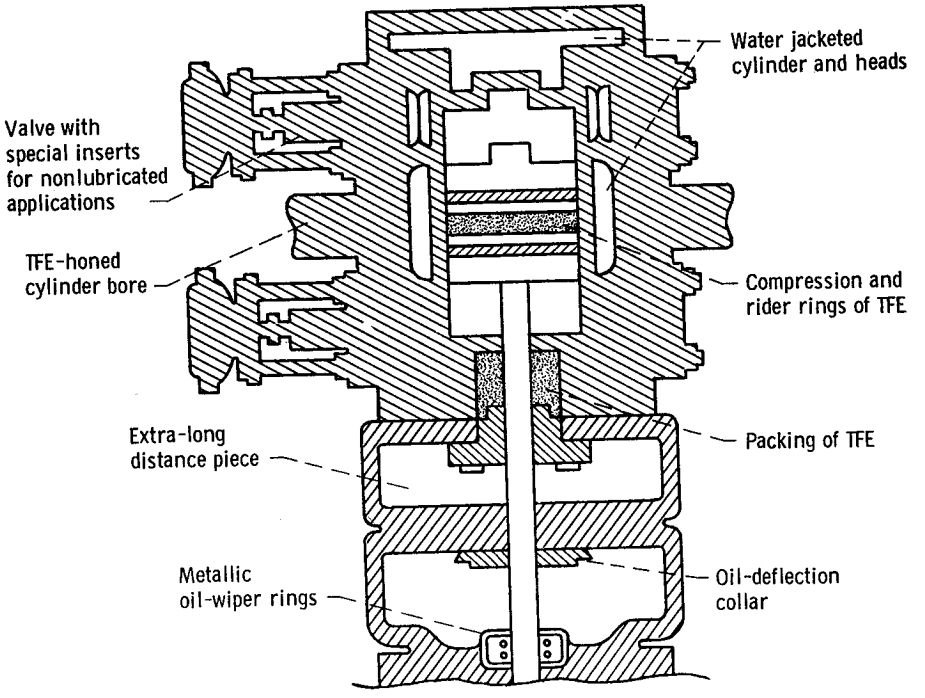


Figure 6-13. - Liquid cooled piston type oxygen compressor (ref. 119, p. 142).

TABLE 6-VI. - PREFERRED MATERIALS FOR PISTON PUMP COMPONENTS FOR OXYGE USE

Component	Liquid oxygen	Gaseous
Cylinder and cylinder head	304 Stainless steel Monel	Cast iron 304 Stainless steel Monel
Gaskets and seals	Asbestos Copper Aluminum Glass-filled TFE CTFE Viton	Asbestos Copper Glass-filled TFE CTFE Viton
Piston	Brass	Brass
Piston rings	Glass-filled TFE Copper-filled TFE Lead-filled TFE	Glass-filled TFE Copper-filled TFE Lead-filled TFE
Piston rod packing	Asbestos TFE CTFE	Asbestos TFE CTFE

CHAPTER 7. VALVE ASSEMBLIES

The major problems with valves are their inherent tendency to leak, trap, and be affected by contaminants. Leakage through valve seats and through actuator seals is aggravated by wear, thermal cycling, erosive flow, water hammer, high pressures, and pressure spikes. The problem of sealing to prevent leakage through valve seats and valve element actuators (or valve stems) is one of the more challenging parts of fluid system design.

Valve assemblies incorporate nearly every type of seal - rotating shaft or sliding shaft seals, seals for many configurations of valve element - valve seat designs, and static seals. Since similar seals are required in many other fluid system components, the basic subject of sealing to prevent leakage is discussed separately in section 4.1 and considerations for seal design are discussed in chapter 9. However, a brief discussion of seals and sealing especially pertinent to valves is included in this chapter. In addition to leakage, many valve failures in liquid and gaseous oxygen systems are often due to the ignition of valve parts from collected contaminants or noncompatible material within the valve. This type of failure generally occurs at the instant that flow conditions begin when the valve is opened. Failures from overstress or abrasion and galling can also initiate a reaction with oxygen in addition to making the valve inoperative or causing leaks.

Most of the design requirements for valves for oxygen service are the same as those for other cryogenic liquid or ambient temperature gaseous systems. However, in oxygen service the consequences of a design weakness, a material incompatibility, or a contaminant can be more severe than for inert fluids or for most fuels.

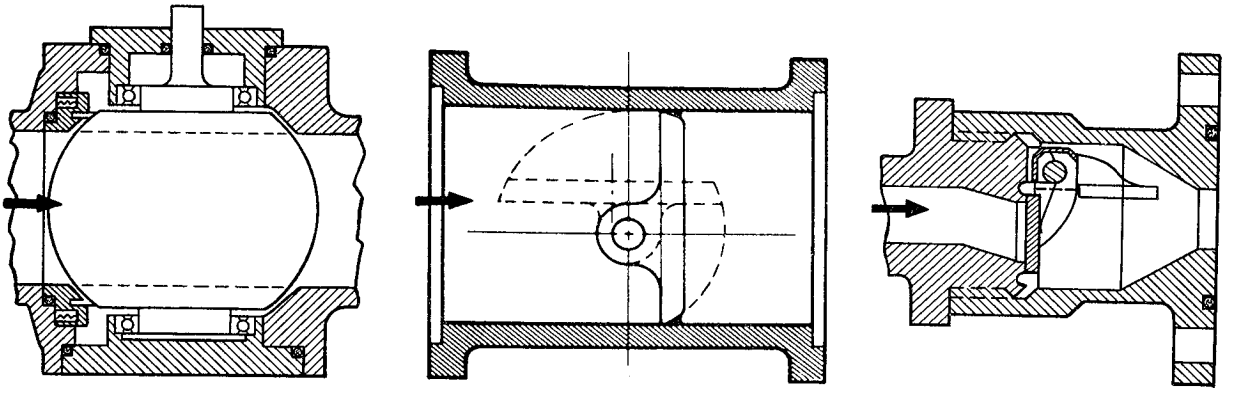
Although valve design and material selection can increase contamination tolerance, contamination of any kind is still hazardous and recommended system cleanliness and oxygen purity must be maintained. Oxygen purity is discussed in chapter 2 and cleaning requirements are provided in section 4.5.

A review of valve design considerations is given in the following sections. High pressure requirements are emphasized because they serve best to illustrate the special considerations required for oxygen systems. The discussion is equally applicable to pressure and flow regulators, check valves, and relief valves since they all involve the regulation and control of fluids and they all use the same basic types of valving elements.

7.1 VALVE ELEMENT TYPES

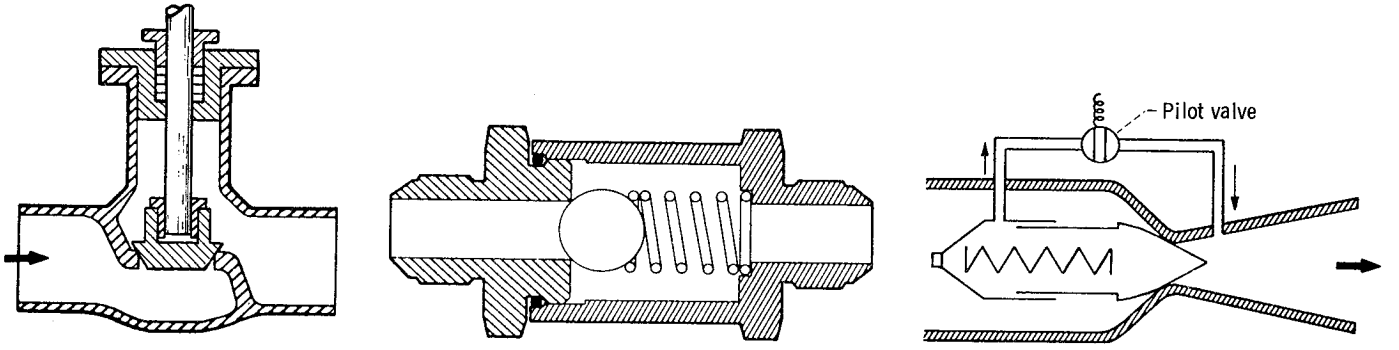
Valve types are categorized by the manner in which they effect closure to flow or throttling. Figures 7-1 to 7-3 illustrate the three basic types of valves and valve elements: (1) rotating elements, (2) translational plug elements, and (3) gate elements.

The ball valve and the butterfly valve (fig. 7-1) are opened by rotating the valve element. The poppet or plug valve (fig. 7-2) simply closes an opening in the valve by a linear motion perpendicular to the seat. The gate or blade valve (fig. 7-3) closes much as a sliding door with the gate having a linear motion whereas the blade rotates into the closed position. The swing check valve (fig. 7-1) is a combination of the poppet and an offset butterfly element.



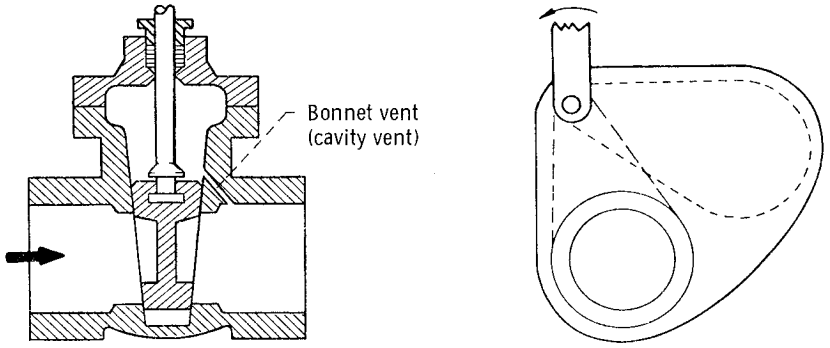
(a) Rotating ball. (b) Butterfly. (c) Swing check.

Figure 7-1. - Rotating element valves.



(a) Globe plug. (b) Ball check. (c) Venturi.

Figure 7-2. - Translational plug element valves.



(a) Gate. (b) Blade.

Figure 7-3. - Gate element valves.

7.2 GENERAL DESIGN CRITERIA

Valves create a discontinuity in the flow line both fluid dynamically and structurally. The flow passage in many valve designs incorporate recesses, pockets, and crevices to accommodate the valve element actuating mechanism and the valve element supporting structure. Some valve designs require a cavity for the valve element to retract into when it is opened (fig. 7-3(a)). These valve mechanisms and the accommodations for them cause stagnation zones where particulate matter may accumulate and create a hazard in oxygen systems. Also, in liquid systems, the element may trap liquid in a closed cavity; unless the cavity is vented, an overpressure condition is created when the liquid vaporizes. Where they cannot be completely avoided, pockets and connecting passages should be designed to be self-cleaning by means of controlled fluid flow through the cavity. However, this criteria to avoid accumulation of contamination by means of a self-cleaning feature rather than by avoiding the cavity can increase pressure losses in the valve. By compromising a smooth fluid dynamic flow passage, turbulent flow can cause cavitation at high flow velocities. At extreme pressures and high flow velocities, such as very high pressure throttle valves, there is a possibility of erosive effects and possible ignition of nonmetal materials if contaminants or particulate matter are present. Therefore, the primary design criteria is to avoid valve design features that create stagnation zones or crevices where particulate matter can accumulate.

Engineering trade-offs to take advantage of available shelf hardware or low cost fabrication must be evaluated for each specific application. Most commercial valves were not designed for oxygen. However, they may be adapted for oxygen service by modifying some of the materials used in their components. An engineering valve design and selection trade study illustrating the factors which must be considered is discussed in reference 120 (pp. 5-46). Because of the thorough discussion contained in this study, no detailed discussion of valve selection is included here. However, considerations

such as material selection, valve life, and internal leakage are reviewed.

To achieve the minimum leakage possible in valves, the valve closure contacting surfaces must meet the basic design criteria for sealing discussed in section 4.1 and chapter 9. To maintain this capability, the design must incorporate features to minimize wear or distortion of the closure contacting surfaces.

7.3 MATERIALS SELECTION

Important considerations for valves for nonflight use are long life, high reliability, low component cost, and low maintenance cost. Since weight is no problem, a wide range of materials may be used because more massive parts can compensate for lower material strength. For flight valves, maximum reliability and low weight are the major design considerations. Weight and strength requirements restrict materials selection.

For higher pressures (3000 to 10 000+ psi) material selection is further reduced to those materials compatible with the severe dynamic conditions of abrasion, impact, and cavitation which cause surface damage, erosion, and the possible ignition of sensitive materials. Therefore, for very high pressures, the strength and compatibility of materials take precedence over low weight for flight hardware and low cost in ground hardware. High pressure service requires the same care in material selection and valve design for either ground or flight systems. The supporting data and detailed information for strength of materials are given in references 20, 69, and 121. Materials compatibility with oxygen is discussed in chapter 3 (see also refs. 23 and 37, pp. 140 to 148).

A list of materials that have been used for oxygen valves in major rocket engine propellant systems is given in table 7-I. It should be noted in table 7-I that Mylar has been used successfully as a secondary seal material in several operational valves even though it has been shown to react with oxygen in the NASA standard impact apparatus. Therefore, its use elsewhere in the valve or in valves of different design operating above 1500 psi should be reviewed carefully and validated by tests which cover all possible service conditions.

For very high and ultrahigh pressures (over 7500 psi), the preferred materials are metals and alloys which have high melting points, high ignition temperatures, a relatively high thermal conductivity, and a low heat of reaction with oxygen (see sec. 3.4). Copper, brass, Monel, 17-7 and 17-4 PH steels, 400 and 300 series stainless steel, and Hastelloy, in this approximate order, best meet these requirements. Aluminum and its alloys may be used, but caution should be exercised when using aluminum in gaseous oxygen in the very high pressure range (>7500 psia) because of its low melting point and very high heat of reaction. Therefore, Monel for strength requirements and

TABLE 7-I. - OXYGEN VALVE MATERIALS FOR ROCKET SYSTEMS

Vehicle and engine	Valve application	Fluid media	Valve element	Valve element material	Seal or seat material	Valve housing material	Dynamic seal type	Secondary seal material	Line size, in.	Operating pressure, psi	Flow rate, lb/sec	Actuator type	Response time, msec
Atlas MA-5	Booster main oxidizer value	LO_2	Butterfly	7075-T6 forging	CTFE	TENS-50 aluminum	Lip seal	Mylar[a]	4.0	782	424.5	Pneumatic piston	400
	Sustainer gas generator	LO_2	Blade	17-7 CRES	CTFE	356-T6 permanent mold casting	Face seal	Kel-F	.75	570	7.27	Pneumatic piston	100
	Vernier propellant valve	LOX	Poppet	2024-T4	CTFE	7075-T6	Lip seal	Kel-F	------	----	-------	---------	----
Saturn S-IB H-1	Main oxidizer value	LO_2	Butterfly	431 CRES	CTFE	356-T6 permanent mold casting	Lip seal	Mylar[a]	4.00	975	545	Hydraulic piston	333
	Gas generator (oxidizer)	LO_2	Poppet	A-286 CRES	FEP Teflon	347 CRES	Bellows	A286 CRES	.609	940	-------	Hydraulic piston	----
Saturn S-IC	Main oxidizer	LO_2	Poppet	6061-T6 aluminum forging	TFE Teflon	6151-T6 aluminum forging	Vented redundant lip seals	Mylar[a]	8.0	1600	2000	Hydraulic piston	600
F-1	Gas generator	LO_2	Ball	Two piece welded A-286	CTFE	7075-T73 die forging/TENS-50 permanent mold casting	Vented redundent lip seals	Kel-F	1.5	1600	121.5	Hydraulic piston	----
	Oxidizer prevalve	LO_2	Ball (visor)	----------	----------	----------	----------	----------	17.0	115	3970	Pneumatic piston	500
Saturn S-II	Main oxidizer valve	LO_2	Butterfly	431 CRES	CTFE	TENS-50 permanent mold casting	Lip seal	Mylar[a]	4.0	911	386	Pneumatic piston	50
	Gas generator (oxidizer)	LO_2	Poppet	A-286	FEP Teflon	6061-T6	Bellows	A-286	.531	1010	3.29	Pneumatic bellows	30
	Propellant utilization	LO_2	Rotating sleeve	440C	None	TENS-50 aluminum casting	Lip seal	Mylar[a]	2.0	1310	1 to 120	Electric motor	Throttling
	Prevalve	LO_2	Butterfly	A-286	CTFE	6061-T6	V-Seal	Teflon-coated Inconel X750	8.0	132	386	Pneumatic bellows	1000
	Propellant tank vent and relief	GO_2	Poppet	7075-T73	CTFE	356-T6	RACO and flat gaskets	Teflon with CRES and Kel-F and Mylar[a]	------	----	-------	---------	----

[a]Mylar generally not recommended for use in liquid oxygen valve seals because it has produced positive reactions in LOX impact sensitivity tests at high impact energy levels.

copper or brass for nonstructural requirements would provide the greatest resistance to ignition at high pressures and temperatures.

7.4 VALVE LIFE

Valve life is determined largely by the wear rate of the moving parts and the contacting surfaces. Valve element, valve seat, and actuator guide and seal wear can affect both external and internal leakage rates. Changes in the surface finish and shape of the valve element - valve seat interface from excessive closure forces can raise the leakage rate and increase the actuation force required to seal above acceptable limits. Useful valve life is achieved by careful specification of the valve element - valve seat materials, their surface finish, contact load, and by preventing relative motion as contact is made or broken. The easiest way to achieve a low leakage of "zero" leakage valve seal is to use a nonmetal seat or insert. This is also the lowest cost approach. All-metal valve elements including the seat can achieve the same leakage specifications but with less reliability and at greater cost. However, nonmetals become increasingly sensitive to erosion and particle impingement at higher oxygen pressures, especially with gaseous oxygen at room temperatures and above. Therefore, as pressures and/or temperatures are increased, material selection becomes more restricted and all-metal components are ultimately required. Limits of materials compatibility and materials selection criteria are given in chapter 3.

7.5 INTERNAL LEAKAGE

Sealing to prevent internal leakage is the most difficult part of valve design. A discussion of leakage through seals is presented in section 4.1. Sealing to prevent leakage and leakage flow tests are discussed in reference 122 (pp. 407 to 418). Considerations for sealing interface design are reviewed in chapter 9. "Zero" leakage as defined in section 4.1 is possible with both metallic and nonmetallic seats. However, the metallic valve element - valve seat is more easily damaged by solid particles trapped on the mating surfaces and from wear and plastic deformation during valve closure than the more compliant nonmetallic element seat. Increased leakage is a consequence of such surface damage. Specifications for permissible valve element - valve seat leak rates are a compromise between cost and performance requirements. Typical leak rates are listed in table 7-II (ref. 123).

TABLE 7-II. - ROCKET ENGINE LEAK RATES IN OPERATIONAL VALVES[a]

Engine system	Valve type and location	Service fluid	Seal type and material	Sealing diameter, in.	Leak test pressure, psig	Leakage, standard in.^{3}/min	Leakage, standard in.^{3}/min per in. of seal
F-1	Poppet main oxidizer	LO_2	Captured Teflon poppet nose seal	8	80	$56GN_2$	2+
J-2	Butterfly main oxidizer valve		Kel-F lip seal	4	500	5He	.4
J-2S	Butterfly main oxidizer valve		Kel-F lip seal	4	500	3He	.25
S-11	Butterfly prevalve		Kel-F lip seal	8	50	450He	<20
MA-5	Blade gas generator		Machined Kel-F ring	1	500	$10GN_2$	3+

[a]Ref. 123, p. 18.

7.5.1 Metallic Seats

Metal seats are generally preferred for very high pressure applications because they are more resistant to damage from pressure stresses and erosive flow. Generally, the valve element in the plug or poppet-type valves is of a harder material than the seat material to prevent galling and contact surface deterioration from the stress of open-close cycling. But this is not critical when the contacting surfaces are not caused to rub or slide under pressure during closure and where closure pressure is within the elastic limit of the valve element - valve seat combination.

The design objective in metal-to-metal valve element - valve seat surfaces is complete contact between the surfaces since effective valve closure depends on close conformity of the mating seat and element surfaces. This is difficult to achieve, even with optically flat surfaces and assuming perfect alinement because of the surface asperities. Ideally, the height of these asperities is limited so that the local deformation required to seal is within the elastic limit of the seat-element materials, and work hardening of the contacting surfaces is minimized.

The real area of a surface may be many times greater than its apparent or projected area depending on the surface finish. The surfaces obtained by polishing and rolling are only slightly greater than their projected areas; a roughed surface from an abrasion process may have a total area three times its projected area (ref. 122, pp. 20 to 29). Even with relatively smooth polished surfaces the asperities prevent 100 percent surface contact. If sufficient pressure is applied to achieve 100 percent surface contact, the asperities are literally mashed beyond the elastic limit and work hardening and galling of the surface results.

The leakage paths are minimized by providing a valve element - valve seat contact surface finished with asperity heights small enough (less than 4 μin. rms) to prevent sig-

nificant localized work hardening. Average machine-finished surfaces have asperity heights of about 125 microinches rms. Metal-to-metal valve plug - valve seat combinations are usually finished to about 16 microinches by lapping the components together. But for high pressure, low leakage, multicycle operations a special care in lapping is taken to achieve surface finishes of 2 to 4 microinches. With additional effort, asperity heights between 1 and 2 microinches can be achieved using a diamond grinding and polishing compound of appropriate grade (ref. 122, p. 40). Even with the proper surface finish good seat life requires careful specifications of maximum seat closing forces to avoid surface damage. The valve element should contact the seat without friction to minimize wear and abrasion, and the quantity and size of particulate material in the oxygen must be controlled. Oxygen purity is discussed in section 2.3 and filtration is discussed in section 7.8 and chapter 10.

7.5.2 Nonmetal Seats

Polymeric valve seat materials are not specifically recommended for pressures above 2000 psi or flow velocities above 500 to 700 kilometers per hour (455 to 638 ft/sec) (see sec. 4.2). However, with proper protection, if the seat material is recessed in a high thermal conductivity metal, polymeric materials may be used after proof tests substantiate the design. This technique reduces the possibility of ignition and prevents "cold-flow" relaxation of the seat. This design technique was used successfully and confirmed in tests with liquid fluorine (ref. 37, p. 142). Nonmetal materials are particularly sensitive to the conditions associated with fluid flow at high pressures and flow velocities (i.e., particle impact, erosion, friction, and shock waves) because of their generally low ignition temperatures and low thermal conductivities.

While several nonmetallic materials have been used successfully in liquid and gaseous oxygen systems, tetrafluoroethylene (TFE), fluorinated ethylenepropylene copolymer (FEP), and chlorotrifluoroethylene (CTFE) filled with glass or metal fibers are preferred for most applications. For oxygen systems at pressures above 2000 psi, such nonmetallic seats should be qualified by proof tests which simulate the use cycle and environment (see ch. 3).

7.6 VALVE ELEMENT ACTUATOR SEALS

Schematic examples of dynamic seal designs generally used for oxygen valve stems and valve actuators are shown in figure 7-4 and in figure 9-1 in the chapter on seals.

In high pressure systems, oxidizer leakage through valve stem packing can be a problem; if leakage gets started, leak erosion enlarges the leak channel with a possibil-

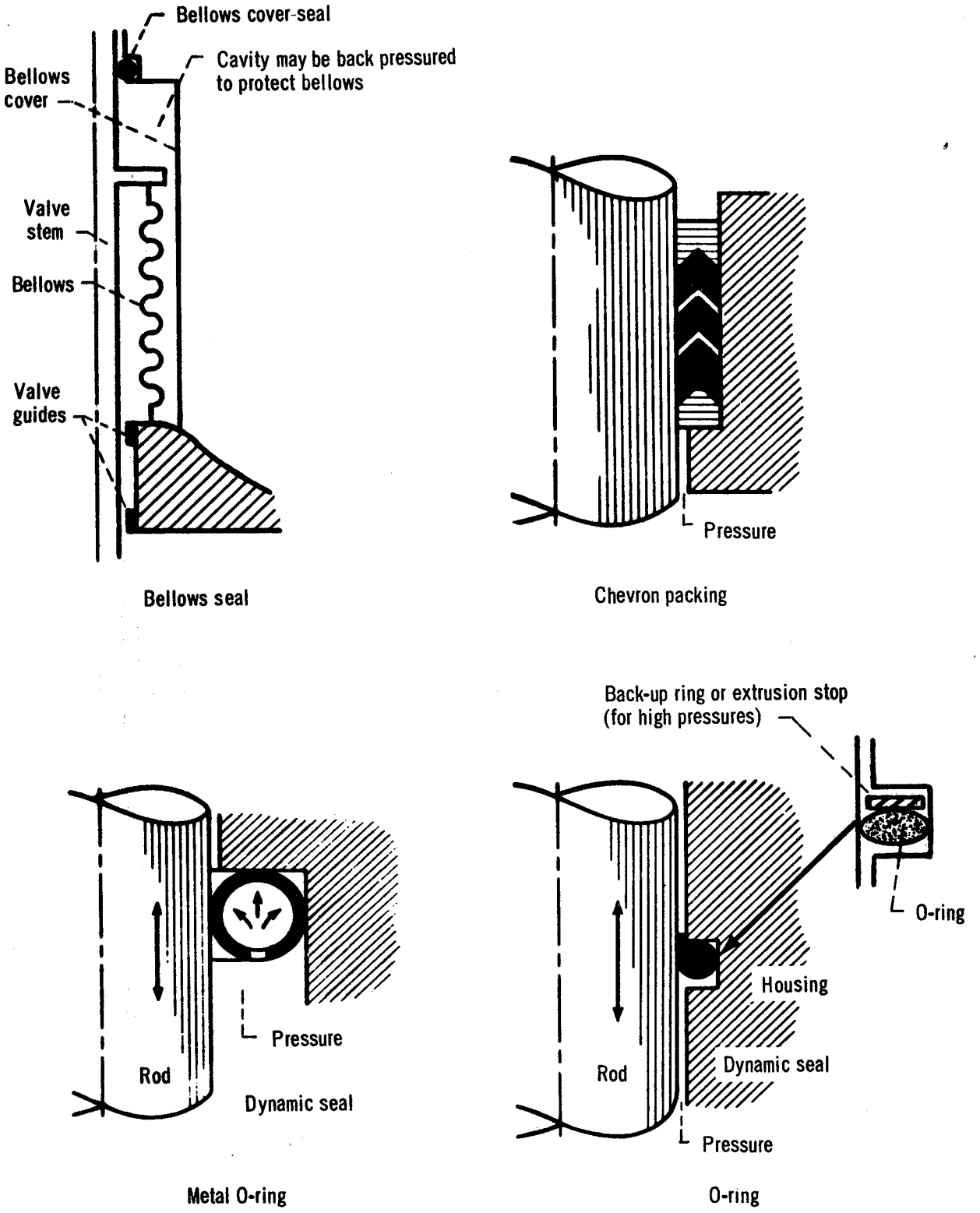


Figure 7-4. - Dynamic seals.

ity of igniting the seal material. To prevent valve packing leaks, frequent servicing and retightening are required. This is especially important for cryogenic valves because of thermal cycling effects. A spring loaded packing gland may be used to accommodate shrinkage and packing wear. A good valve stem packing is self-lubricating and wear resistant. The wear rate may be reduced by selecting packing with a low friction coefficient acting with a polished valve stem. The surface polish on the stem should be at least 8 to 10 microinches (ref. 70, p. 290). Stainless steel stems and Chevron or O-ring packing of tetrafluoroethylene (TFE) and chlorotrifluorethylene (CTFE) are preferred. For very high pressures dual or stepdown seals may be used. Silicone rubber does not pass the NASA standard impact test for ignition but has been used successfully in valves as a dynamic seal at pressures up to 7500 psia in the Apollo Personnel Life Support System. The Viton O-ring originally used failed because of oxygen absorption when exposed to 7500 psia oxygen pressure in the regulator valve. When the system was depressurized, the material fractured from the pressure of the absorbed gas (ref. 124). Section 9.3.3 discusses the qualification of silicone rubber for use in high pressure oxygen systems.

Bellows seals or diaphragms may be used for valve dynamic seals to achieve "zero" leakage. However, these present problems of fatigue cracking, accidental overpressure failure, differential pressure limits, and corrosion. Corrosion problems and prevention criteria are discussed in section 3.2. Internal corrosion can be prevented by maintaining dew point limits in the system and in any pressurant gas which contacts the bellows to -50° F or less.

Sliding surfaces in valves and regulators including dynamic O-ring seals and some valve stem packing may require a lubricant to reduce the breakout and running friction. The lubricant must be effective over the operating temperature range and be compatible with liquid or gaseous oxygen. The TFE lubricants or CTFE grease or oil (sparingly used) are preferred.

7.7 EROSION

In addition to entrained particulate erosion, erosion by cavitation may occur in valves handling liquid oxygen at very high pressures whose downstream static pressure is close to its vapor pressure. Very high pressure drops and the associated acceleration of the liquid over the valve element - valve seat surfaces or through packing leaks may cause erosion that can limit the seat-plug life or destroy an actuator seal (see sec. 4.2). The erosion rate increases with pressure at which cavitation occurs because of the increased driving force. Valve element - valve seat contours which avoid abrupt changes in flow direction are less subject to erosion damage. Erosive effects are most severe on lips and sharp edges exposed to the flow or on a static seal that begins to

leak. In addition to producing surface damage, high flow velocities have caused ignition of nonmetallic materials and all metal high pressure flange seals. The probability of ignition can be expected to increase with pressure because the apparent ignition temperature is reduced and because of the effect of flow on ignition of materials noted previously.

7.8 FILTRATION REQUIREMENTS

In very high pressure oxygen systems where near zero leakage is desired and where all-metal valve elements are used, filtration should remove particles within one or two orders of magnitude of the roughness of the valve seat interface surfaces to prevent seal deterioration. Additionally, valve stem guides, sleeve valve elements, butterfly lip seals, and ball valve seals are examples of valve components that are sensitive to solid particle contamination because of the close clearances. If solid particles become trapped, valve malfunction may result. Reference 123 (p. 94) records the case of a sticking poppet valve on a reaction control system engine. The poppet valve guide-stem clearance was 0.002 to 0.003 inch (2000 to 3000 μin.) and filtration was provided to remove particles down to 10 to 25 microns (400 to 1000 μin.). However, valve sticking continued until the poppet guide-stem clearance was increased to 0.008 inch (8000 μin.). Therefore, for this case, particles had to be removed that exceeded approximately one-eighth the clearance gap. If 10 percent is used as a nominal requirement, the original 0.003 inch clearance would have required filtration down to 300-microinch particles.

This example suggests that the established practices of filtering particles equal to or larger than the operating clearances in the valve are inadequate. While it is unsound to generalize from a single case, it is suggested that system cleaning and oxygen filtration of particle sizes no larger than 10 percent of the operating clearance may serve as an interim guide for systems where clearance clogging or possible binding from particulates could occur (see ch. 10). In most cases where motion exists between surfaces of close clearances, forces are such that particles would not bind the mechanism nor permit accumulation. However, the particulates would tend to increase the wear rate of the contacting surfaces.

CHAPTER 8. LINES, CONNECTORS, JOINTS, AND FITTINGS

Lines, tubing, pipes, ducting, and their associated hardware are subject to two conditions or circumstances that are of special concern in oxygen systems: unaccounted for overstress and high velocity flow of gaseous oxygen. Their length to diameter ratio allows very high leverage for excessive bending stresses in addition to stresses from internal pressure, thermal expansion-contraction, water-hammer, and cyclic stresses from vibration or chugging. Lines are often assembled without regard to slight misalinements (because it is so easy to do), and a prestress results which is additive to the working stress. These stresses are generally concentrated at a discontinuity such as a weld joint, connector, valve, elbow, or material flaw.

Sonic flow of gaseous oxygen in lines can impale entrained solid particles into an elbow or flow system component with sufficient energy to cause erosion or even ignition in sensitive materials.

This section is a review of the factors that should be taken into account to help assure a reliable oxygen transport system for liquid and gaseous oxygen for all possible pressures.

8.1 ALLOWABLE WORKING PRESSURE

The allowable working pressure for piping and tubing for ground-based systems is established in accordance with ANSI piping code for pressure piping (refs. 125, pp. 11 to 21, and 126, pp. 6 to 25).

For flight weight systems, the calculation of allowable stress is based on the material property and the required safety factor for each specific application. The structural integrity of the lines should be demonstrated by test as early in the prototype phase as possible. Recommended test practices are the following:

1. Subject the line to hydrostatic stress levels 1.25 to 1.5 times the maximum expected operating levels for proof testing and 2.5 times maximum operating levels for burst testing.

2. When thermal gradient tests or tests at operating temperatures are inconvenient, simulation of these stress levels or reduction in material strength should be accounted

for by additional pressure or loads at ambient temperature.

3. Vibration testing should be performed with the duct flowing the operating fluid at the maximum operating condition whenever possible to account for fluid mass and possible coupling of flow-induced and mechanical vibration.

Piping used to contain high pressure oxygen (over 2000 psia) should be X-rayed and visually inspected for imperfections. Unacceptable flaws should be cut out of the raw stock before fabrication processes. (Unacceptable flaws are discussed in sec. 5.1.5.)

8.2 MATERIAL SELECTION

Materials for pipe, tubing, or ducting for liquid oxygen systems are selected to meet the chemical compatibility requirements of the use environment as well as the required structural ductility and notch sensitivity characteristics at cryogenic temperatures.

Examples of preferred materials, based on the preceding criteria, and general experience for oxygen plumbing systems are presented in table 8-I for a range of pressures and temperatures.

TABLE 8-I. - MATERIALS FOR LINES FOR OXYGEN SYSTEMS

Material	Remarks
Aluminum 1114, 2024-0, 3003, 5052-0, 6061-0, 6061-T6, 6061-T4	Aluminum alloys used mainly as tubing with tube connectors; pressure limits determined by type of connector; not recommended for very high pressures (over 7500 psi)
Monel 400, K500	Tubing and pipe stock good for very high pressures and welded connections
Inconel 600, 718	Tubing and pipe stock good for very high pressures and welded connections
Stainless steel 304, 316, 317, 321, 347 Some 400 series stainless AM-350	Tubing and pipe stock good for very high pressures and welded connections
Rene 41	Tubing and pipe stock good for very high pressures and welded connections
Carbon steel	Welded joints or other; not usable below -30° F
Copper, copper alloys	Brazed joints or tube fitting connectors; not recommended for very high pressures

8.3 FLEXIBLE HOSE

For flexible hose requirements, wire reinforced stainless steel corrugated sections are generally used. Flexible metal ducting up to 18 inches in diameter is available for cryogenic liquid up to several atmospheres. The pressure drop through convoluted flexible tubing can be 10 to 15 times the pressure losses of straight wall tubing which suggests minimal use. Nonmetal materials are not generally used since they do not meet the flexibility requirements for use with low temperature gaseous or liquid oxygen. The brittle point of most oxygen compatible polymeric materials is above the temperature of liquid oxygen (-297° F). The TFE, CTFE, and FEP fluorocarbon polymers have brittle points lower than liquid oxygen temperature and could be used as a liner for flexible hose with liquid oxygen. However, this is not recommended because of the reduced cycle life at these temperatures. Brittleness temperatures are generally determined by impact tests (ASTM-D746-72, ref. 127, pp. 253-259). (The brittleness temperature limits are not the same as bending limits; some degree of bending can be tolerated at temperatures below the measured brittle point.) However, the brittle temperature may be used as a guide to determine the low temperature use limit of oxygen compatible polymer tubing or tubing liners for special test or laboratory applications. The brittle temperature of selected oxygen compatible polymers is presented in table 8-II.

For practical applications, the polymer lined flexible hose should be limited to ambient indoor and outdoor temperatures. Where cycle life is important, it should be predetermined by test.

TABLE 8-II. - BRITTLE POINT TEMPERATURES

OF SELECTED POLYMERS[a]

Material	Brittle point temperature, °F
TFE	-420
FEP	-420
CTFE	-400
Silicone rubber	-90 to -200
Fluorosilicone rubber	-90
Polyvinylidene fluoride	-80
Vinylidene fluoride - hexafluoropropylene (Viton and Fluorel)	+10 to -60

[a]Ref. 51, pp. 12.3.2-2 and 3.

8.4 BELLOWS

Where flexible sections are necessary, bellows with conventional convoluted shape are recommended for liquid oxygen use. The convolution height, width, and shape may be varied to achieve the desired strength and flexibility. Welded bellows are more prone to overpressure damage and early fatigue failure than formed bellows, and they are generally more difficult to clean and keep clean. However, when greater flexibility is required in applications such as centrifugal pump secondary seals, welded spring bellows may be preferred (see table 6-V). An analysis of past fatigue failures indicates that mechanical and/or flow induced vibrations have caused cracking. Overdeflection due to mishandling has also contributed to some failures. Minor flaws have a tendency to propagate rapidly unless low magnitude stresses are maintained. Mechanical restraint linkage must be used to limit overflexure of the bellows beyond acceptable stress limits.

Dents, nicks, and scratches in the most highly stressed area of the bellows (the convolution crown) due to abusive handling during fabrication, shipment, or installation have also been a major contributor to bellows failures. The only solution to this problem is care in handling and suitable inspection to ensure quality control. Since excessive internal or external pressure causes buckling or buckling instability of the bellows, the design must permit the maximum surge pressure with the bellows in any operating position without exceeding the total stress limitations. Design criteria and sample calculations for bellows ducting and bulging stress limit calculations are provided in reference 70 (pp. 374 to 379).

8.4.1 Flow Induced Vibration Failures

Self-induced oscillation or vibration of bellows sections (or flexible lines) can occur at certain pressure - flow velocity combinations. Pressure variations of the fluid flowing over the convolutions at a given velocity can become resonant with the natural frequency of the bellows section and cause oscillations that result in cycle fatigue and cracking of the bellows.

An analytical method for determining the susceptibility of a bellows to flow induced vibration is given in references 128 to 130 (pp. 25 to 49). The observed frequency varies directly as a function of the fluid velocity and inversely with twice the bellows pitch distance. Preventing the impingement of the flow stream on the convolutions by using an internal sleeve has been used to prevent flow induced vibration. However, the installation of the sleeve presents complications in the design and fabrication and makes cleaning the duct for oxygen use more difficult. Damping devices such as external sleeves or travel limit braces can also prevent damaging oscillation.

8.4.2 Bellows to Duct Attachment

Wherever practical, the bellows to duct joint should be a full penetration V-notch butt-weld. If this is impractical, the design alternate should have all overlaps and crevices welded closed (see sec. 8.6.1).

A doubler contoured to fit snugly against the end convolution (fig. 8-1) is also an acceptable design; however, the convolution is partially inactivated, thus applying increased strain into the remaining convolutions.

If the end of the doubler is permitted to touch the convolution, a stress riser can be created when bellows are deflected or subjected to a vibration environment, which can promote early fatigue failure. A clearance of at least 0.05 inch is recommended as shown in figure 8-2.

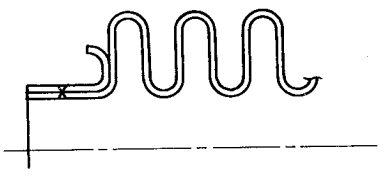


Figure 8-1. - Welding neck doublers.

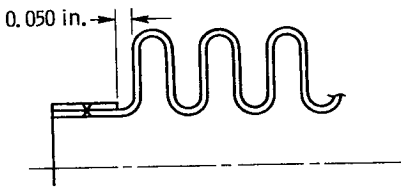


Figure 8-2. - Doubler clearance requirements.

8.4.3 Bellows Materials

Bellows materials suitable for oxygen use are given in table 8-III (refs. 70 and 131). The materials listed are primarily for formed bellows. Materials used most for

TABLE 8-III. - BELLOWS MATERIAL FOR OXYGEN USE[a]

Metal	Metal
304 Stainless steel	Aluminum 6061-T6
301 Stainless steel	Aluminum 7075
347 Stainless steel	Beryllium copper
A-286	Nonmetal[b]
Inconel 718	
Inconel X	TFE
Hastelloy-C	CTFE

[a]Refs. 70 (p. 376) and 131 (p. 46).
[b]Ambient temperature.

TABLE 8-IV. - ALLOWABLE STRESS FOR BELLOWS MATERIALS

Bellows materials	Operating temperature, °F	Estimated stress for failure in 106 cycles, psi	Suggested design values, psi
CRES 321	70	45 000	22 500
	-320	88 000	44 000
	-420	98 000	49 000
	400	40 000	20 000
Hastelloy-C	800	50 000	25 000
Inconel 718	70	55 500	27 750
	-320	65 400	32 800

electrodeposited bellows are nickel and copper.

Suggested design values of allowable stress are tabulated in table 8-IV for some of the common bellows materials. These suggested design values have been tabulated for a bellows life of 10^6 cycles. A life of 10^6 cycles was chosen because the S-N (stress-number of cycles) curves for most materials are relatively flat for greater than 10^6 cycles.

8.5 COUPLINGS AND FITTINGS

There are a multitude of coupling and threaded connector configurations available from many manufacturers incorporating various seal designs. In order to simplify the discussion of these components, this section is limited as much as possible to the coupling configuration, and the discussion of the seal design is covered in chapter 9.

8.5.1 AN, MS, and MC Couplings

The AN (Air Force/Navy Aeronautical), MS (Military Standard), and MC (NASA Marshall Center) connectors are the commonly used flared tube connectors which can be made to government or industry specifications. These connectors are basically the same except for their sealing interface specifications. The general configuration of these connectors is shown in figure 8-3.

The MS (Military Standard) version of the coupling has a 32-microinch finish on the 37° conical sealing surface.

The NASA Marshall Center (MC) connector (ref. 132, p. 5) has the following:

(1) Conical sealing surfaces are controlled to 8 microinch (rms) profile for steel and 16 microinch (rms) profile for aluminum.

(2) Sealing surfaces are round within 0.003 inch with maximum deviation of 0.0001 in any 60° arc.

(3) Concentricity of sealing surfaces are within 0.003 inch total indicator reading (TIR).

Standard AN's are excellent for low pressure requirements; for higher pressures, up to 3000 psia for larger sizes and 7500 psia for smaller sizes, the addition of conical seals are recommended (fig. 8-4). At the higher pressures, the possibility of coupling failure exists because of the tube slipping out of the fitting. This is more prevalent with aluminum or copper alloy fittings than with steel. A "rule of thumb" has evolved that recommends using these types of couplings be limited to 2 inches in diameter for steel tubing and 3/4 inch for aluminum or copper tubing at pressures in the range of 1500 psia. However, this is not a valid limitation because of the many variables in coupling designs.

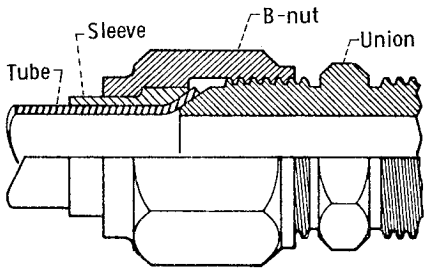


Figure 8-3. - AN, MS, and MC couplings. Materials available in 300 series stainless steel, 2024T-6 aluminum, and brass; seamless tubing preferred above 2000 psi.

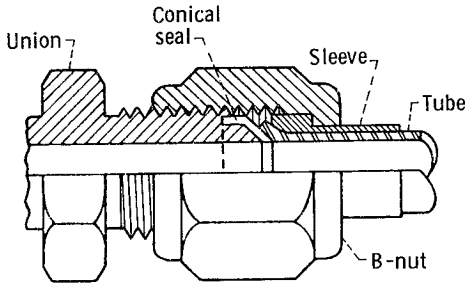


Figure 8-4. - Standard Air Force/Navy Aeronautical (AN) connector with metal conical seal. Materials available in 300 series stainless steel, 2024T-6 aluminum and brass; conical seal material - nickel, 6061-T4, 6061-T6, 6061-0, aluminum, or soft copper.

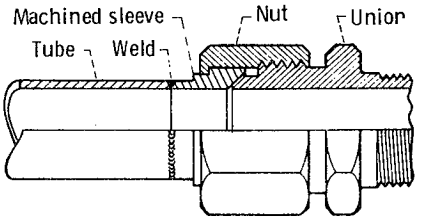


Figure 8-5. - Machined sleeve coupling.

But, greater care must be taken to effect a tight seal as the diameter is increased because of the longer seal interface and the increase in the possible leak paths. It is recommended that couplings for oxygen service meet a proof pressure test of 1.5 times the maximum expected working pressure. A better flared coupling is the machined flare where the flare and the ferrule, or sleeve, is one machined part (fig. 8-5); however, the tube must be welded to the fitting.

Threaded couplings for use in oxygen systems should be designed so that the threaded nuts, sleeves, and collars which provide the compression force may be lubricated without any portion of the seal interface being contaminated with lubricant; that is, the parts that effect the seal should not require lubricant for proper torque. Torque should always be specified for flight systems and for all high pressure systems. When torque values are specified, the specification should indicate whether or not a lubricant should be used. Preferred lubricants for oxygen systems are fluorocarbon polymers (solids, liquids, or grease) or molybdenum disulfide.

Thermal distortion of the connector will occur when the flow of liquid oxygen begins and ends. Repeated cycling of such distortion can cause sealing pressure relaxation and increase the leakage rate. An example of the magnitude of the relaxation that can occur during thermal cycling is shown in figure 8-6 (ref. 133). Examples of the increase in leakage rate with temperature cycles between 200° and -320° F are presented in reference 133 (pp. 243 to 246). To avoid such leaks, retorquing should be part of the stand-

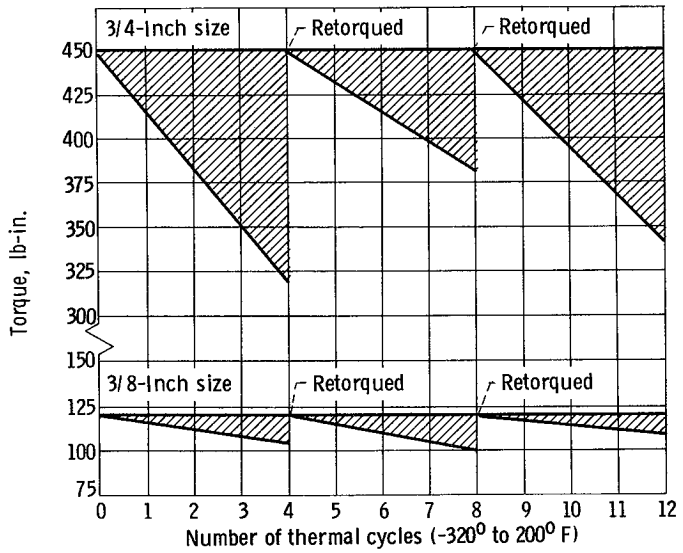


Figure 8-6. - Pressure relaxation from thermal cycling (ref. 133, p. 248). Tubing connectors (lubricated), 3/4 and 3/8 inch.

ard operating procedures for systems whose connectors are subjected to such temperature cycling.

Connector life and leakage rate are affected by the number of assembly-disassembly cycles, since each cycle may damage the surface finish. Also, as shown by the experimental data in reference 133 (pp. 252 to 259), the sensitivity of a fitting to repeated assembly and disassembly varies widely for the various designs tested. Redressing the mating surfaces before reassembly will extend the service life of a connector. It is also important to thoroughly clean the connection and lightly lubricate the male thread before each assembly. (Care must be taken not to contaminate the coupling passage.) The best practice is to use a connector which incorporates a replaceable seal and to always replace the seal (gasket) when reassembling the coupling.

B-nuts and sleeves of certain alloys develop stress corrosion cracks when exposed to seacoast atmosphere. B-nuts and/or sleeves manufactured of 2014, 2017, 2024, and 7075 aluminum alloys in the T4 or T6 tempers or type 303 stainless steel are not recommended for use for extended periods in a salt atmosphere.

Additional detail on the selection, design, and use of couplings and threaded connectors is provided in references 51 (secs. 5.11 and 5.12), 133 (pp. 182 to 202), and 134 (sec. I).

The design of an improved threaded connector using various ring seal materials and configurations is presented in figure 8-7. According to reference 135 the design combines the best features of many different connectors. The methods and techniques for calculating the design of each part of the connector are presented in reference 135 (pp. 3-1 to 3-18).

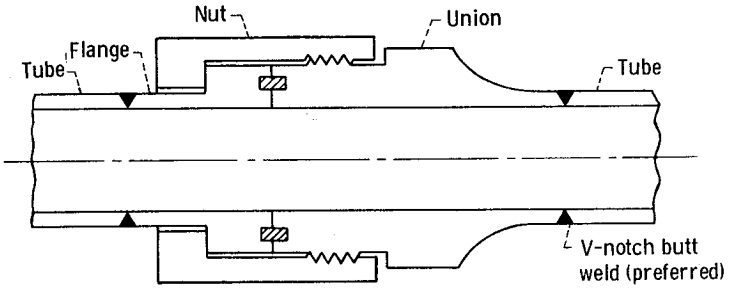


Figure 8-7. - Ring seal connector configuration (ref. 135, p. 3-3).

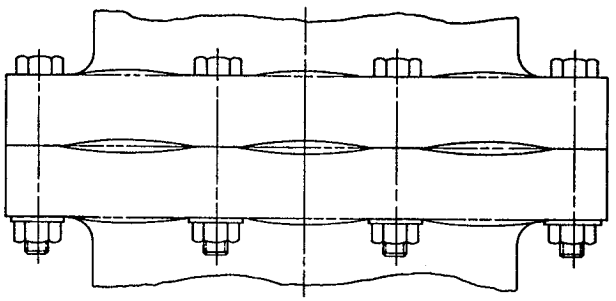
8.5.2 Flanged Couplings

Flanged couplings are the recommended fittings where connections must be frequently made and broken. Flange fittings are also applicable for semipermanent connections and are particularly suitable for high pressure systems and large diameter lines. Although these couplings are often sealed with flat soft aluminum or copper gaskets between serrated faces, they may also be designed to use single or dual ring seals, crush seals, or other compression type seals. Flanged connections for oxygen service should offer a minimum of pockets or cracks where residue or contaminants could accumulate. The design criteria and recommended design practice for the seal part of the coupling is covered in chapter 9 and in reference 37 (pp. 135 and 136) (see also fig. 9-2).

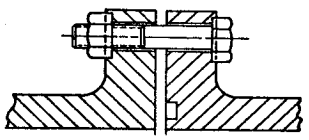
The degree of rigidity required for a coupling is directly related to the seal element which must compensate for deflections and distortions. Typical deflections and distortions which can cause leakage problems are shown in figure 8-8.

The ASME boiler code and the ANSI piping standards (refs. 73 (appendix 2), 104 (p. 20), 126 (pp. 26 and 27), and 136 (p. 27)) have been used as the standard for designing pressure vessels and piping systems that include flange joints. Where weight is not a special consideration, as with ground support equipment, the code provides safety factors of from 4 to 10. At the stress levels implied by these safety factors the deflection and distortion of the members are negligible.

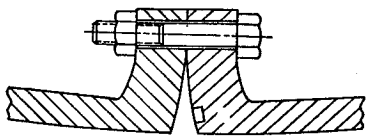
For flight weight hardware and the temperature extremes of aerospace systems, deflections and distortions become important considerations. Since materials for aerospace application are subjected to 60 percent or more of their yield strength, distortions and deflections are greater than the corresponding flange designed according to the ASME code. Therefore, for flight weight flanged joints the determination of flange thickness, bolt size, and bolt spacing to prevent flange distortion and leakage becomes increasingly critical as flange diameter and fluid pressures increase. An example of flange and seal design calculations for medium pressure aerospace use is presented in reference 133 (pp. 69 to 83).



(a) Bowing (circular deflection or distortion).



(b) Flange separation
(bolt strain and bolt hole distortion).



(c) Flange rotation
(angular and axial deflections or distortions).

Figure 8-8. - Types of deflections and distortions in flanged joints (ref. 133, p. 18).

Cryogenic cycling tends to loosen bolted connections; therefore, flange bolt tensions must be checked after 1 or 2 cycles and then again before each use interval. Many compression-type fittings and mechanical clamping techniques to hold the fitting together are commercially available. The design and choice of sealing materials in many of these fittings are suitable for use in oxygen systems.

The design loading of the seal faces by the flange assembly must include allowances for the mechanical stresses from thermal and mechanical forces. Proper assembly of the flanged coupling is equally important. Nonsymmetrical bolt loading can compress the gasket beyond yield locally so that subsequent torquing to even loading will still result in leakage past the yielded section. Suggested bolt torque values recommended for various bolt sizes and materials are tabulated in reference 137 (pp. 40 and 41). In general, the following practices and standards should be used:

(1) All bolts and nuts in the same bolt circle should be identical in material, size, length, and thread unless specifically designed otherwise.

(2) Avoid placing bolt fasteners in a shear stress; provide for shear or torque by splines, keyways, or coupling locks that permit the bolts to be loaded in tension.

(3) Where (2) cannot apply, use bolt hole sizes 0.5 percent larger than the bolt diameter maximum in order to provide a snug fit and prevent play. (This will require a bolt hole diameter tolerance of ±0.003 to 0.005 in.)

(4) One hundred percent of the nut threads should be loaded in contact with the bolt threads when tightened to specified torque values. (Specified values should include whether a lubricant should be used. Fluorocarbon or molybdenum disulfide lubricants are preferred.)

For additional discussion of design practice and analytical methods see references 51 (sec. 5.12.4) and 135 (pp. 2-1 to 2-50).

8.5.3 Threaded Pipe Couplings

Threaded pipe fittings should normally be avoided in high pressure oxygen service. But when it is necessary to use pipe fittings, they should be installed by welding or brazing in such a manner that the threads are completely isolated from the oxygen. The main concern in using pipe threaded fittings is the prevalent use of lubricants which, for oxygen, is undesirable and there is also the possibility of contaminants accumulating in the crevice formed. In addition, since the tapered threaded section of the fitting causes very high radial pressure on the female fitting, cracking from overstress is not uncommon. This problem is less for low pressure systems since less torque is required to effect a seal. With this taken into consideration, threaded pipe couplings for low pressure oxygen systems may be used. Where threaded couplings are used, Teflon tape may be safely employed as a thread lubricant.

8.6 WELDED AND BRAZED JOINTS

Properly welded or brazed joints have the highest potential for zero leakage and are the preferred method of joining pipe sections. But a common problem is the occurrence of cracks in welded and brazed joints. Cryogenic cycling and vibration commonly cause weld boundary cracking and stress corrosion. The latter can be more severe in oxygen especially when slight contamination is present. Therefore, inert gas shielded arc welding is generally preferred to avoid poor penetration and contamination (oxidation, flux, or slag inclusion).

8.6.1 Welded Joints

Pipe ends to be welded should be beveled suitable for full-penetration V-notch butt welding with minimum bead on the inside of the pipe. Sleeve joints (or socket joints) are unacceptable in oxygen systems and should be avoided unless the overlap joint can be brazed or isolated by welding. This is particularly important in high pressure systems and is good practice in any system. An inert gas backup should be used to prevent the pipe from being contaminated with slag that cannot be removed by normal cleaning procedures. The weld penetration or depth of fusion must be to the bottom of the V-groove:

the excess penetration of a bead 1/16 inch high on the inside of the pipe should be avoided or minimized.

Welded seams and connections used in oxygen installations over 150 psi require X-ray inspection of all welded joints. Welds with poor penetration, flux, or slag inclusion, pockets, bubbles, craters, or surface flaking cannot be permitted. Any visible imperfection should be ground out and rewelded. Inert gas shielding arc welding using tungsten electrodes (TIG welding) is the most widely used joining method. Both EB (electron beam) and GMA (gas metal arc) welding are being used where the unique characteristics of these welding methods are required. Resistance seam welding has been used on the Atlas and Thor engines, but manufacturing fit-up problems, corrosion susceptible crevices, and stress concentrations were experienced. Due to its flexibility, TIG welding has been used extensively on the J-2, F-1, Thor, and Atlas engines for fabricating joints. The F-1 engine was originally fabricated with the automatic, single pass, sleeve weld configuration for tube joints because of more repeatable weld quality and lower cost than welds produced by manual operation. However, sleeve joints are not the best practice from a system compatibility standpoint and were changed to the preferable butt weld joints in the J-2S. The in-service failures encountered with the F-1 tube sleeve weld configuration were in the form of fatigue cracks in the heat-affected zone of the weld. The cause was attributed to the high vibration environment of the engine and partial penetration welds. Addition of the fillet weld to the joint for increased fatigue strength and the use of vibration damping clamps on the tubing, located properly to reduce amplitudes, have resolved this problem.

The J-2S engine uses butt welded tube joints throughout with no weld stub-outs on components and no inplace welding. The J-2S, being a simplified version of the J-2, has fewer lines with less complicated routing and thus accommodated the installation of complete line assemblies without interference. Line assemblies are equipped with flanges at each end for makeup into static seal, bolted flange couplings.

Electron beam welding is generally used to join materials where a narrow weld bead and/or minimum heat input to the part is required. Electron beam welding is generally accomplished without the use of filler material and is limited to butt or sleeve-type tubular joints.

Control of weld repair requires some explanation since the effects on the joint are not obvious. The repair of a weld joint involves either completely restoring the component parts, then rejoining by the same method used for the original joint, or attempting a localized repair of the weld. Little or no difficulty can be expected with the part restoration - reweld procedure. However, a localized repair causes an enlarged heat-affected zone which may cause a local distortion resulting in residual stress sufficient to reduce the joint stress tolerance. Therefore, the complete restoration of the joint is preferable.

8.6.2 Brazed Joints

The preferred brazing methods for oxygen components are furnace brazing and induction brazing. To protect the metal from oxidation during the braze cycle, furnace brazing is done preferably in a vacuum or an argon hydrogen atmosphere. Similarily, induction brazing requires an argon shield on both the inside and the outside of the joint.

Figure 8-9 is a plot of shear strength as a function of temperature for selected braze alloys. These alloys are commonly used in design of tube joints for rocket propulsion fluid systems.

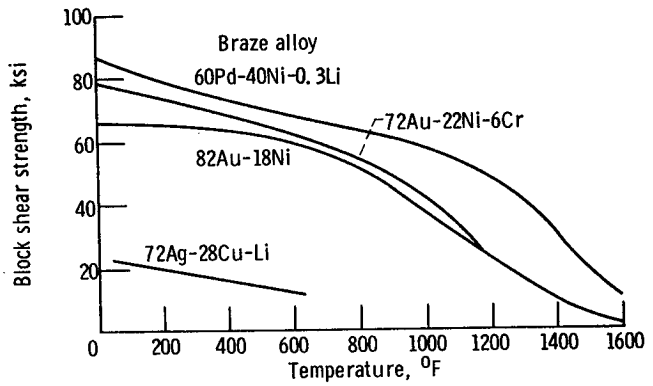


Figure 8-9. - Block shear strength as function of temperature properties of braze alloys (ref. 51, p. 5.12.5-3).

8.6.2.1 Stress corrosion of brazed joints. - The nickel alloys and chromium nickel steels are subject to stress corrosion cracking as a result of exposure to molten brazing filler metals. If there is residual or applied stress on the parts being brazed, or if stress is caused from thermal gradients during the brazing process, stress corrosion can occur. The braze material can penetrate the grain boundaries of the base alloy which reduces its strength.

Stress corrosion cracking can be prevented by the following:

(1) Use annealed materials for brazing.

(2) Prevent or remove externally applied stress during the brazing process.

(3) To reduce thermal stresses heat bulky parts to brazing temperature slowly enough to allow an even temperature to be reached.

Stainless steels containing chromium and carbon are subject to carbon precipitation when heated to temperatures between 800° and 1500° F. Carbon-chromium precipitation into the grain boundaries is particularily susceptible to stress corrosion from braze metals. Precipitated carbon may be redissolved before brazing by heat treating

at 1850° to 2000° F followed by rapid cooling.

If the brazing can be done rapidly (5 to 10 min), no appreciable amount of precipitation can occur. Preferred stainless alloys that are less affected by this phenomenon are types 347 and 321.

Preferred base metal - filler metal combinations are given in table 8-V (ref. 138).

TABLE 8-V. - BASE METAL FILLER METAL COMBINATIONS

[Ref. 138, (pp. 37 to 45) lists specific compositions of each filler material.]

	Al and Al alloys	Mg and Mg alloys	Cu and Cu alloys	Carbon and low alloy steels	Cast iron	Stainless steel	Ni and Ni alloys
Al and Al alloys	BAlSi						
Mg and Mg alloys	X	BMg					
Cu and Cu alloys	X	X	BAg, BAu, BCuP, RBCuZn				
Carbon and low alloy steels	BAlSi	X	BAg, BAu, RBCuZn	BAg, BAu, BCu, RBCuZn, BNi			
Stainless steel	BAlSi	X	BAg, BAu	BAg, BAu, BCu, BNi	BAg, BAu, BCu, BNi	BAg, BAu, BCu, BNi	
Ni and Ni alloys	X	X	BAg, BAu, RBCuZn	BAg, BAu, BCu, RBCuZn, BNi	BAg, BCu, RBCuZn	BAg, BAu, BCu, BNi	BAg, BAu, BCu, BNi

8.6.2.2 Braze joint cleanliness. - The usual cleaning procedure preparatory to brazing is to remove everything down to base metal (a thin oxide film will reform even at room temperature). It is important that the cleaned surface not be contaminated by handling prior to brazing. Since aluminum, magnesium, manganese, and beryllium oxides resist hydrogen reduction and some steels can become embrittled by hydrogen, brazing should be done in a helium or argon atmosphere, or better in a vacuum.

8.6.2.3 Clearances. - The clearance between surfaces to be brazed is generally held between 0.001 and 0.003 inch (ref. 139). A common practice in brazing pipe or tubing is to provide a brazed joint depth of 1 to $1\frac{1}{2}$ diameters.

8.7 LINE RUPTURE

A gas at ambient temperature escaping from the open end of a line or vessel yields a specific impulse of approximately 50 seconds, which is a considerable amount when it is realized that no chemical reaction is taking place. For example, a 1-inch line charged to 200 psi can develop approximately 175 pounds of thrust (see table 8-VI, ref. 140). Therefore, should a rupture occur in a line, flex hose, or bellows, the unrestrained sections may cause severe damage or injury. Restraints, fasteners, and braces should be used to prevent this type of occurrence especially in high pressure systems (over 2000 psia). From this example, the hazards of accidently uncoupling an "empty" line that in reality is under pressure become obvious.

TABLE 8-VI. - OPEN LINE THRUST FORCE[a]

To calculate the force acting on line opening, select applicable diameter and multiply right-hand column by the source pressure (psi).

Diameter opening, in.	Calculated force factor for each psi of source pressure	Diameter opening, in.	Calculated force factor for each psi of source pressure
1/8	0.18506	5/8	0.5777
1/4	.2832	3/4	.6759
3/8	.3814	7/8	.7741
1/2	.4796	1	.8723

[a]Ref. 140, Design Note 3G1.

CHAPTER 9. SEALS

Seals as applied to turbopump shafts, valve seats, and valve stems have been discussed in sections 6.1.3, 7.5, and 7.6, respectively. While the sealing principles and design considerations are generally the same, pump seals and valve seals have special requirements; these special requirements were discussed as a part of the component overall design.

The various types of seal configurations generally found in fluid systems are shown in figure 9.1. In order to achieve a seal, the contacting surfaces must be pressed together with sufficient force per unit area to close all leak paths. If a secondary material is used to achieve a seal between the surfaces, the material must maintain the pressure without being squeezed out or permitting pressure relaxation due to cold flow or creep. In the case of dynamic seals, the seal material must resist wear from rubbing friction to avoid seal surface damage by abrasion and pressure relaxation from wear.

9.1 STATIC SEALS

A good static seal is obtained when complete contact occurs between the mating surfaces at a uniform pressure, which is always greater than the contained pressure. This can be done either by forcing the two surfaces together such that plastic flow of the seal material results or by polishing the surface smooth enough so that elastic flow of the seal material will result in uniform surface contact. The plastic flow method is permissible for a single or a very limited number of sealing cycles, whereas the elastic yield method can be used when multicycle sealing is required, such as with a poppet valve.

Most of the leakage problems are caused by compromising the preceding principles. Typically, the seal surface pressure is reduced by cold flow or creep of seal material as a result of temperature cycling or over stressing. Other causes are inadequate confinement of seal material which permits extrusion, poor surface preparation, or improper material selection for the range of pressure and temperature conditions.

Flat gaskets are mainly used to seal flanged pipe connections, access covers for tanks, and assembled parts such as pump housings, clamshell valve housings, etc. A flat gasket must be thin enough to prevent extrusion or "blowout" from pressure and

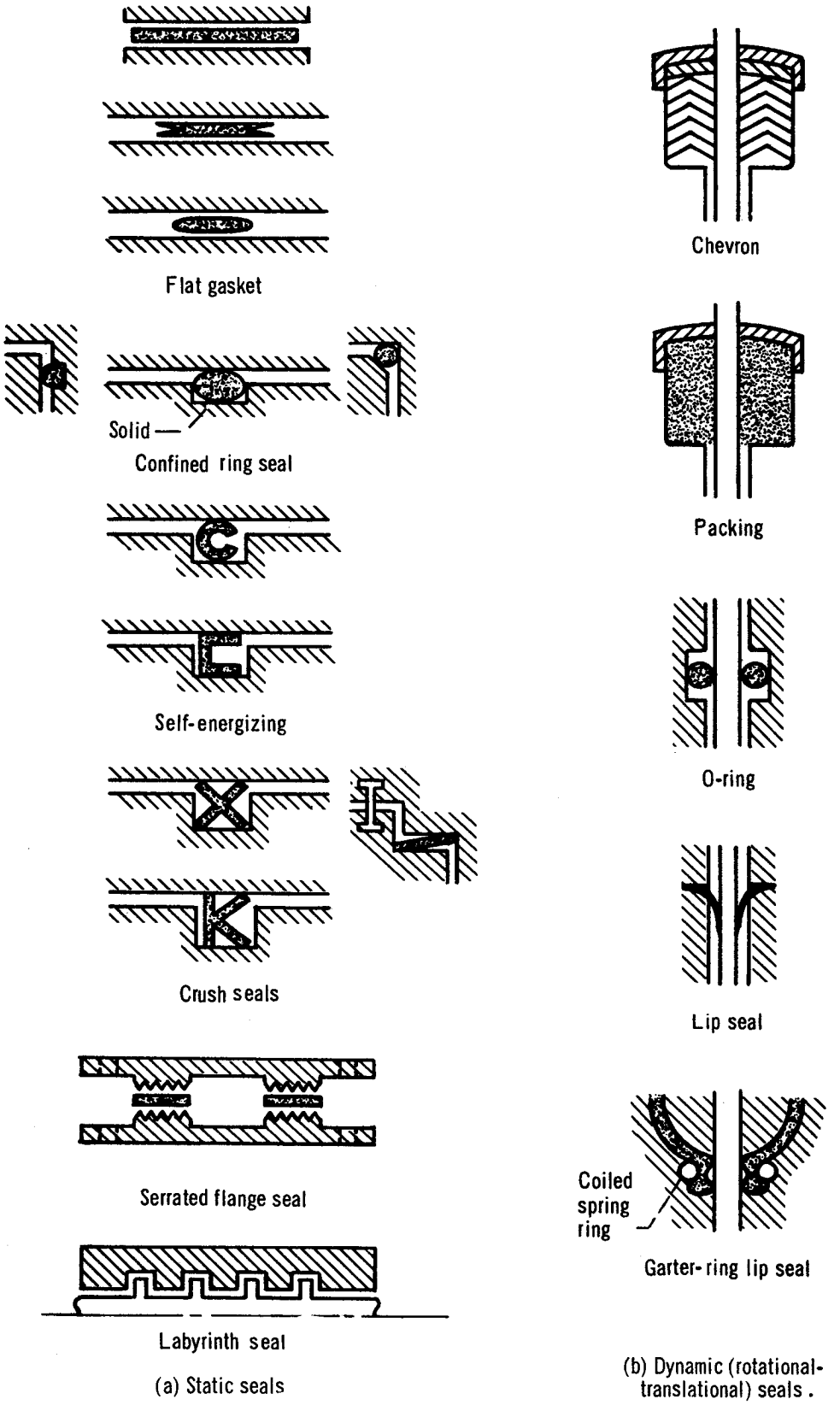


Figure 9-1. - Types of seals.

thick enough to seal surface irregularities and waviness.

The relatively large high surface area of flat gaskets makes uniform pressure distribution more difficult. Flange faces tend to bow out between the bolts, and surface waviness from any cause permits low sealing pressure zones that may allow leakage to begin (see sec. 8.5.2 and fig. 8-8). The use of serrations of the flange faces reduces cold flow, increases sealing pressure (force per unit contact area), and permits using metal materials in a flat gasket type application. The recommended design for the serrated seal is shown in figure 9-2.

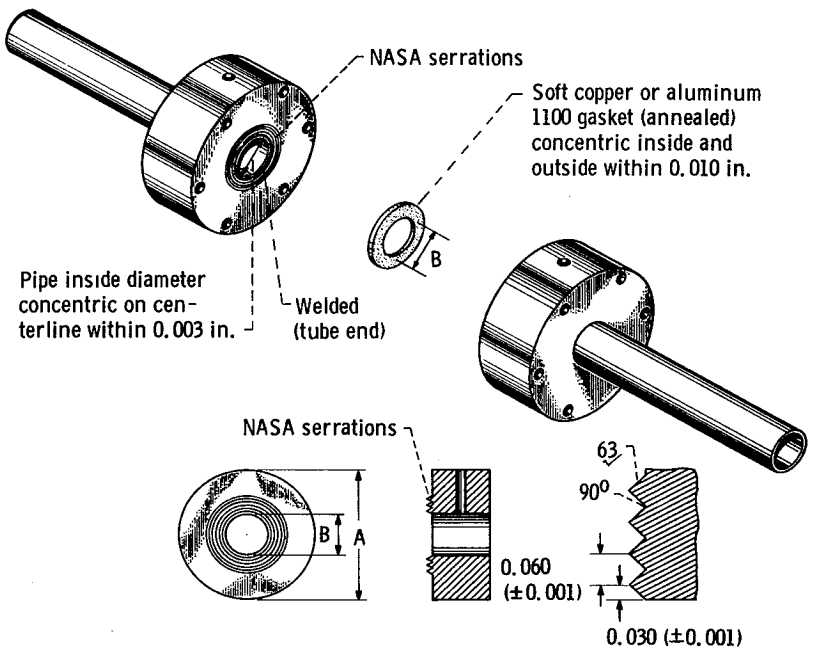


Figure 9-2. - Flange-type connectors for oxygen (ref. 37, p. 135). Flange connector bolts must be periodically retorqued since they tend to loosen under cryogenic-ambient temperature cycling.

Ring seals may have a wide variety of configurations. Some examples are shown in figure 9-1. Ring seals have a relatively low contact area; therefore, the force per unit area can be as high as desired and can be accurately controlled.

Providing a recess for the ring seals can prevent extrusion or blowout. In a V- or C-ring configuration, high pressure fluid can enter the open side and help provide a sealing pressure. The same applies to dynamic chevron seals or lip seals. For extra sealing pressure in lip seals, garter rings may be used.

Surface finishes for elastomer-metal contact surfaces are not too critical; that is, the average machine finish can be tolerated if the elastomer coating or thickness is greater than three times the maximum asperity height or surface finish roughness. However, depending on the application, 20 to 40 microinches is recommended for the

metal-nonmetal surfaces and 4 to 20 microinches for metal-metal surfaces. See section 7.5 for valve element - seat surface finishes.

Figure 9-3 shows the surface finish range that results from various processes.

Surface roughness measuring instruments and their measurement capability (ref. 122, pp. 11 to 22) are as follows:

(1) Electromechanical stylus (vertical readout, ×50 000). (Typical tip radius is 0.005 to 0.0001 in. or 500 to 100 μin. diam.)

(2) Optical interferometer (sensitive to 0.02 μin.)

(3) Electron microscope (0.2 μin.)

(4) Optical microscope (6.7 μin.)

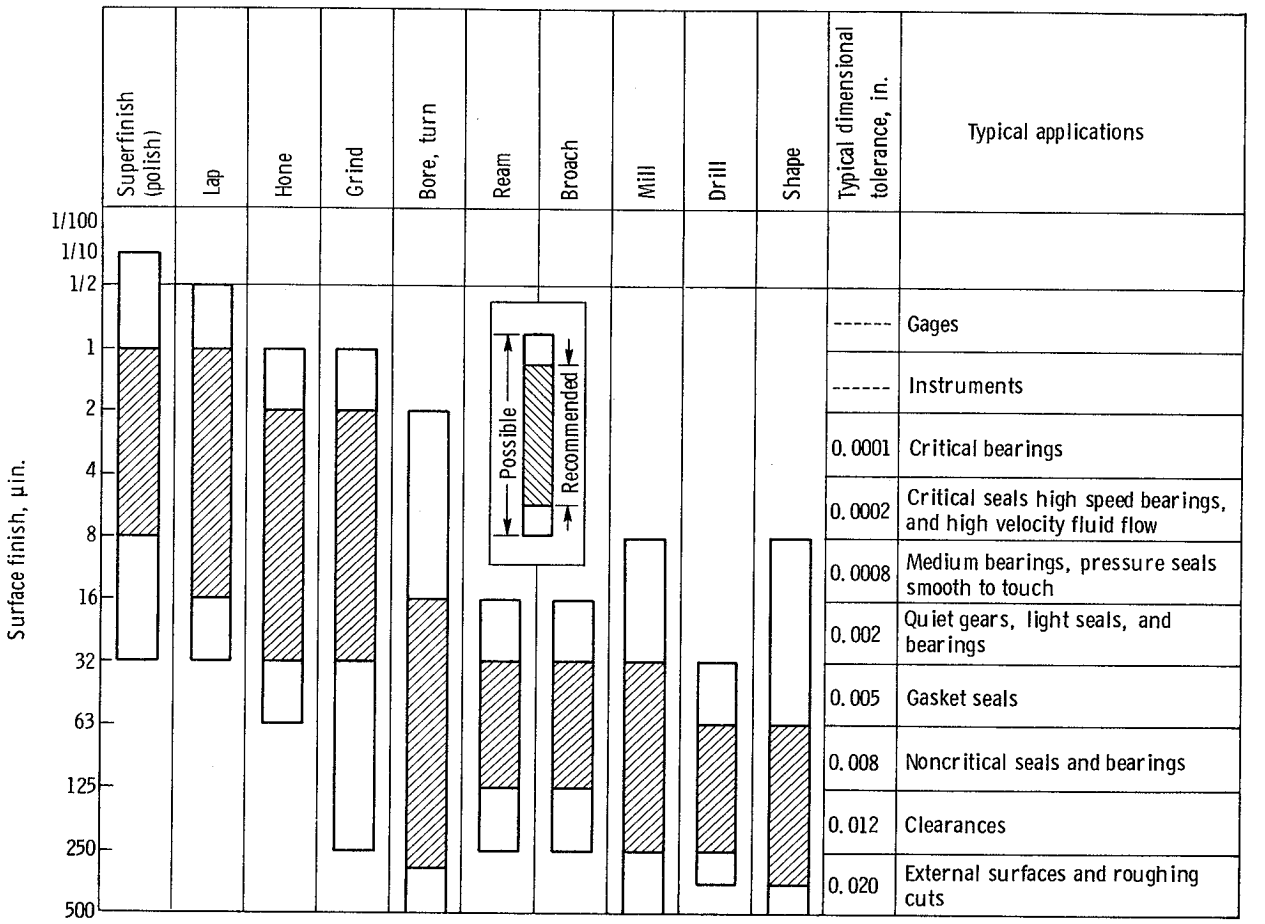


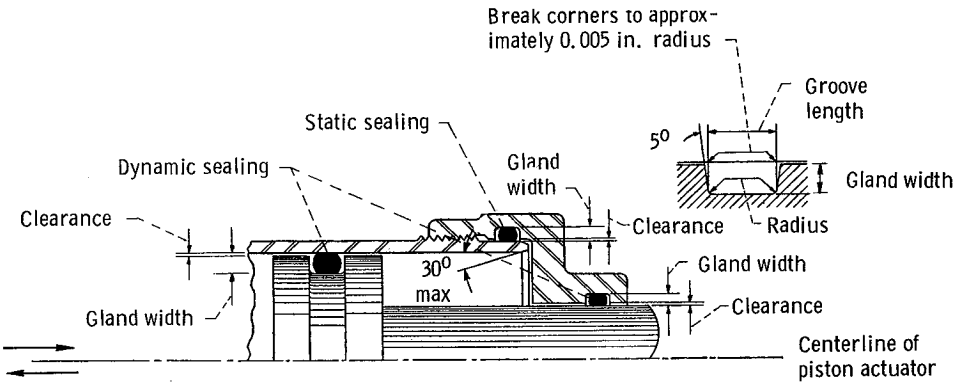
Figure 9-3. - Typical surface finishes produced by various manufacturing techniques (ref. 51, p. 6. 3. 2-7).

9.2 DYNAMIC SEALS

The basic requirement for a minimum leakage dynamic seal is the same as the static seal, except that the design condition must be maintained with relative motion between the seal and mating surface.

The dynamic joint design is the result of compromises between permissible leakage rates, joint life, and many other factors that affect these two variables. For example, the amount of rotation of a valve stem is extremely small compared to a turbopump shaft seal. In the case of the valve stem, near zero leakage can be obtained with relatively low seal wear. Zero leakage can be achieved with sliding shaft seal designs by using bellows or diaphragms.

Typical design specifications for dynamic O-ring seals are given in figure 9-4. Seal material selection for dynamic seals are discussed in sections 9.3 and in 6.3.2 and 7.3 for pumps and valves, respectively.



O-ring nominal section diameter, in.	O-ring section diameter, in.	Diametral squeeze, min.		Gland width, in.		Groove length, in.	Radius min	Two times diametral clearance (max), in.
		Dynamic	Static	Dynamic[a]	Static[b]			
1/16	0.070 ± 0.003	0.010	0.015	0.057	0.052	3/32	1/64	0.005
3/32	.103 ± .003	.010	.017	.090	.083	9/64	1/64	.005
1/8	.139 ± .004	.012	.022	.123	.113	3/16	1/32	.006
3/16	.210 ± .005	.017	.032	.188	.173	9/32	3/64	.007
1/4	.275 ± .006	.029	.049	.240	.220	3/8	1/16	.008

Fluid pressure	O-ring compound hardness
0-1000 psi	70 Shore "A" durometer
1000-2000 psi	80 Shore "A" durometer
2000 psi and higher	90 Shore "A" durometer

[a]Tolerance, +0.000, -0.001 in.
[b]Tolerance, +0.000, -0.005 in.

Figure 9-4. - Dynamic seal for translation or rotation (ref. 70, p. 290).

9.2.1 Surface Finish Requirements

The sliding surfaces in contact with dynamic O-ring seals should be ground, honed, or polished to a finish of 8 to 10 microinches rms. A finish within this range yields a longer life than either rougher or smoother finishes. Codirectional patterns, as produced by honing, have been proven to be the best surface finish for any type of dynamic sliding seal. For still better results, after an initial finishing, the surface could be hard chrome or nickel plated and again finished. The plating provides a hard, slippery surface that resists corrosion, wear, and scratching.

9.2.2 Friction of Dynamic O-Ring Seals

The breakaway friction of a dynamic O-ring seal is usually about three times the running friction. Breakaway and running frictions increase with fluid pressure, O-ring hardness, diametral squeeze, and temperature decrease. Accurate values of O-ring frictions can only be obtained experimentally for a given design.

9.3 SEAL MATERIALS

An example of the types of materials preferred for use in liquid or gaseous oxygen systems is given in table 9-I. Except for the silicone rubber, these materials meet MSFC Specification 106-B (ref. 45) for compatibility with oxygen. Their physical properties vary enough to meet almost any sealing requirement. Silicone rubber has been included based on service experience with the Apollo Personnel Life Support System. Viton was being used as a seal material in this system; however, the Viton O-rings exposed to a 7500 psia oxygen pressure in the regulator valve failed because of oxygen absorption. When depressurized, the material was fractured from the pressure of the absorbed gas. A modified Viton, identified as D-80, has been developed for use with oxygen at pressures up to 3000 psia (ref. 141, appendix II and p. 4).

The hardness and/or compressive strength of materials are the best physical properties when comparing the mechanical characteristics of materials for seal application. Where the sealing force or loading is high and the seal contact surface area is small, a harder material must be used to resist unwanted deformation and to resist creep. Where the sealing force or loading is low and the seal contact surface is large, a softer more compliant material must be used to permit maximum surface to surface contact. Figure 9-5 shows the hardness range of selected materials. The hardness and stiffness of each material increases with increasing shore or Rockwell value.

TABLE 9-I. - PREFERRED SEAL MATERIALS FOR OXYGEN

[Nonmetals may also be used as plating material.]

(a) Nonmetals

Trade name	Chemical name or description
Teflon TFE	Polytetrafluoroethylene
Halon TFE, G-80	Polytetrafluoroethylene
Rulon A	Polytetrafluoroethylene with MoS_2 filler
Nickel-filled Teflon	Polytetrafluoroethylene with nickel-powder filler
15-Percent glass-filled Teflon	Polytetrafluoroethylene with glass fibers
Teflon FEP	Fluorinated ethylene proplene
Kel-F 81	Polychlorotrifluoroethylene (CTFE)
Kel-F 82	Copolymer of CTFE and 3 mole percent vinylidene fluoride
Plaskon 2400	Polychlorotrifluoroethylene (CTFE)
Halon TVS (now called Plaskon 2200)	Polychlorotrifluoroethylene (CTFE)
Kynar	Vinylidene fluoride
Viton A	Copolymer of vinylidene fluoride and hexafluoropropylene
Fluorel	Copolymer of vinylidene fluoride and hexafluoropropylene
Silastic	Silicone rubber

(b) Metals

Aluminum	Copper alloys	Lead	Rhodium[a]
Aluminum alloys	Gold[a]	Monel	Silver[a]
Chromium[a]	Inconel	Nickel	Stainless steel
Copper	Indium[a]	Platinum[a]	Tin[a]

[a]Usually restricted to use as a surface plating material.

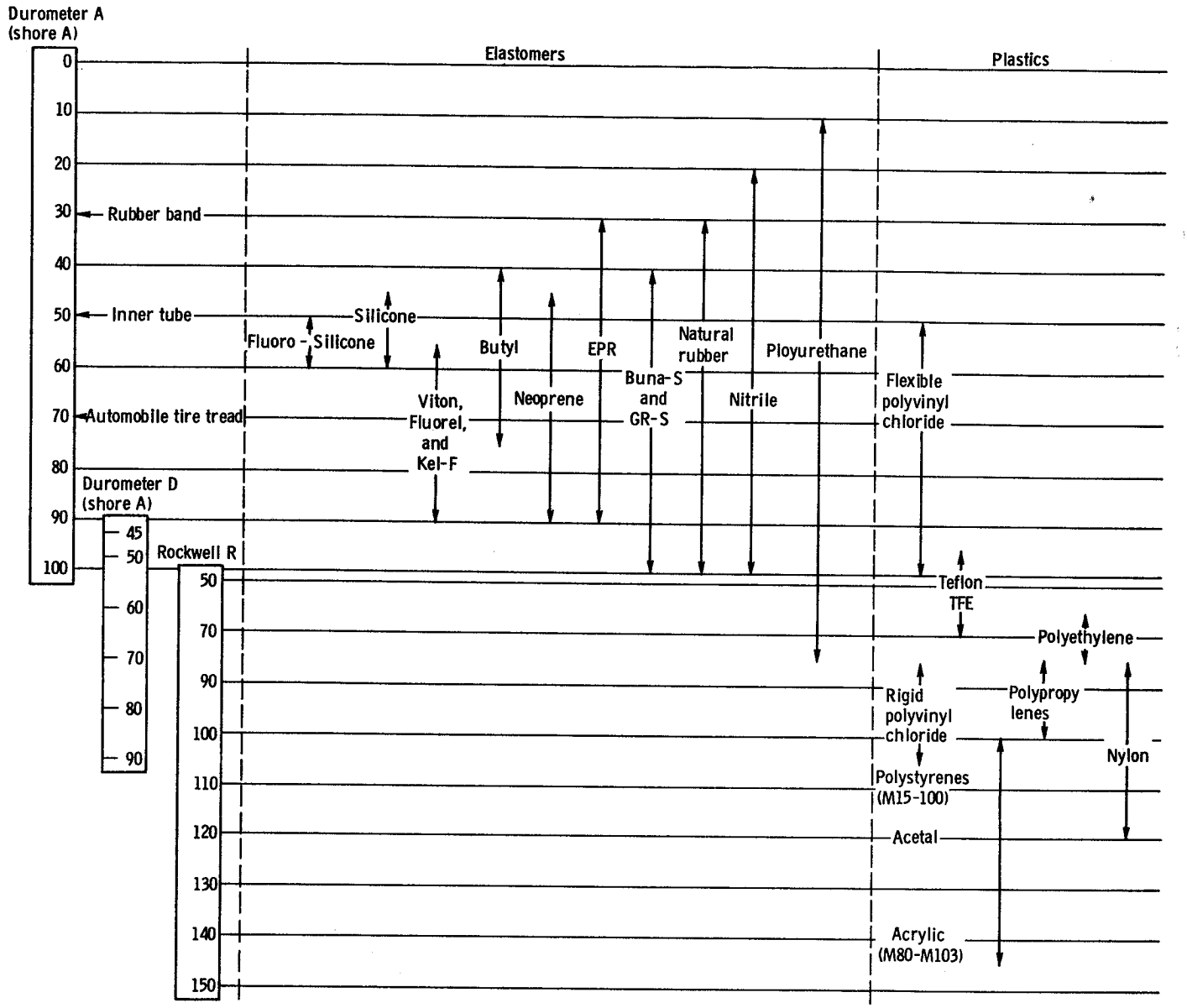


Figure 9-5. - Hardness spectrum for elastomers and plastics (ref. 51, p. 12. 3-1).

9.3.1 Extrusion

The problem of O-ring extrusion under various pressures and applications is shown pictorially in figure 9-6. The extrusion tendency of a material can be estimated from figure 9-7. This figure related the tendency to extrude or to resist extrusion as a function of the clearance gap and the pressure differential and shore hardness. A proper combination of clearance gap and O-ring hardness may prevent extrusion. Extrusion may also be avoided by providing a backup ring on the side of the O-ring opposite the high pressure source (fig. 9-6). For dynamic seals for pressures in excess of 800 psi,

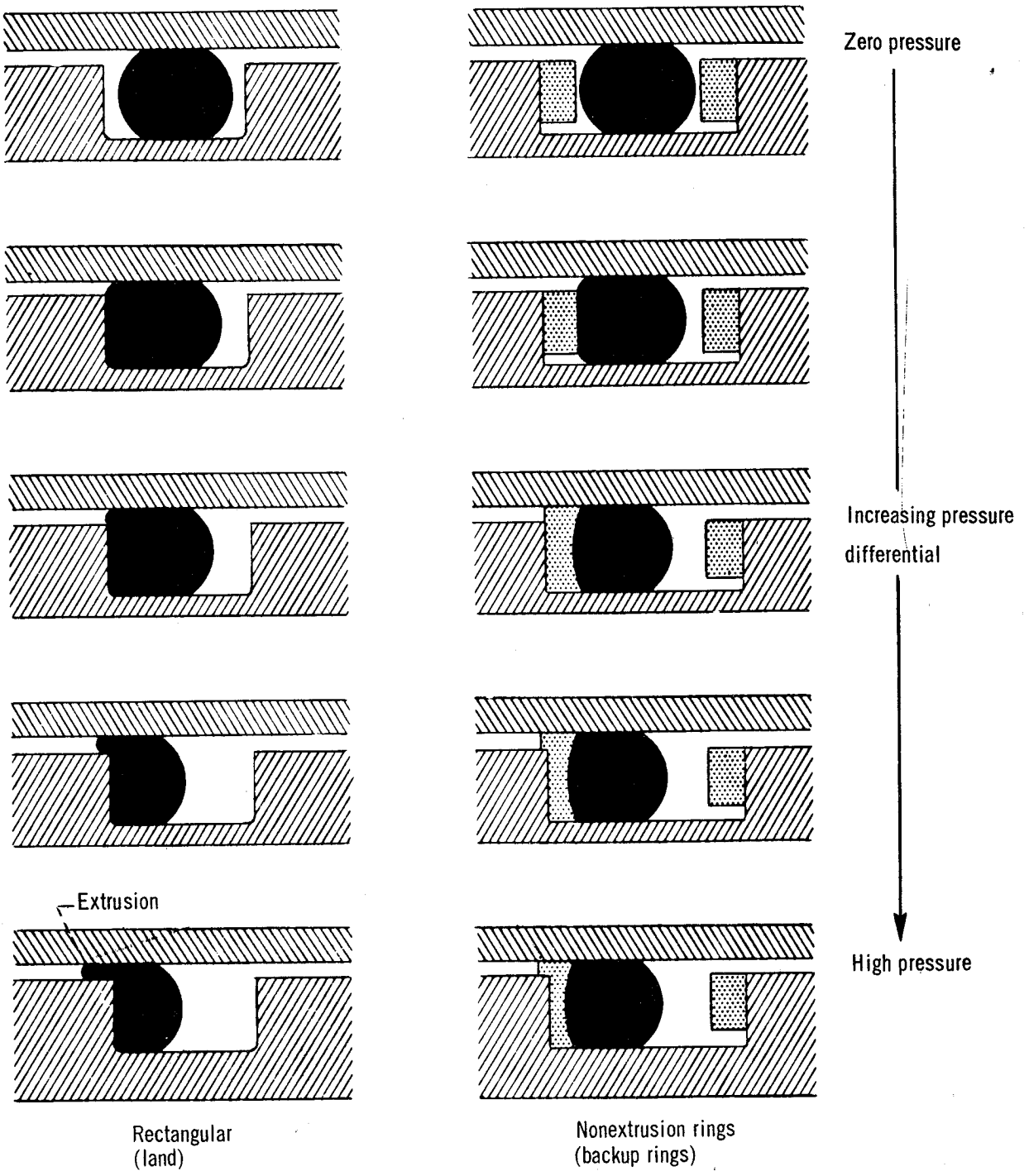


Figure 9-6. - O-ring extrusion (ref. 140, design note 3F2, p. 4).

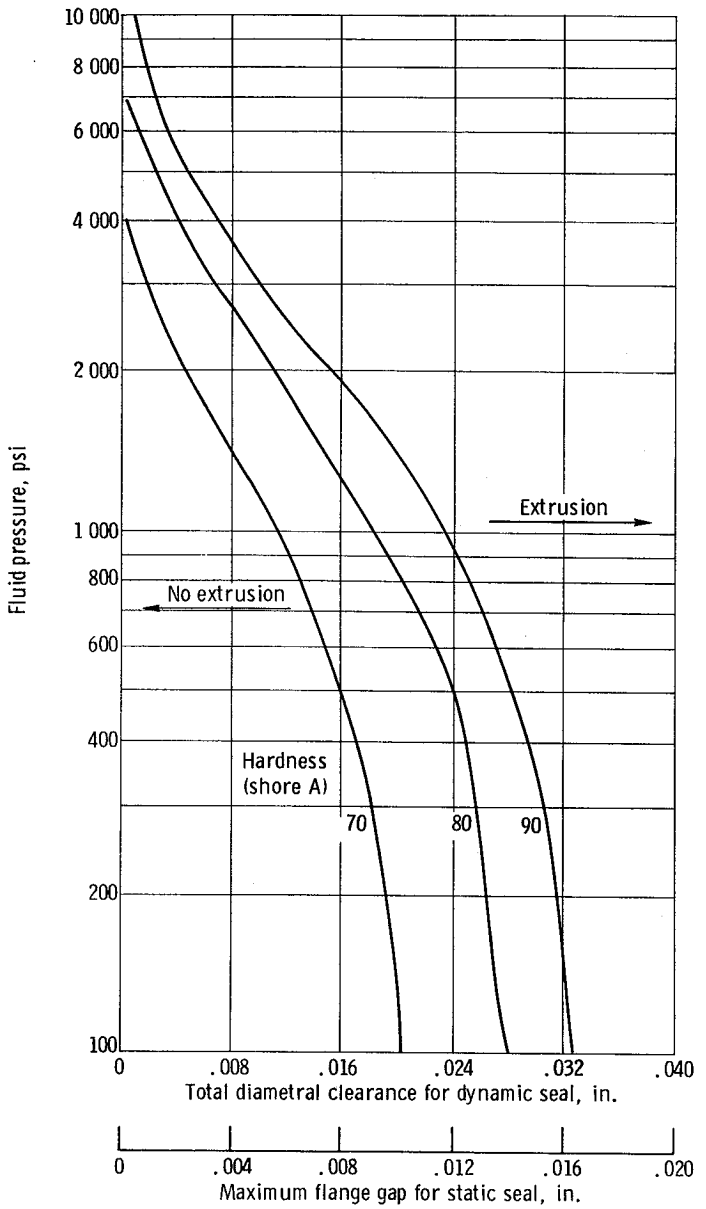
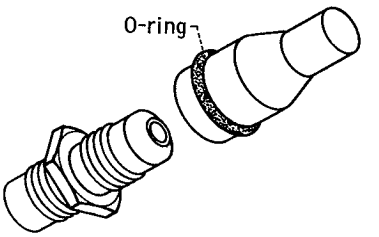
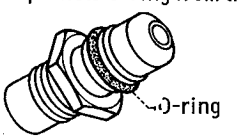


Figure 9-7. - Extrusion characteristics of O-rings (ref. 133, p. 60). Information originally from Seal Compound Manual, Parker Seal Co. Catalog C5702, July 1964.



(a) New method. O-ring rolled over sleeve type tool which protects O-ring from threads.



(b) Old method. O-ring rolled over threads which can damage O-ring.

Figure 9-8. - Tool for preventing O-ring damage during installation (ref. 140, design note 3F2, p. 6).

Teflon or Kel-F backup rings are recommended. Where it is required that pressure be applied from either direction, a backup ring on both sides of the O-ring may be used. Sharp corners around, in, or near O-ring grooves should be avoided. Seals forced into sharp corners can damage the seal ring surface (see inset in fig. 9-4). Seal failures can also occur from cuts sustained by installation over sharp edges such as threads. An installation tool such as that shown in figure 9-8 can help to alleviate this problem.

9.3.2 Creep

Permanent dimensional changes (set) in a material due to an imposed load (below normal yield stress) are referred to as cold flow or creep. Such dimensional changes in seals can result in leakage. The effect of crystallinity, temperature, and pressure on the creep characteristics of materials commonly used in oxygen systems is shown in figures 9-9 to 9-15.

Creep data for selected materials at room temperature exposed to a 3000 psi stress are given in figure 9-9 (ref. 142). Figure 9-10 (ref. 143) illustrates the effect of crystallinity on the creep rate. For Teflon, a sharp reduction in creep rate exists over a narrow band of crystallinity between 70 and 80 percent. Thus, it can be helpful to specify the crystallinity of polymeric material where creep must be minimized. Additional

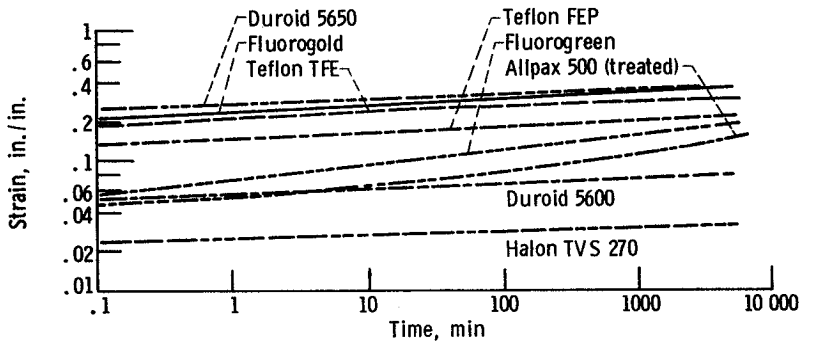


Figure 9-9. - Creep data for various gasket materials at ambient temperature and stress of 3000 psi (ref. 142, p. 20). Duroid 5600 and 5650, ceramic-filled Teflon; Fluorogold, fiberglass-filled Teflon; Fluorogreen, fiberglass-filled Teflon; Allpax 500, Fluorolub treated asbestos fiber with Styrene/Butadiene binder (not recommended for oxygen systems); Halon TVS, modified CTFE.

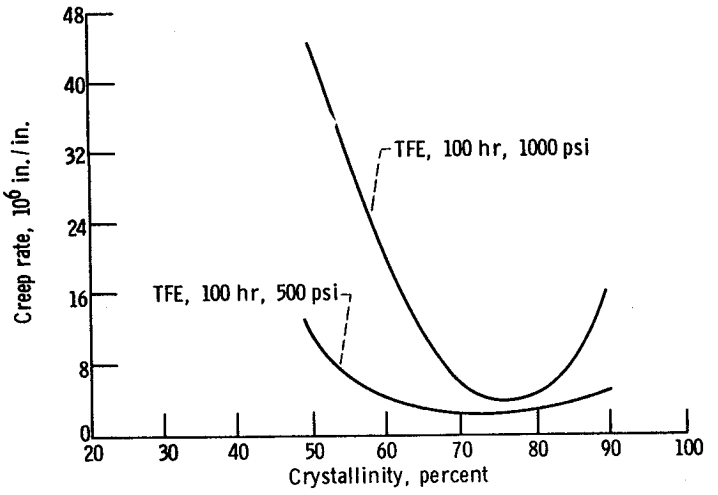


Figure 9-10. - Effect of crystallinity on creep rate (ref. 143, p. 98).

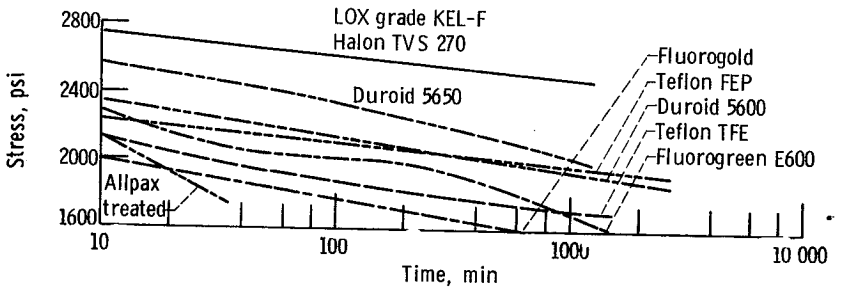


Figure 9-11. - Room temperature stress relaxation data (ref. 142, p. 21). Trade name designations in figure 9-9.

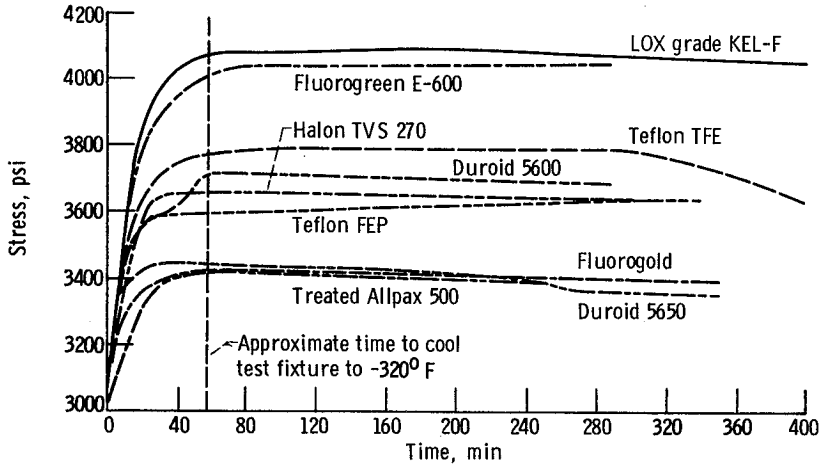


Figure 9-12. - Stress relaxation data for -320° F (-196° C) (ref. 133, p. 22). See figure 9-9 for trade name identifications.

data showing the effects of crystallinity on physical properties for selected materials are given in tables 3-XII and 3-XIII. Stress relaxation data for the same materials are given for room temperature and at -320° F in figures 9-11 and 9-12, respectively. Note that the creep at cryogenic temperature is nearly zero at the test loads. Creep data for selected metal candidates for seal application are given in figures 9-13 to 9-15.

The coefficient of thermal expansion-contraction of seal materials varies considerably and should also be taken into account in all seal design (see table 9-II).

A commonly used solution to the creep problem and the expansion-contraction problem is to use metal seals coated with the appropriate polymer (in most cases a fluorocarbon polymer). This provides a combination of the overall hardness, strength, and thermal expansion characteristics of a metal seal and the surface characteristics of a polymer seal. This technique is more successful in static seals than in dynamic seals, however, because the relatively thin polymeric coatings are more easily damaged in sliding seals.

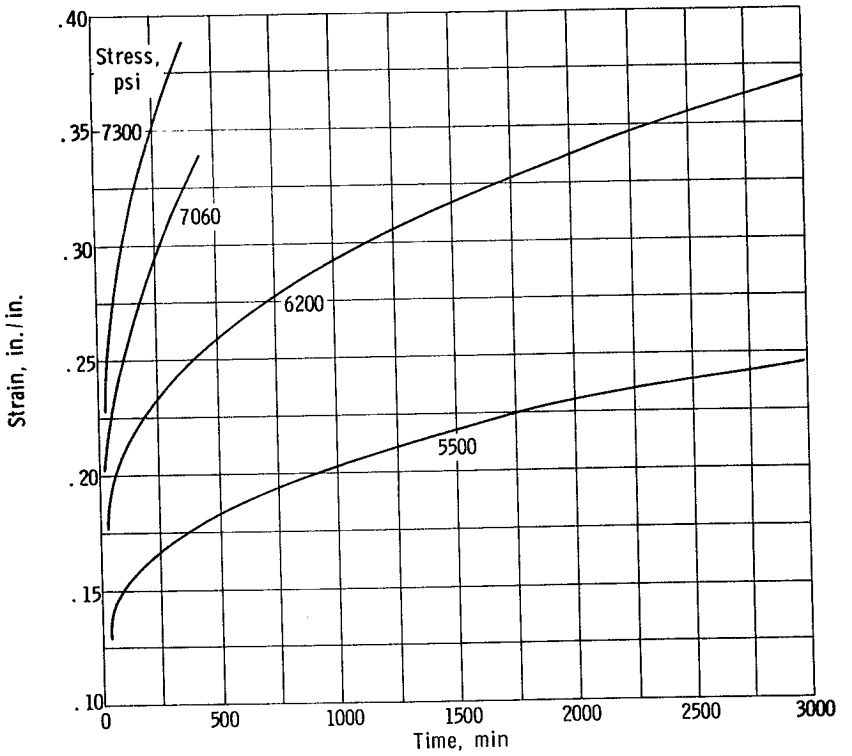


Figure 9-13. - Creep characteristics of 1100-0 aluminum at 196° F (ref. 133, p. 21).

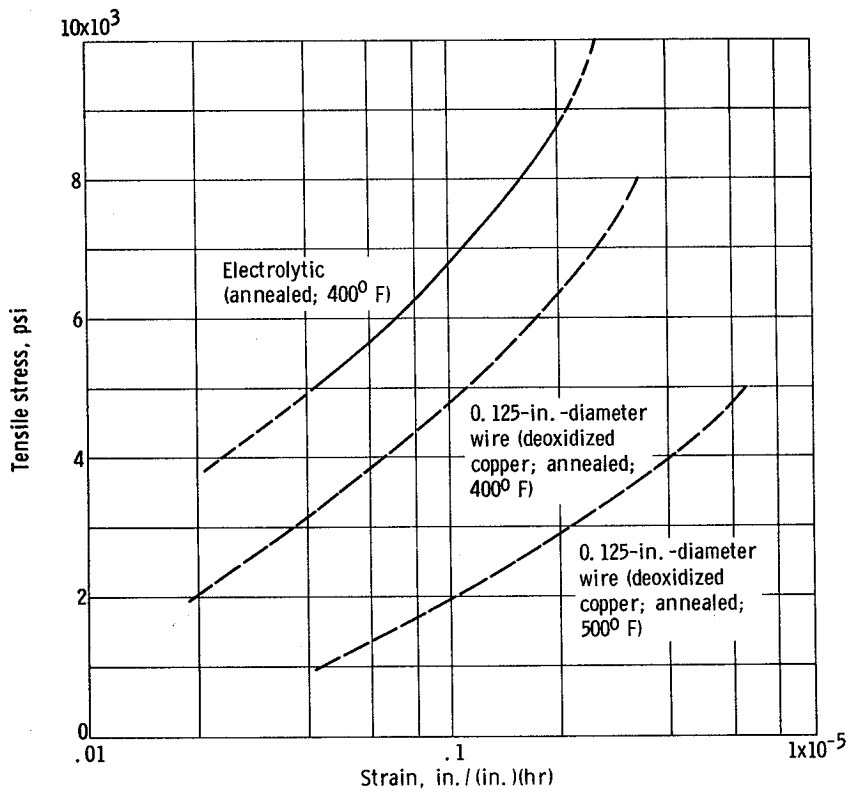


Figure 9-14. - Creep properties of copper (ref. 133, p. 19).

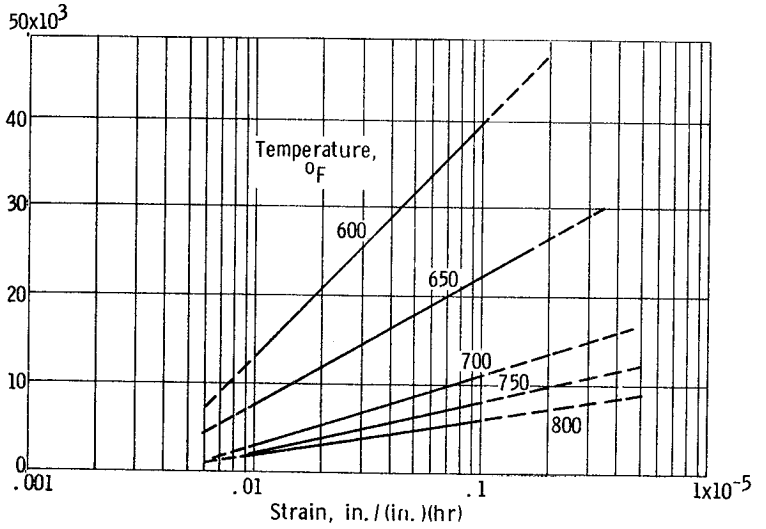


Figure 9-15. - Creep properties of "A" nickel (ref. 133, p. 20).

TABLE 9-II. - LINEAR THERMAL EXPANSION

OF TYPICAL SEAL MATERIALS[a]

Material	Contraction (+75° to -65° F), in./ft	Expansion (-75° to +375° F), in./ft	Coefficient of expansion, in./(in.)(°F)
Teflon	0.093	0.148	5.5×10^{-5}
Nitrile, general purpose	.218	.468	13.0
Chloroprene	.190	.407	11.3
Viton-A	.130	.277	9.0
Kel-F	.064	.137	3.5
Silicone	.252	.540	15.0
High-temperature aluminum, 2017	.022	.047	13.0×10^{-6}
Stainless steel, type 302	.016	.035	9.6

[a]Ref. 51, sec. 6.3.2.7.

9.3.3 Special Considerations for Very High Pressures

During the early phases of the Apollo program silicone rubber O-ring seals were used for the high oxygen pressure applications in the personnel life support system (PLSS) and the emergency oxygen system. The material was selected because of the favorable experience gained during the Mercury and Gemini programs where silicone rubber was used for high pressure oxygen applications. Subsequent to the Apollo 7 fire, all of the silicone rubber seals in the high pressure (over 5000 psia) portable life support system and oxygen pressurization system applications were replaced by Viton be-

cause Viton passed the standard mechanical impact compatibility test and silicone rubber did not. However, the Viton seals were found to be functionally unsuitable at this pressure and silicone rubber O-ring seals were reinstituted.

The rationale exercised in reinstituting silicone rubber seals is completely explained in reference 124. Basically, the problem encountered with the Viton-A seal centered on its absorption of oxygen gas under high pressures and its subsequent inability to relieve the internal pressure from absorbed gases without rupture when the system was depressurized. Alternate materials were considered and rejected for various reasons: three such reasons are (1) similarity to Viton-A, (2) inadequate test data, and (3) poor compressive set characteristics. It was finally concluded that, based on extensive satisfactory experience (in excess of 19 500 hr of logged and estimated operating experience) in the Mercury, Gemini, and Apollo programs, at pressures exceeding 5000 psia, silicone rubber was the most satisfactory seal material available. Then, since the seals in this application were heat sinked and not exposed directly to oxygen flow, and in view of additional ignition tests successfully performed, silicone rubber seals were reinstituted. Representative high pressure (7500 psi and above) seal designs using silicone rubber are illustrated in figure 9-16 for both static and dynamic applications.

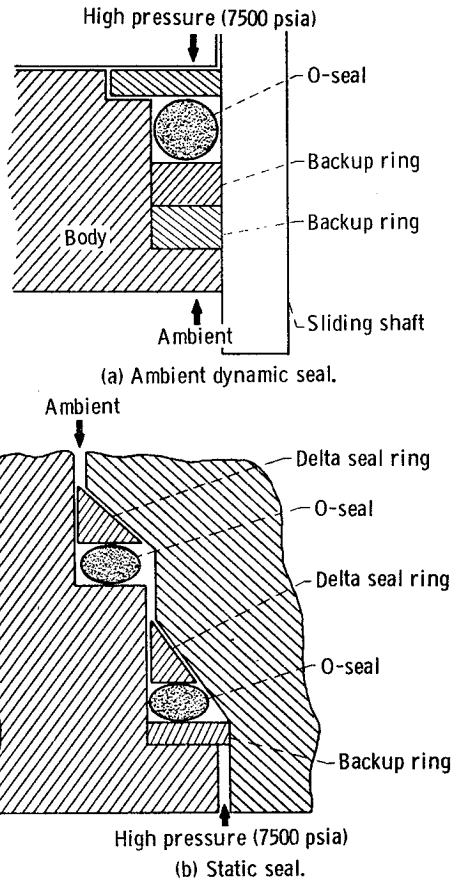


Figure 9-16. - Dynamic and static seals (ref. 124).

9.4 LEAK TESTS

Leak testing may be categorized as either leak measurement, the total leak measurement, or leak location. Generally, the procedure is to measure total leakage and then, if necessary, locate the individual leaks.

Laminar flow leaks can have very tortuous paths and, even for pressures above 3000 psi, a test time of 3 to 4 hours may be required for leak detection by measuring pressure loss in the system. Other commonly used test techniques vary widely in sensitivity and complexity: these techniques can vary from soap solution bubble testing (maximum sensitivity to 10^{-4} std cm^3/sec) to a bell jar - helium mass spectrometer (maximum sensitivity better than 10^{-9} std cm^3/sec, or 1 std cm^3/32 yr). Soap solution testing may be quite adequate for many oxygen propellant ground and flight systems using nitrogen as a pressurant gas. However, as leakage requirements become more stringent, as for a long duration interplanetary mission, it may become necessary to employ the more sensitive testing techniques such as the helium mass spectrometer. These techniques are discussed in references 55 (pp. 11 to 13) and 56.

Since helium is the most common tracer gas used for leak measurement, table 9-III is included showing some acceptable leak detection methods for various allowable helium

TABLE 9-III. - LEAKAGE MEASUREMENT USING GASEOUS HELIUM

Allowable leakage, standard cm^3/sec	Approximate equivalent	Leak detection method	Remarks
1.0×10^{-2}	0.6 cm^3/min (6 to 10 average size bubbles in 2 min)	Water submersion, wet test meter, or flowmeter	Detectable and measable with simple equipment
1.0×10^{-3}	1 cm in 17 min (no bubbles in 2 min)	Water submersion or wet test meter	Easy to get false indications; trapped gas between flanges, outside of seal, and desorbed gases from external surfaces may indicate leakage
1.0×10^{-6}	1.0 cm^3 in 12 days	Mass spectrometer	Leak check requires approximately 1/2 hr to set up and 1/4 hr to test
1.0×10^{-7}	1.0 cm^3 in 4 months	Mass spectrometer	Leak check requires approximately 1/2 hr to set up and 1/4 hr to test

leak rates. A discussion of leakage, including specification limits for system leakage in terms of helium gas, and a discussion of zero leakage, may be found in section 4.1.

A summary of commonly available test techniques and their approximate sensitivities are shown in figure 9-17.

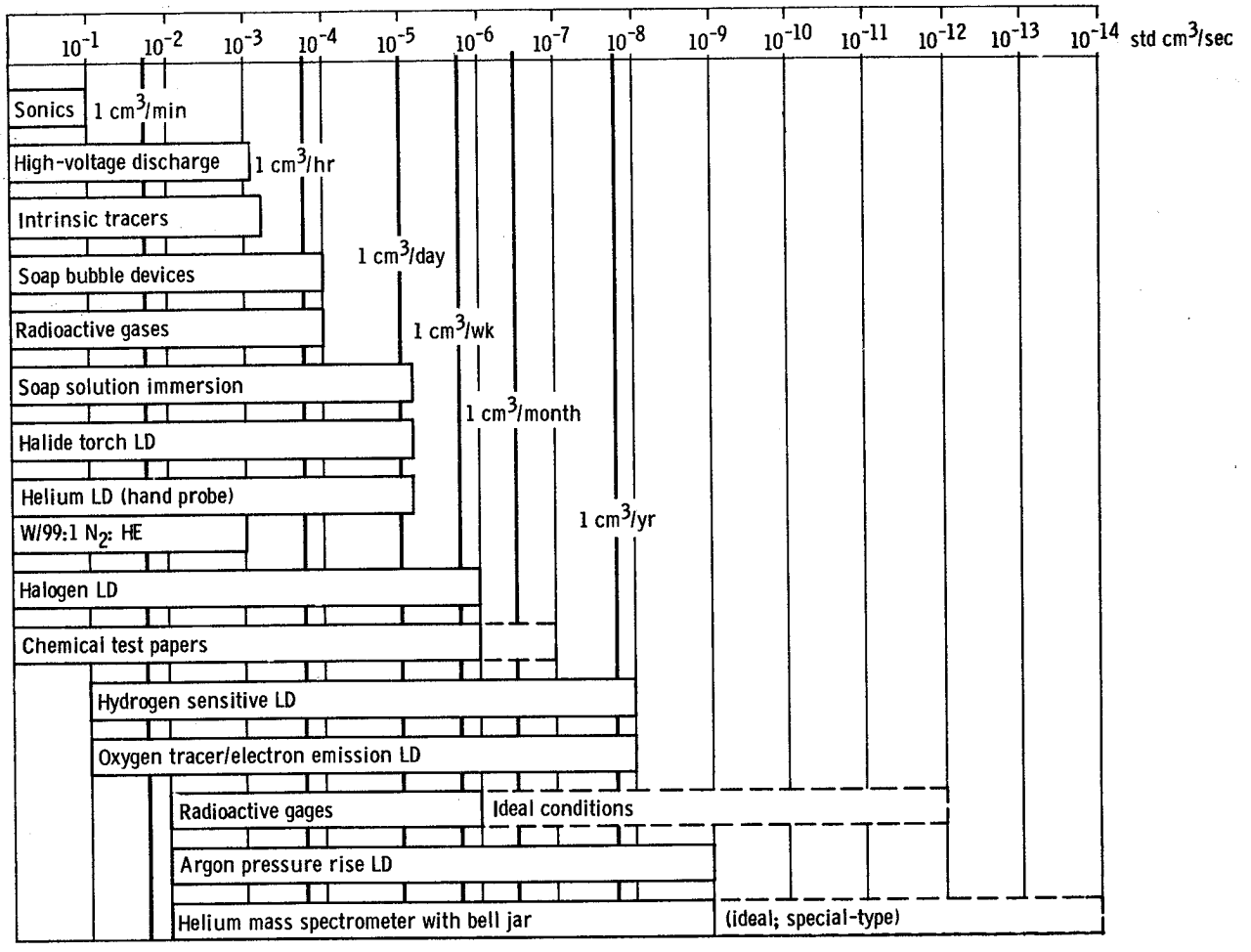


Figure 9-17. - Test methods and their test sensitivities (ref. 55, p. 12). Leak detector, LD.

CHAPTER 10. FILTERS

As noted earlier, solid particles in oxygen systems can cause abrasion and impact ignition of sensitive materials and clogging of close clearances. Generally, the oxygen as supplied by the vendor meeting MSFC Specification 399A (table 2-VII) has been filtered to remove particles greater than 10 microns nominal and 40 microns absolute. This is adequate for most oxygen system requirements provided that no additional contaminant is introduced by subsequent handling.

Particulate contamination is most critical in high pressure gaseous oxygen systems for two reasons: first, gaseous systems are generally at room temperature or higher, which reduces the energy requirement to cause ignition, and second, gaseous systems can easily accelerate particles to sonic or even supersonic velocities. This results in very high impact energies. Consequently, filters may be required, especially in high pressure gaseous oxygen systems. Where high reliability is required, careful control of particulate contamination and system cleanliness verification (sec. 4.5) must be maintained.

Where it is possible to provide contaminant-controlled oxygen to a contaminant-free system, system filters may not be required. Where filters are required to guarantee particle control, they should be installed in the section of the oxygen system which has a low flow velocity. This provides for a minimum ΔP, lower potential for high velocity particle impact, and minimal scrubbing action of the fluid through the filter. The degree of filtration is dictated by (1) size of orifices, pores, slots or passages, (2) clearances between sliding (or static) surfaces, and (3) the hazard of entrained material impacting or abraiding a surface.

Unless test data permit otherwise, the following criteria are suggested:

(1) Filter to a particle size that is 10 percent less than the smallest orifice, pore, or passage to remain unplugged.

(2) Remove by filtration particles that exceed 10 times the asperity height of the land surfaces where all metal valve surfaces are used in a shutoff valve application (see sec. 7.8).

(3) Solid particulates should be limited as follows:

4000 to 1000 microinches for low pressure gaseous oxygen systems (500 to 2000 psia)

1000 to 250 microinches for medium pressure (2000 to 7500 psia)
250 to 100 microinches for high pressure (7500 to 10 000 psia)
100 to 40 microinches for pressure above 10 000 psia

Oxygen filters require special design and maintenance considerations. Usually, filters are changed when the pressure loss across the element becomes too great. With oxygen filters it must be remembered that the unit is filtering and storing solid contaminants. If the contaminants include a high percentage of hydrocarbons, which may be increasing with each use, it should also be assumed that the filter could be sensitive to shock and ignition sources (ref. 144, p. 10).

Filter isolating valves should be installed in the line so that the pressure in the filter can be relieved and the filter element removed for cleaning. This may mean two filters in parallel where the flow of oxygen cannot be interrupted while the filter element is being cleaned. Bypass lines to permit removal of the filter element for cleaning are not recommended unless a high degree of control can be exercised over the use of the bypass line.

Since pressure losses across the filter increase with filter fineness and residue accumulation, system tolerance for such pressure loss must be provided. The standard procedure for monitoring the filter condition is by ΔP measurement.

Because of the pressure drop across a filter, filters may not be tolerable in liquid systems. However, components may be protected from damage due to large particulates by a screen which introduces only a slight pressure drop.

Some of the more common filter element types are listed in table 10-I. A chart of square mesh wire screen sizes is included as table 10-II and standard grades of twilled dutch double weave wire cloth in table 10-III.

Filter elements of bronze, nickel, monel, or stainless steel are preferred. Typical elements are sintered bronze or screens of materials as listed in table 10-III. In operation, the manufacturer's maximum recommended pressure drop must not be exceeded because the loss of filter element integrity in an oxygen line or component could easily result in a fire.

When conical wire mesh screens are used, the cone must point upstream so that the screen will be self-cleaning by washing debris to the wall of the pipe. This orientation will result in collecting particles in a location which will result in the least possible pressure drop across the screen.

TABLE 10-I. - FILTER ELEMENT TYPES[a]

Filter	Filtration	Filtration rating range available, μ[b]	
		Nominal[c]	Absolute
Square mesh wire cloth or twilled Dutch single weave wire cloth	Surface	--------	40 and up
Sintered square mesh wire cloth or sintered twilled Dutch single weave cloth	Surface	--------	40 and up
Wound wire cloth	Depth	2 and up	---------
Twilled Dutch double weave wire cloth	Surface		8 to 100
Sintered porous metal	Depth	2 to 60	5 to 135
Composite sintered porous metal and mesh	Depth	2 to 60	---------
Etched disk	Depth	0.5 to 75	1 to 150
Edge (ribbon or stacked washer)	Surface	40 to 125 25 to 500	---------

[a]Ref. 51, p. 5.10.4-2.

[b]1 μ = 39.4 μin.

[c]Nominal rate shown only for reference when absolute ratings are not commonly employed for medium.

TABLE 10-II. - SQUARE MESH WIRE SCREEN SIZES[a]

U. S. sieve number (mesh)	50	100	140	200	270	325	400
Wire per in.	52.36	101.01	142.86	200.0	270.26	323.00	400
Wire diameter, in.	0.0085	0.0043	0.0030	0.0021	0.0015	0.0012	0.0010
Sieve opening, in.	0.0117	0.0059	0.0041	0.0029	0.0021	0.0017	0.0015
Sieve opening, μ	297	149	105	74	63	44	37

[a]Ref. 51, p. 5.10.2-2.

TABLE 10-III. - STANDARD GRADES OF TWILLED DUTCH DOUBLE WEAVE WIRE CLOTH[a]

(a) Wire cloth specifications

Grade	Nominal mesh count	Absolute micron rating	Wire diameter, μ		Nominal thickness, in.	Nominal weight, lbf/ft^2
			Warp	Shute		
01	24 × 230	100.0	380	220	0.0350	-----
02	30 × 250	75.0	250	200	.0280	0.719
03	50 × 250	50.0	250	200	.0280	.633
04	80 × 745	35.0	100	76	.0110	.241
28	165 × 1350	20.0	70	40	.0057	.159
41	200 × 1350	15.0	70	40	.0057	.161
51	250 × 1350	12.5	55	40	.0051	.160
67	325 × 2100	10.0	38	25	.0033	.100
75	375 × 2150	7.5	34	24.5	.0031	.095

(b) Allowable tolerances

Warp wire mesh count		Shute wire mesh count		Wire diameter	
Warp wire mesh count	Number of tolerance wires per inch	Shute wire mesh count	Number of tolerance wires per inch	Wire diameter, μ	Diameter tolerance, μ
Up to 49	±0.3	Up to 250	±20	Up to 25	±1/2
50 to 74	±.5	251 to 1000	±25	26 to 99	±1
75 to 99	±1.1	1001 to 2000	±30	100 to 199	±2
100 to 400	±2.0	2001 to 3000	±50	200 to 400	±3

(c) Available materials

Finest available grade	Finest wire size, μ	Type of material
Grade 75: 375 × 2150	18	AISI 304, 304L stainless steel
Grade 41: 200 × 1350	25	AISI 316, Monel, nickel
Grade 04: 80 × 745	50	AISI 321, 347 stainless steel

[a]Ref. 51, p. 5.10.4-4.

APPENDIX A

DEFINITION OF ABBREVIATIONS AND ACRONYMS AND TRADE NAME IDENTIFICATION

This appendix contains a listing of acronyms and abbreviations used in the text along with their definitions. Also included is a listing of chemical terms used and their common trade names. This list of chemical terms is included only for assistance to the reader and is not meant to imply endorsement of the trade names listed nor disapproval of those which may have been omitted.

DEFINITION OF ABBREVIATIONS AND ACRONYMS

Term	Definition
ABS	acrylonitrile-butadiene-styrene copolymer
AN	Air Force/Navy Aeronautical
ANSI	American National Standards Institute
ASRDI	Aerospace Safety Research and Data Institute
ASTM	American Society for Testing and Materials
ASME	American Society of Mechanical Engineers
CGA	Compressed Gas Association
CM	command module
CNR	carboxy nitroso rubber
CTFE	(poly) chlorinatedtrifluoroethylene
DN	bearing bore × rpm
DOT	Department of Transportation
EB	electron beam
EPR	ethylene propylene rubber

Term	Definition
EVA	extravehicular activity
FEP	fluorinated ethylene-propylene (copolymer)
FLOX	fluorine-oxygen mixtures
FRC	Flight Research Center
g	acceleration of gravity (32.2 ft/sec^2)
GMA	gas metal arc
GN_2	gaseous nitrogen
GOX	gaseous oxygen
GSE	ground support equipment
GTA	gas tungsten arc
JP4	jet fuel grade kerosene
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KSC	Kennedy Space Center
LeRC	Lewis Research Center
LM	lunar module
LOX	liquid oxygen
MC	Marshall Center (Marshall Spaceflight Center)
MS	Military Standard
MSC	Manned Spacecraft Center, see JSC
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Standards
OPS	oxygen purge system
PBI	polybenzimidazole
PLSS	Personnel Life Support System
PV	pressure-velocity
PVC	polyvinylchloride

Term	Definition
RCS	reaction control system
RTV	room temperature vulcanizing
SCFM	standard cubic feet per minute
SCIM	standard cubic inches per minute
SM	service module
STP	standard temperature and pressure
TFE	(poly) tetrafluoroethylene
TGA	thermogravimetric analysis
TIG	tungsten inert gas
TNT	trinitrotoluene
T.O.	technical order
USAF	United States Air Force

TRADE NAME IDENTIFICATION

Trade or common name	Chemical name or definition
AFD-E-124D	terpolymer of perfluorovinyl ether and Teflon (TFE) (experimental fluoroelastomer)
Allpax 500	fluorolube treated asbestos fiber with styrene butadiene binder
Armalon	Teflon (TFE) coated glass fiber
Arylon T-3198	polyaryl ether
Atlac 711	polyester
Avisun 2356	polypropylene
Bakelite phenolic	phenolic resin
Buna-S	polybutadiene-styrene copolymer
Butyl rubber	isobutylene-isoprene copolymer
Cab-o-sil	sintered colloidal silica particles
Celcon	polyacetal

Trade or common name	Chemical name or definition
Cosden 825 TV	polystyrene
Cycolac KT and KL	acrylonitrile-butadiene-styrene copolymer (ABS)
Cycovin KA	acrylonitrile-butadiene-styrene copolymer (ABS)
Dacron	polyester fiber (polyethylene terephthalate)
DC-33	silicone grease
DC-41	silicone grease
Dowclene 10	emulsion of caustic soda, detergent, and sequestering agent
Drilube 822	fluorinated silicone
Durez 2311	acrylonitrile-butadiene-styrene copolymer (ABS)
Duroid (5000 series)	filled Teflon (TFE)
Dylene 8X	polystyrene
Epon	epoxy adhesive
Fluorel	vinylidene fluoride-hexafluoropropylene copolymer
Fluorogold	fiberglass filled Teflon (TFE)
Fluorogreen	fiberglass filled Teflon (TFE)
Fluorosilicone	fiberglass filled Teflon (TFE)
Formvar	polyvinyl formal
Geon 101	polyvinylchloride (PVC)
Glyptal	polyester plasticiser
Halocarbon	halogenated hydrocarbon
Halon	polytetrafluoroethylene (TFE)
Halon TVS	modified chlorotrifluoroethylene (CTFE)
Kel-F 81	chlorotrifluoroethylene (CTFE)
Kel-F 82	chlorotrifluoroethylene-vinylidene fluoride copolymer

Trade or common name	Chemical name or definition
Kynar	vinylidene fluoride
Lexan	polycarbonate
Lucite	polymethylmethacrylate
Mylar	polyester film (polyethylene terephthalate)
Natural rubber	polyisoprene
Neoprene	polychlorobutadiene
Nitrile rubber	polybutadiene acrylomitrile
Nomex	polyimide fiber (aromatic polyamide)
Noryl 731	polyphenylene oxide polymer
Nylon	polyamide
Orlon	polyacrylonitrile fiber
Oxyseal	graphite and chlorinated hydrocarbon
Perlite	volcanic glass
Plaskon 1070	polypropylene
Plaskon 2200 and 2400	chlorotrifluoroethylene
Plenco 200D	epoxy
Plexiglass	polymethylmethacrylate
Polyox WSR-35	polyethylene oxide
Profax 6505	polypropylene
RTV polymers	polysiloxane
Rulon	filled Teflon (TFE)
Salox-M	bronze-filled Teflon (TFE)
Santocel A	silica gel
Saran	polyvinylidene chloride
Shell 325	polystyrene
Silastic	polysiloxane
Silicone	polysiloxane
Teflon	polytetrafluoroethylene (TFE)

Trade or common name	Chemical name or definition
Textolite	phenolic-paper laminate
Turco	nonsilicated alkaline cleaner
Vespel	polyimide
Viton A	vinylidene fluoride-hexafluoropropylene copolymer

APPENDIX B

CONVERSION FACTORS

NASA policy dictates the use of the International System of Units (SI) as the standard in published documents. This volume, because of its wide use of references which present data in various systems of units, has deviated from that policy. Accordingly, the following tables of conversion factors for the most frequently used properties are included here. A more complete list of conversion factors for the SI system may be found in NASA SP-7012 - "International System of Units - Physical Constants and Conversion Factors."

ENERGY

abs J	int. J	cal	t.[a] cal	Btu	int. kW-hr	ft-lb (wt)	liter-atm	hp-hr
1	0.999835	0.239006	0.238849	0.947831×10^{-3}	2.77732×10^{-7}	0.737561	9.86896×10^{-3}	3.72505×10^{-7}
1.000165	1	0.239045	0.238889	0.947988×10^{-3}	2.777778×10^{-7}	0.737682	9.87058×10^{-3}	3.72567×10^{-7}
4.1840	4.1833	1	0.999346	3.96573×10^{-3}	1.162030×10^{-6}	3.08595	4.12917×10^{-2}	1.558562×10^{-6}
4.18674	4.18605	1.000654	1	3.96832×10^{-8}	1.162791×10^{-6}	3.08797	4.13187×10^{-2}	1.559582×10^{-6}
1055.040	1054.866	252.101	251.996	1	2.93018×10	778.156	10.41215	3.93008×10^{-4}
3 600 594	3 600 000	860 563	860 000	3412.76	1	2 655 656	35534.1	1.341241
2 684 525	2 684 082	641 617	641 197	2544.48	0.745578	1 980 000	26493.5	1
1.355821	1.355597	0.324049	0.323837	1.285089×10^{-3}	3.76555×10^{-7}	1	1.338054×10^{-2}	5.05051×10^{-7}
101.3278	101.3111	24.2179	24.2021	0.0960417	2.81420×10^{-5}	74.7354	1	3.77452×10^{-5}

[a]Thermochemical.

THERMAL CONDUCTIVITY

$\frac{(W)(cm)}{(cm^2)(K)}$	$\frac{(W)(in.)}{(in.^2)(^oF)}$	$\frac{(cal)(cm)}{(sec)(cm^2)(K)}$	$\frac{(Btu)(in.)}{(hr)(ft^2)(^oF)}$	$\frac{(Btu)(ft)}{(hr)(ft^2)(^oF)}$	$\frac{(Btu)(in.)}{(sec)(in.^2)(^oF)}$	$\frac{(Btu)(in.)}{(hr)(in.^2)(^oF)}$
1	1.411	0.2389	6.9340×10^{2}	57.79	1.338×10^{-3}	4.816
0.7087	1	0.1693	4.914×10^{2}	40.95	9.480×10^{-4}	3.413
4.1858	5.907	1	2.9027×10^{3}	2.419×10^{2}	5.602×10^{-3}	20.16
1.442×10^{-3}	2.035×10^{-3}	3.445×10^{-4}	1	8.33×10^{-2}	1.929×10^{-6}	6.944×10^{-3}
1.730×10^{-2}	2.442×10^{-2}	4.135×10^{-3}	12	1	2.315×10^{-5}	8.33×10^{-2}
7.4738×10^{2}	1.0548×10^{3}	1.785×10^{2}	5.184×10^{5}	4.3191×10^{4}	1	3.600×10^{3}
0.2076	0.2930	4.960×10^{-2}	1.44×10^{2}	12	2.778×10^{-4}	1

PERMEABILITY

$$\left[\text{Standard unit: } \frac{\text{cc(STP)cm}}{(\text{cm}^2)(\text{sec})(\text{bar})} = 1.\right]$$

Units system	Multiplication factor for converting to standard units	Units system	Multiplication factor for converting to standard units
$\frac{\text{scc cm}}{\text{cm}^2 \text{ sec cm Hg}}$	7.501×10^{1}	$\frac{\text{scc mil}}{\text{cm}^2 \text{ day atm}}$	2.901×10^{-8}
$\frac{\text{scc cm}}{\text{cm}^2 \text{ sec mm Hg}}$	7.501×10^{2}	$\frac{\text{scc mil}}{\text{in.}^2 \text{ hr lb/in.}^2}$	1.023×10^{-5}
$\frac{\text{scc mm}}{\text{cm}^2 \text{ sec sm Hg}}$	7.501	$\frac{\text{liter mm}}{\text{cm}^2 \text{ sec mm Hg}}$	7.501×10^{4}
$\frac{\text{scc mm}}{\text{m}^2 \text{ day atm}}$	1.142×10^{-10}	$\frac{\text{scc mm}}{\text{cm}^2 \text{ hr atm}}$	2.741×10^{-5}
$\frac{10^{-5} \text{ ft}^3 \text{ mil}}{\text{min ft}^2 \text{ atm}}$	1.273×10^{-8}	$\frac{\text{scc mil}}{100 \text{ in.}^2 \text{ day } 17.3 \text{ psi}}$	3.82×10^{-9}
$\frac{\text{scc mm}}{\text{cm}^2 \text{ sec atm}}$	9.8692×10^{-2}	$\frac{\text{scc mil}}{\text{in.}^2 \text{ day atm}}$	2.901×10^{-12}
$\frac{\text{scc mil}}{100 \text{ in.}^2 \text{ day atm}}$	4.497×10^{-11}	$\frac{\text{scc mil}}{100 \text{ m}^2 \text{ day } 17.7 \text{ psi}}$	2.408×10^{-14}
$\frac{\text{scc cm}}{\text{cm}^2 \text{ sec atm}}$	9.8692×10^{-1}		

LENGTH

cm	mm	μ	mμ	Å
1	10	10^{4}	10^{7}	10^{8}
10^{-1}	1	10^{3}	10^{6}	10^{7}
10^{-4}	10^{-3}	1	10^{3}	10^{4}
10^{-7}	10^{-6}	10^{-3}	1	10
10^{-8}	10^{-7}	10^{-4}	10^{-1}	1

cm	m	in.	ft
1	0.01	0.397	0.032808333
100	1	39.37	3.2808333
2.5400051	0.025400051	1	0.083333333
30.48061	0.30480061	12	1

SURFACE TENSION

dyne/cm	erg/cm^2	mg/mm	mg/in.	lb/ft
1	1	0.10197	2.5901	6.853×10^{-6}
9.80665	9.80665	1	25.400051	6.72×10^{-4}
0.38609	0.38609	0.03937	1	2.6459×10^{-5}
14592.15	14592.15	1488	37 794	1

VISCOSITY[a]

poise[b]	(lb force)(sec)/ft^2[c]	lb mass/ft-sec
1	2.0886×10^{-3}	0.0672
4.788×10^{2}	1	32.174
14.9	3.108×10^{-2}	1

[a]Absolute viscosity; kinetic viscosity = absolute viscosity/density.
[b]Poise = 1 (dyne)(sec)/cm^2 = 1 g/(cm)(sec).
[c]1 (lb force)(sec)/ft^2 = 1 slug/ft-sec.

FORCE[a]

	dynes	g	kg	J/cm	J/m	lb	poundals
dynes	1	980.7	9.807×10^{5}	10^{7}	10^{6}	4.448×10^{5}	1.383×10^{4}
g	1.020×10^{-3}	1	1000	1.020×10^{4}	102.0	453.6	14.10
kg	1.020×10^{-6}	0.001	1	10.20	0.1020	0.4536	1.410×10^{-2}
J/cm	10^{-7}	9.807×10^{-5}	9.807×10^{-2}	1	0.01	4.448×10^{-2}	1.383×10^{-3}
N/m or J/m	10^{-5}	9.807×10^{-3}	9.807	100	1	4.448	0.1383
lb	2.248×10^{-6}	2.205×10^{-3}	2.205	22.48	0.2248	1	3.108×10^{-2}
poundals	7.233×10^{-5}	7.093×10^{-2}	70.93	723.3	7.233	32.17	1

[a]Conversion factors between absolute and gravitational units apply only under standard acceleration due to gravity conditions.

AREA

cm^2	m^2	$in.^2$	ft^2
1	10^{-4}	0.15499969	1.0763367×10^{-3}
10^4	1	1549.9969	10.763867
6.4516258	6.4516258×10^{-4}	1	6.9444444×10^{-3}
929.03412	0.092903412	144	1

VOLUME

cm^3	$in.^3$	ft^3	mliter	liter	gal
1	0.061023378	3.5314455×10^{-5}	0.9999720	0.9999720×10^{-3}	2.6417047×10^{-4}
16.387162	1	5.7870370×10^{-4}	16.38670	1.638670×10^{-2}	4.3290043×10^{-3}
28317.017	1728	1	28316.22	28.31622	7.4805195
1.000028	0.06102509	3.531544×10^{-5}	1	0.001	2.641779×10^{-4}
1.000.028	61.02509	0.03531544	1000	1	0.2641779
3785.4345	231	0.13368656	3785.329	3.785329	1

MASS

g	kg	lb	metric ton	ton
1	10^{-3}	2.2046223×10^{-3}	10^{-6}	1.1023112×10^{-6}
10^3	1	2.2046223	10^{-3}	1.1023112×10^{-3}
453.59243	0.45359243	1	4.5359234×10^{-4}	5×10^{-4}
10^6	10^3	2204.6223	1	1.1023112
907184.86	907.18486	2000	0.90718486	1

SPECIFIC HEAT

cal/(g)(K)	J/(g)(K)	W-sec/(g)(K)	Btu/(lb)(^{o}R)
1	4.1840	4.1840	0.9995826
0.239006	1	1	0.238849
1.000654	4.18674	4.18674	1

ENTHALPY

cal/g	J/g	W-sec/g	Btu/lb
1	4.1840	4.1840	1.798823
0.239006	1	1	0.429929
0.555919	2.32597	2.32597	1

DENSITY

g/cm^3	$g/in.^3$	kg/gal	kg/ft^3	lb/gal	lb/ft^3
1	16.3872	3.78543	28.3170	8.34545	62.4283
0.0610232	1	0.23100	1.72800	0.509268	3.80959
0.264171	4.32900	1	7.48052	2.20462	16.4917
0.0353145	0.578704	0.133681	1	0.294715	2.20462
0.119826	1.96360	0.453592	3.39311	1	7.48052
0.0160184	0.262496	0.0606365	0.453592	0.133681	1

PRESSURE

	atm	bars or dynes/cm^2	cm Hg at 0° C	in. Hg at 0° C	in. H_2O at 4° C	kg/m^2	lb/ft^2	lb/in.^{2}	tons (short)/ft^2	N/m^2	torr or mm Hg	micron	bar
atm	1	9.869×10^{-7}	1.316×10^{-2}	3.342×10^{-2}	2.458×10^{-3}	9.678×10^{-5}	4.725×10^{-4}	6.804×10^{-2}	0.9450	9.869×10^{-6}	1.316×10^{-3}	1.316×10^{-6}	0.9869233
bars or dynes/cm^2	1.013×10^{6}	1	1.333×10^{4}	3.386×10^{4}	2.491×10^{-3}	98.07	478.8	6.895×10^{4}	9.576×10^{5}	10	1333	1.333	10^{6}
cm Hg at 0° C	76.00	7.501×10^{-5}	1	2.540	0.1868	7.356×10^{-3}	3.591×10^{-2}	5.171	71.83	7.501×10^{-4}	0.1	10^{-4}	75.006
in. Hg at 0° C	29.92	2.953×10^{-5}	0.3937	1	7.355×10^{-2}	2.896×10^{-3}	1.414×10^{-2}	2.036	28.28	2.953×10^{-4}	3.937×10^{-2}	3.937×10^{-5}	29.52993
in. H_2O at 4° C	406.8	4.015×10^{-4}	5.354	13.60	1	3.937×10^{-2}	0.1922	27.68	384.5	4.015×10^{-3}	0.5354	5.354×10^{-4}	402
kg/m^2	1.033×10^{4}	1.020×10^{-2}	136.0	345.3	25.40	1	4.882	703.1	9765	0.1020	13.60	1.360×10^{-2}	1.0197
lb/ft^2	2116	2.089×10^{-3}	27.85	70.73	5.202	0.2048	1	144	2000	2.089×10^{-2}	2.785	2.785×10^{-3}	2188
lb/in.^{2}	14.70	1.450×10^{-5}	0.1934	0.4912	3.613×10^{-2}	1.422×10^{-3}	6.944×10^{-3}	1	13.89	1.450×10^{-4}	1.934×10^{-2}	1.934×10^{-5}	14.5038
tons (short)/ft^2	1.058	1.044×10^{-6}	1.392×10^{-2}	3.536×10^{-2}	2.601×10^{-3}	1.024×10^{-4}	0.0005	0.0720	1	1.044×10^{-5}	1.392×10^{-3}	1.392×10^{-6}	1.044
N/m^2	1.013×10^{5}	10^{-1}	1.333×10^{3}	3.386×10^{3}	2.491×10^{-4}	9.807	47.88	6.895×10^{3}	9.576×10^{4}	1	133.3	0.1333	1×10^{5}
torr or mm Hg	760	7.501×10^{-4}	10	25.40	1.868	7.356×10^{-2}	0.3591	51.71	718.3	7.501×10^{-3}	1	10^{-3}	750.0617
micron	7.60×10^{5}	0.7501	10^{4}	2.540×10^{4}	1868	73.56	359.1	5.171×10^{4}	7.183×10^{5}	7.501	1000	1	7.5×10^{5}

APPENDIX C

SOLUBILITY OF HYDROCARBONS OR CARBON DIOXIDE IN OXYGEN

This appendix contains graphical presentations of the solubilities of some saturated and unsaturated hydrocarbons and carbon dioxide in liquid oxygen as a function of oxygen temperature.

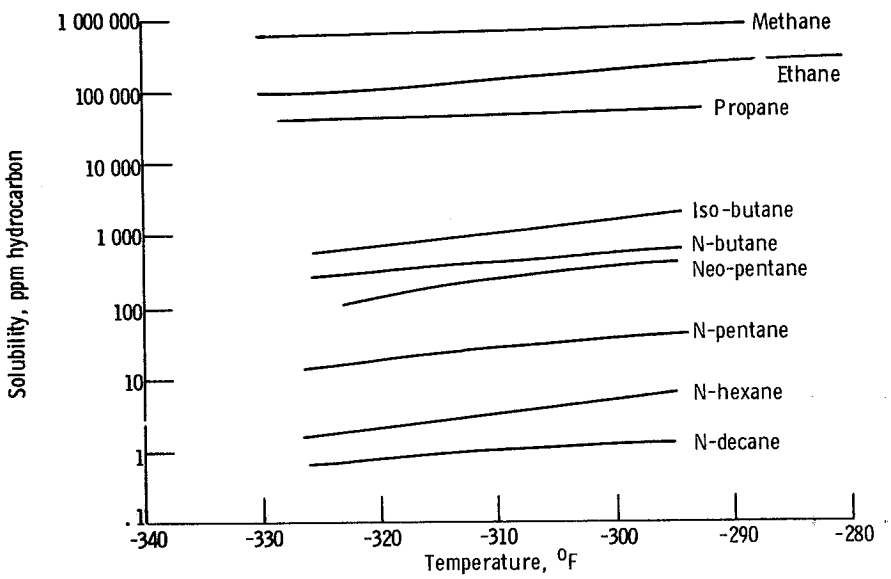


Figure C-1. - Solubility of saturated hydrocarbons in liquid oxygen (ref. 145, p. 19).

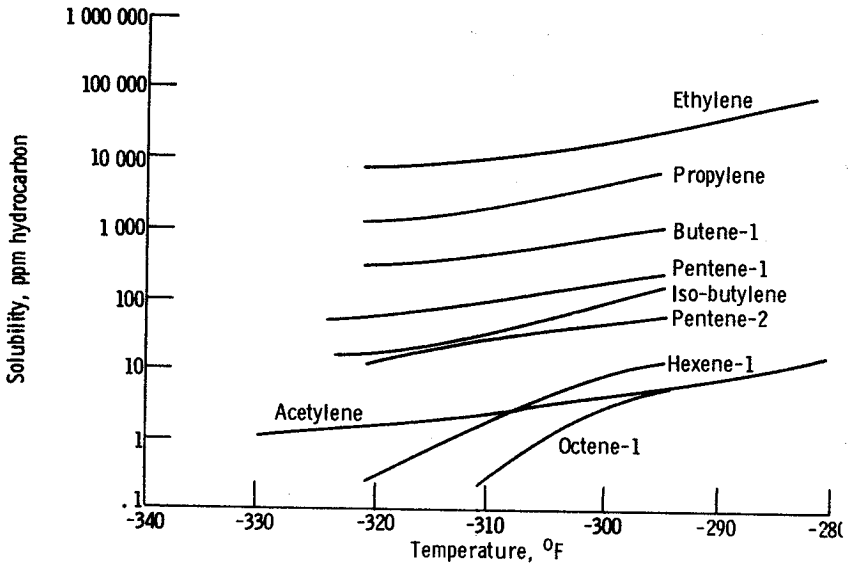


Figure C-2. - Solubility of unsaturated hydrocarbons in liquid oxygen (ref. 145, p. 20).

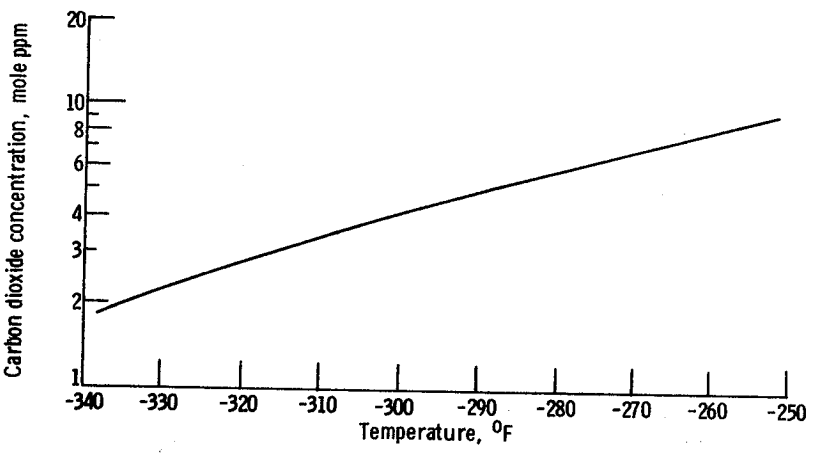


Figure C-3. - Solubility of carbon dioxide in liquid oxygen (ref. 2, p. 22).

APPENDIX D

IGNITION TEMPERATURES OF METALS

This appendix contains figures showing the measured ignition temperatures of metals and a table (from ref. 146) giving ignition temperature ranges for various magnesium alloys. The measured ignition temperatures of metals are plotted against the logarithm of oxygen pressure. In cases where the test environment was other than 100 percent oxygen, such as air, oxygen-nitrogen or oxygen-helium mixtures, the pressures plotted are oxygen partial pressures (i.e., if test gas is air at 1 atmosphere, the oxygen pressure plotted is 0.21 atmosphere).

The data plotted have been compiled from several references. These references are identified on the plots. Accordingly, such variables as test procedures and techniques, instrumentation, test specimen shape and purity, and quenching effects of the diluent gas are not accounted for.

The following table gives the pages on which the ignition temperature of the metals are shown:

Figure	Metal	Page	Figure	Metal	Page
D-1(a)	Aluminum	182	D-1(k)	Zinc	184
D-1(b)	Copper		D-1(l)	Bismuth and barium	
D-1(c)	Iron		D-1(m)	Strontium and calcium	
D-1(d)	Lead		D-1(n)	Beryclo-10	
D-1(e)	Magnesium		D-1(o)	Brass	
D-1(f)	Molybdenum	183	D-1(p)	Mild (carbon) steel	185
D-1(g)	Tantalum		D-1(q)	Nickel alloys	
D-1(h)	Tin		D-1(r)	Stainless steel	
D-1(i)	Titanium		D-1(s)	Miscellaneous	
D-1(j)	Tungsten				

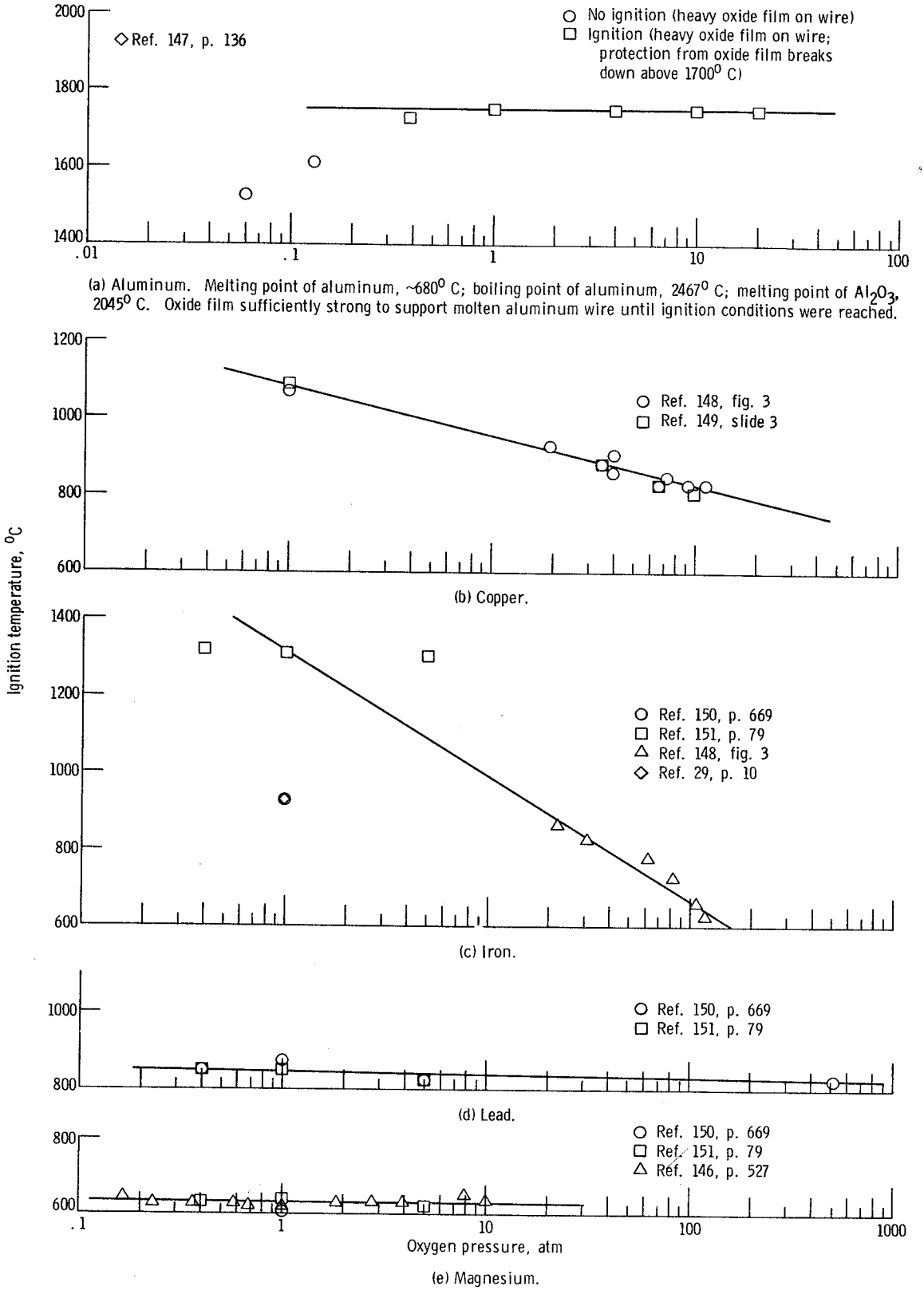
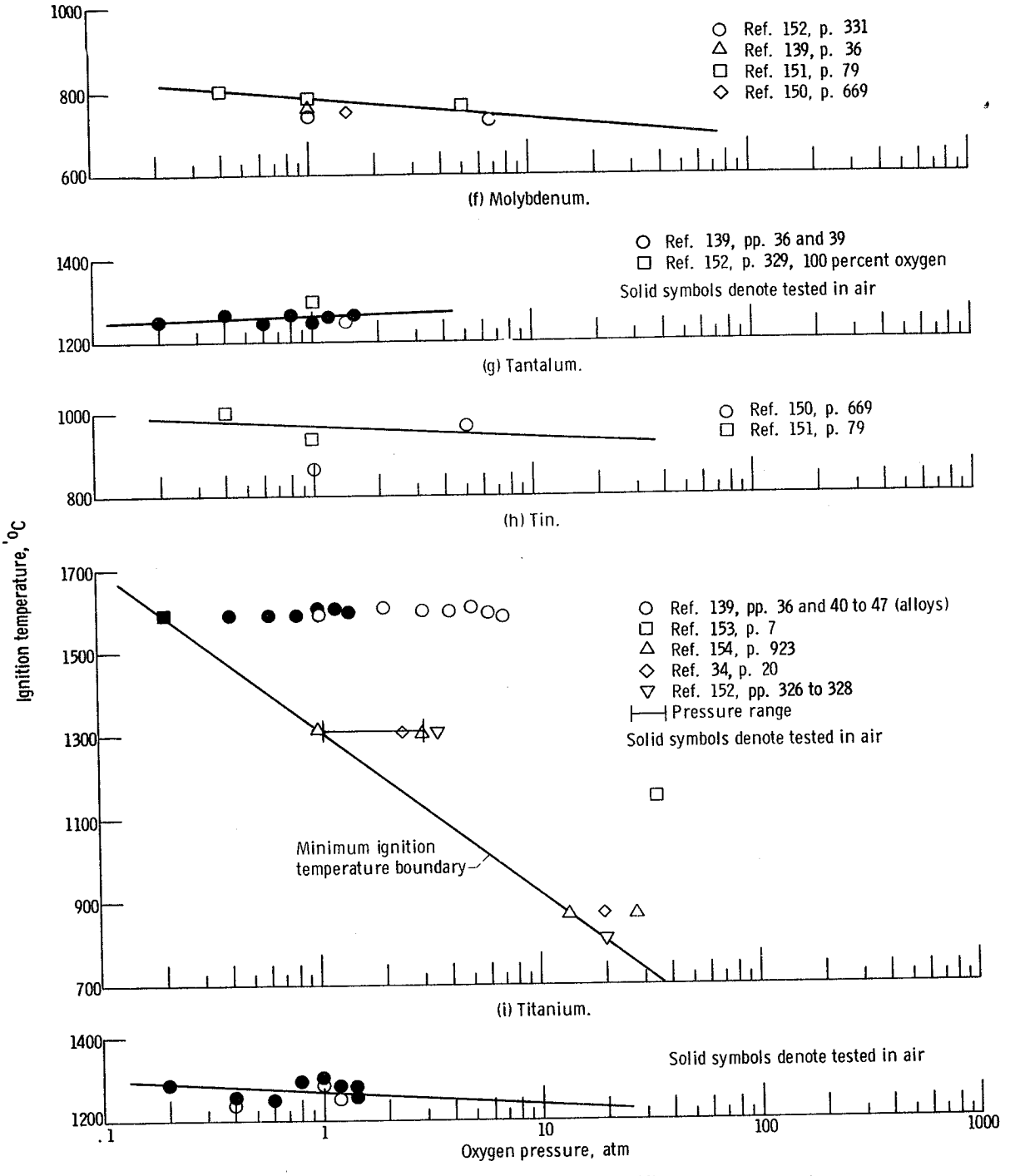
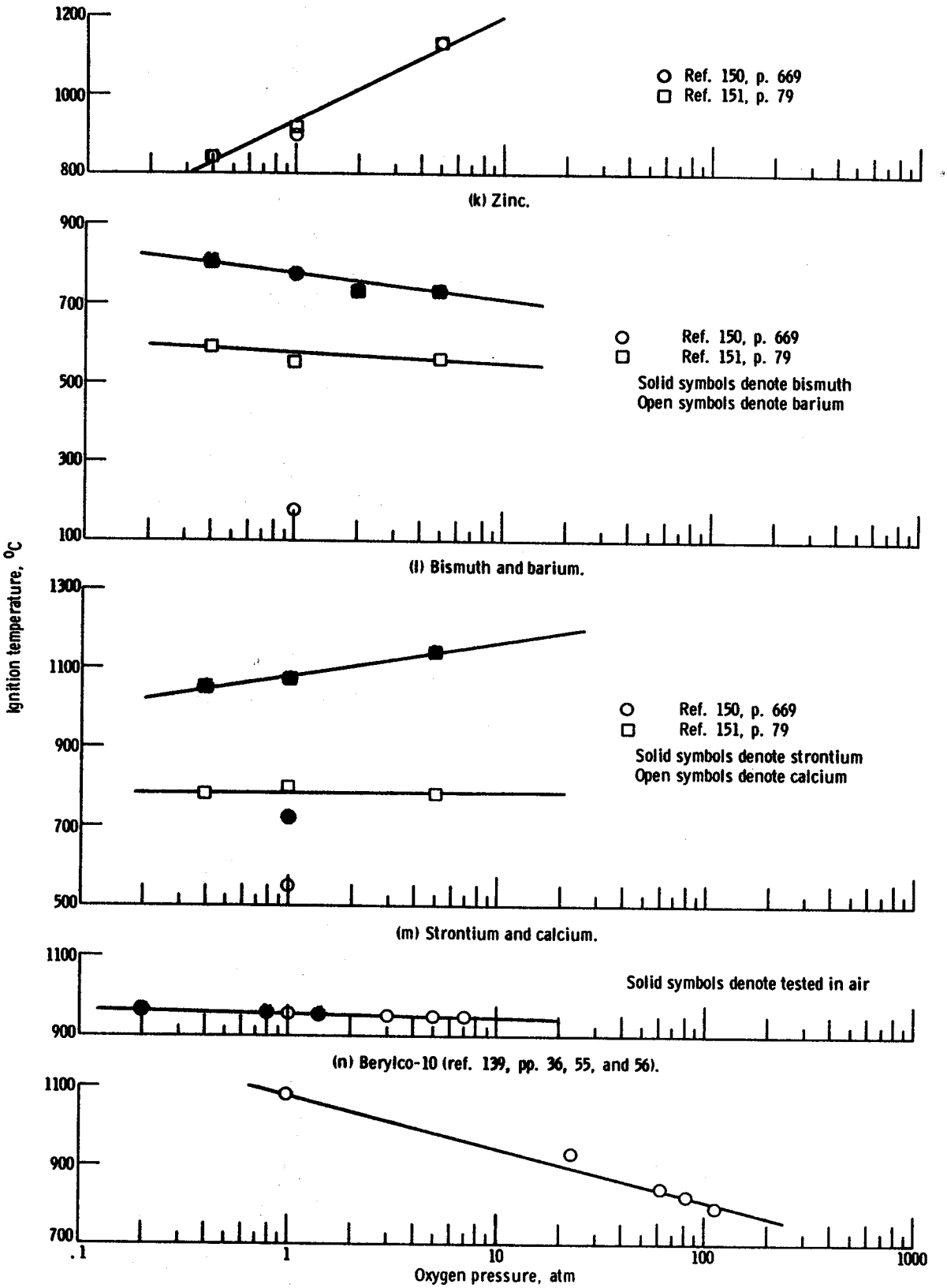


Figure D-1. - Ignition temperatures of metals.



(j) Tungsten (ref. 139, p. 36).

Figure D-1. - Continued.



(k) Zinc.

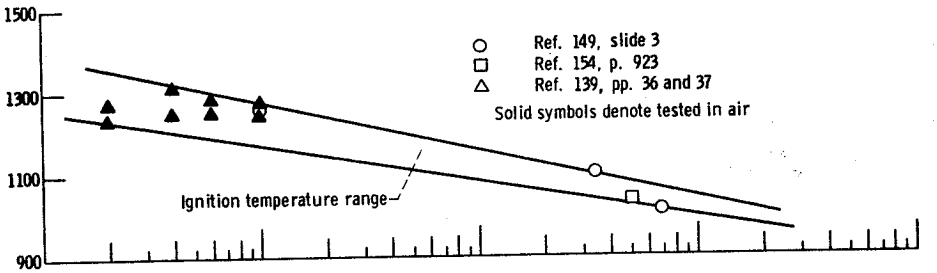
(l) Bismuth and barium.

(m) Strontium and calcium.

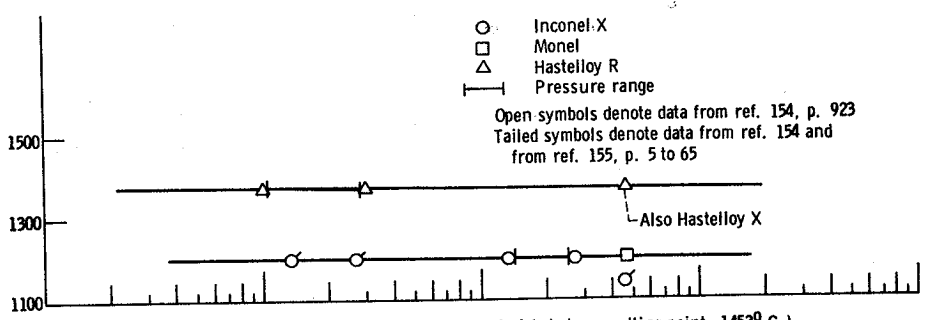
(n) Berylco-10 (ref. 139, pp. 36, 55, and 56).

(o) Brass (ref. 148, fig 3).

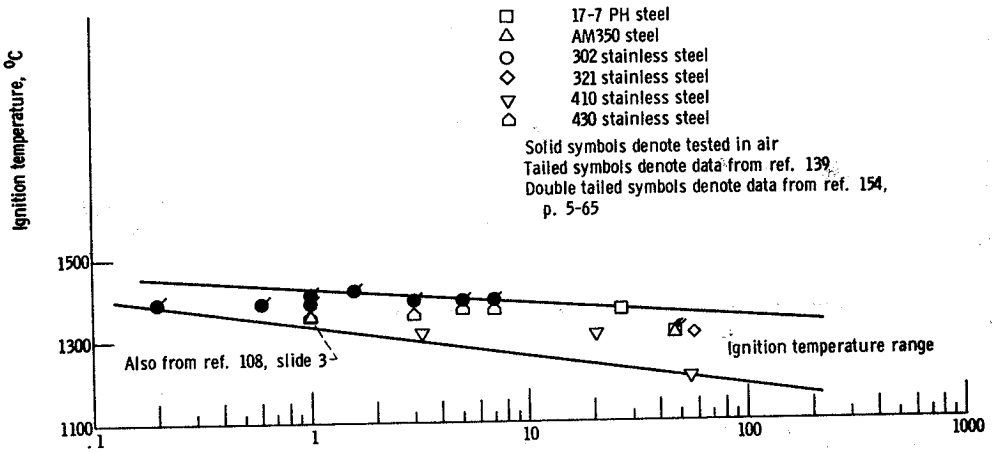
Figure D-1. - Continued.



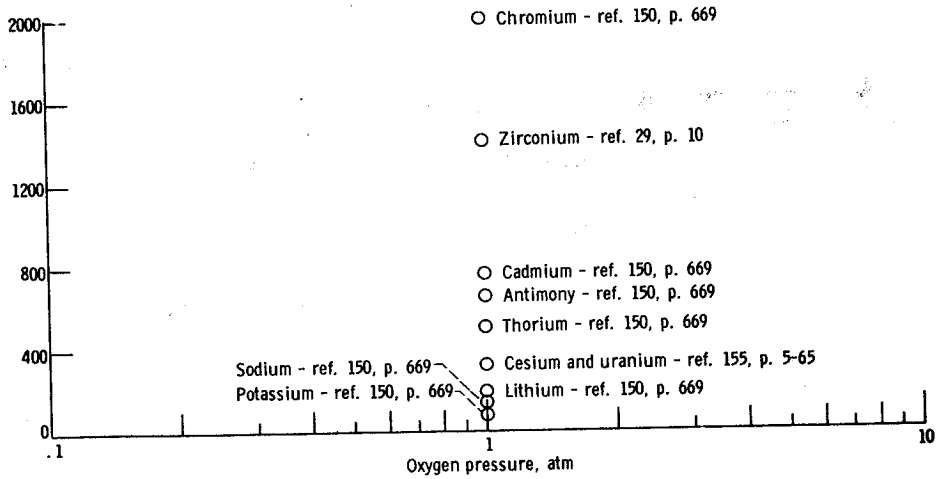
(p) Mild (carbon) steel.



(q) Nickel alloys. (Ignition temperature of nickel above melting point, 1453° C.)



(r) Stainless steel.



(s) Miscellaneous metals.

Figure D-1. - Concluded.

TABLE D-I. - IGNITION TEMPERATURE RANGES FOR VARIOUS MAGNESIUM ALLOYS AT 1-ATMOSPHERE OXYGEN PRESSURE[a]

Alloy	Ignition temperature range, °C
Mg - Ag (4.8 - 14.12 Ag)	537 to 550
Mg - Al (5.67 - 63.15 Al)	462 to 558
Mg - Al (80.33 - 93.73 Al)	>900
Mg - Cd (7.15 - 90.52 Cd)	517 to 612
Mg - Cu (10.3 - 30.76 Cu)	519 to 537
Mg - Ni (5.0 - 20.0 Ni)	508 to 517
Mg - Sn (9.88 - 25.62 Sn)	556 to 576
Mg - Pb (16.4 - 58.26 Pb)	504 to 575
Mg - Zn (3.04 - 89.33 Zn)	509 to 595

[a]Ref. 146, p. 524.

APPENDIX E

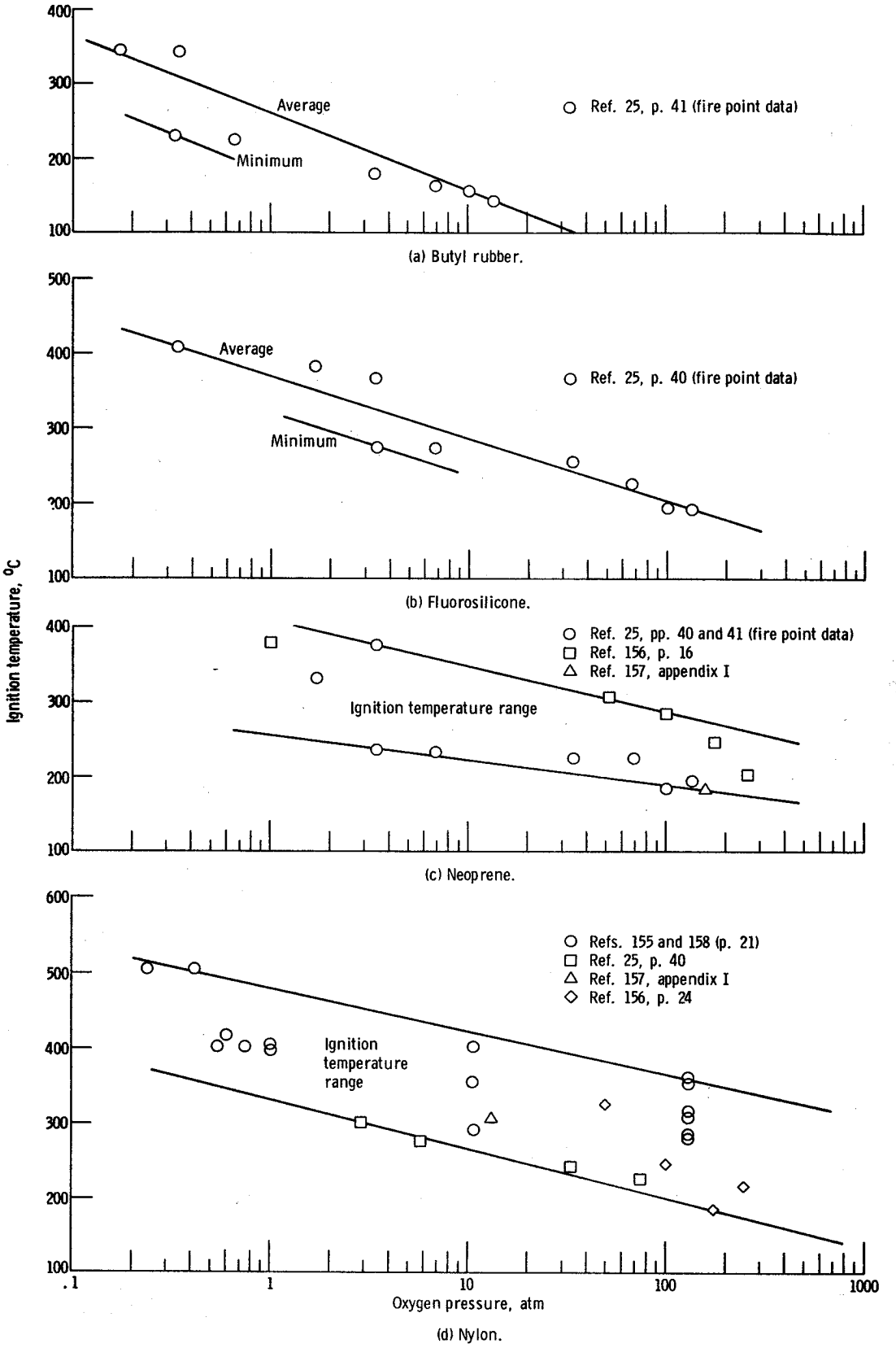
IGNITION TEMPERATURES OF NONMETALS

This appendix contains figures showing measured ignition temperatures of nonmetal (polymeric) materials. The measured ignition temperatures of nonmetal materials are plotted against the logarithm of oxygen pressure. In cases where the test environment was other than 100 percent oxygen, such as air, oxygen-nitrogen or oxygen-helium mixtures, the pressures plotted are oxygen partial pressures (i.e., if test gas is air at 1 atmosphere, the oxygen pressure plotted is 0.21 atmosphere).

The data plotted have been compiled from several references. These references are identified on the plots. Accordingly, such variables as test procedures and techniques, instrumentation, test specimen, shape and purity, and quenching effects of the diluent gas are not accounted for. Also, firepoint data from flash and firepoint testing have been included as ignition temperature data but are so identified on the plots.

The following table gives the pages on which the ignition temperatures of some nonmetals are shown:

Figure	Nonmetal	Page	Figure	Nonmetal	Page
E-1(a)	Butyl rubber	188	E-1(j)	Polytegrafluoroethylene (TFE)	190
E-1(b)	Fluorosilicone	↓	E-1(k)	Polyrinylalcohol	↓
E-1(c)	Neoprene	↓	E-1(l)	Polyvinylchloride (PVC)	↓
E-1(d)	Nylon	↓	E-1(m)	Polyvinylidene - fluoride	↓
E-1(e)	Polychlorotrifluoroethylene (CTFE)	189	E-1(n)	Silicone grease	191
		↓	E-1(o)	Silicone rubber	↓
E-1(f)	Polyethylene	↓	E-1(p)	Viton A	↓
E-1(g)	70 Percent polyethlene - 30 percent fiberglass	↓	E-1(q)	Viton and Fluorel	↓
			E-1(r)	Dacron fabric	192
E-1(h)	Vespel	↓	E-1(s)	Nomex fabric	↓
E-1(i)	Polymethylmethacrylate (Plexiglas or Lucite)	↓	E-1(t)	Nylon fabric	↓
			E-1(u)	Orlon fabric	↓



(d) Nylon.

Figure E-1. - Ignition temperatures of nonmetals.

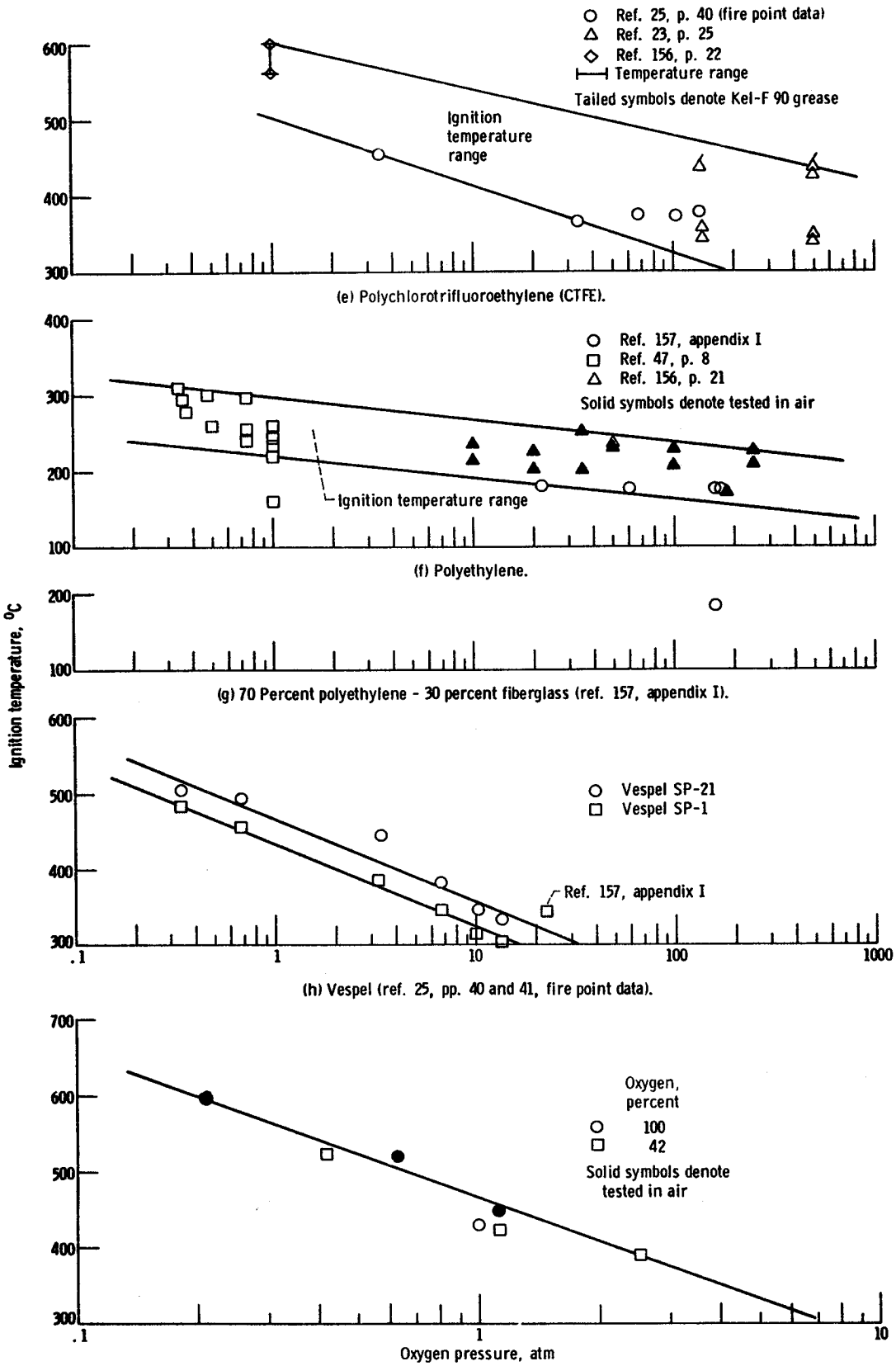
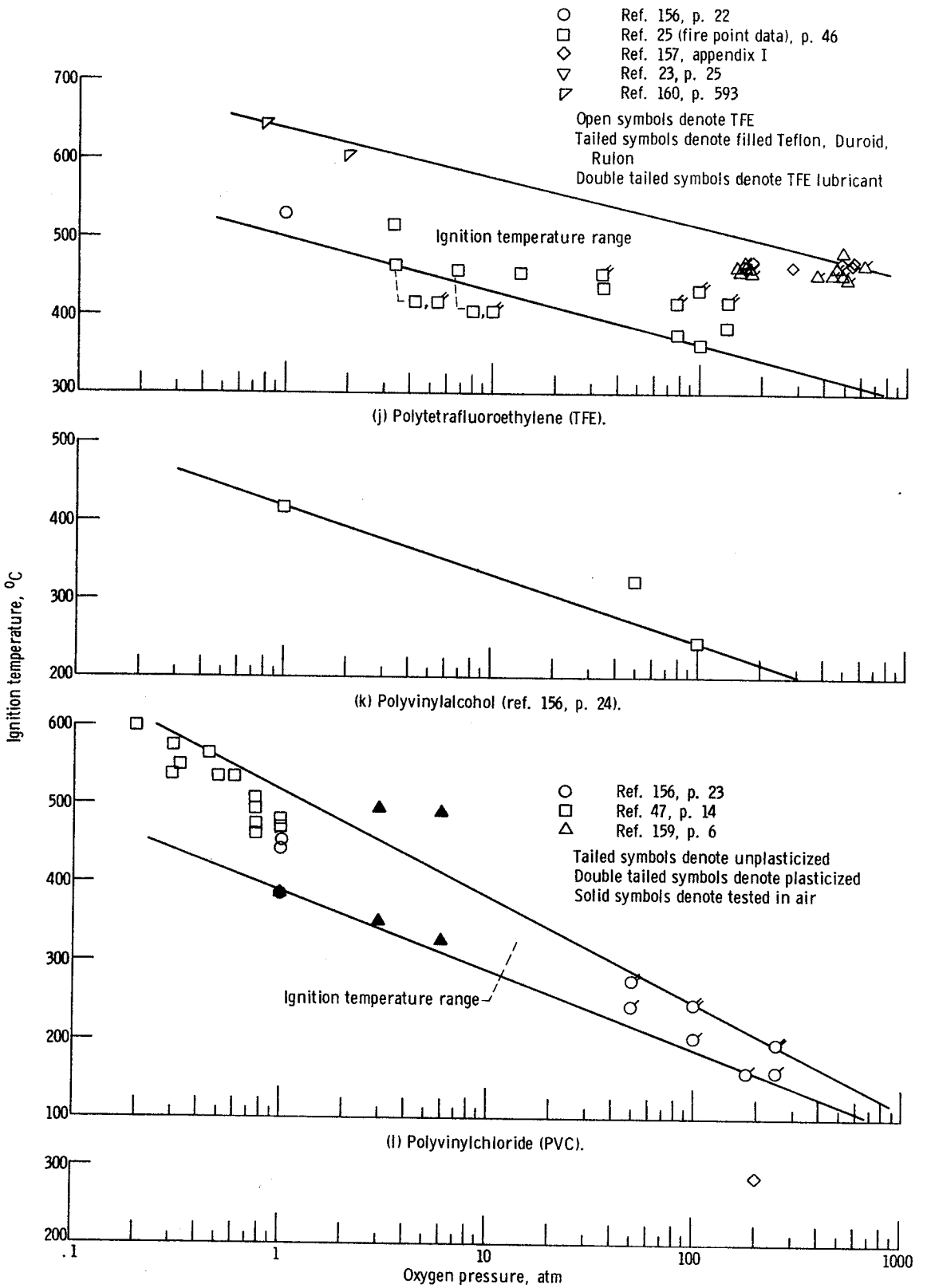
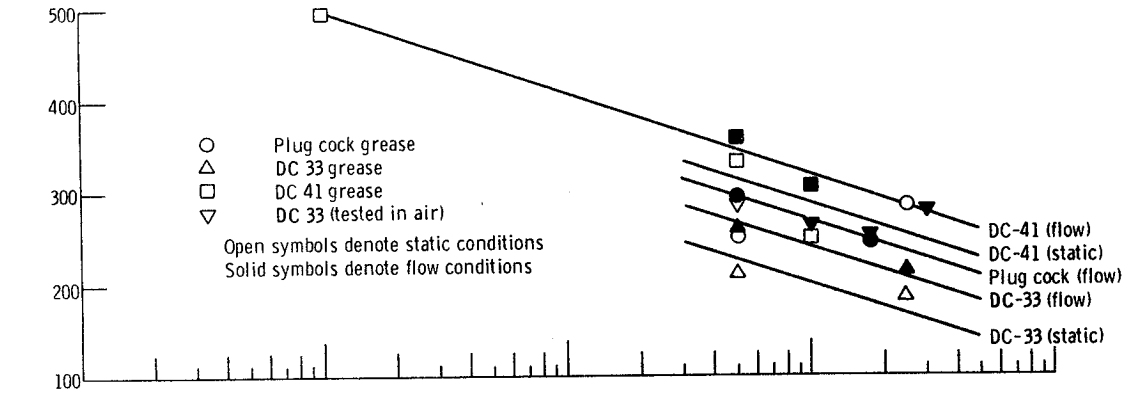


Figure E-1. - Continued.

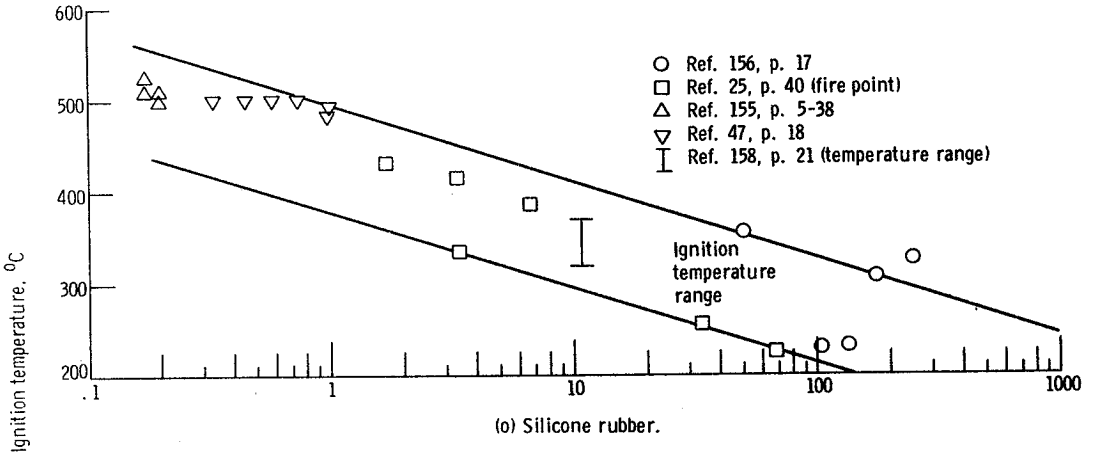


(m) Polyvinylidene-fluoride (ref. 157, appendix I).

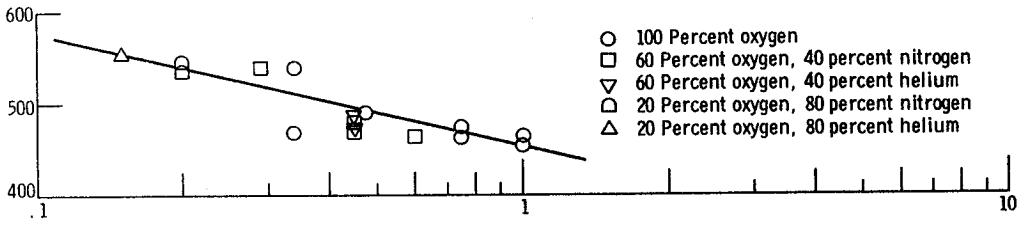
Figure E-1. - Continued.



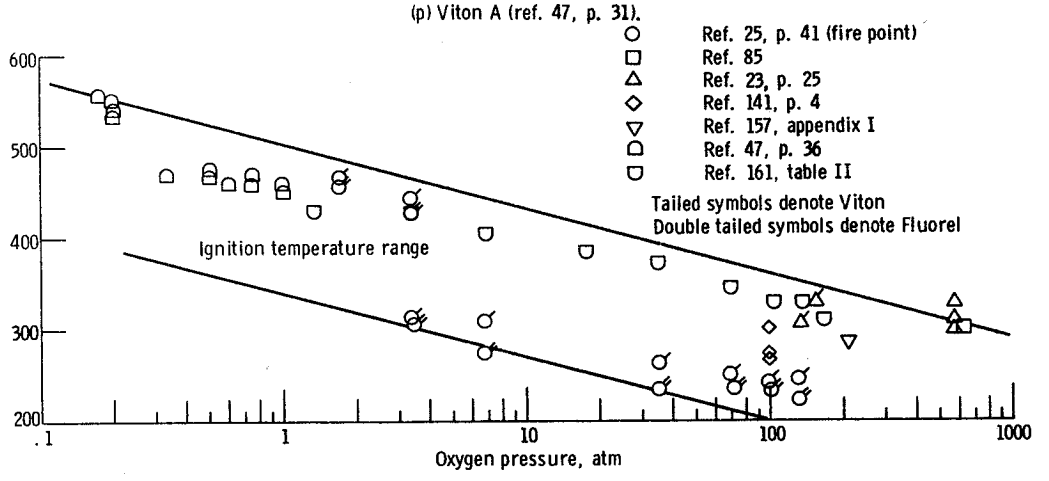
(n) Silicone grease (ref. 156, pp. 9 and 10).



(o) Silicone rubber.

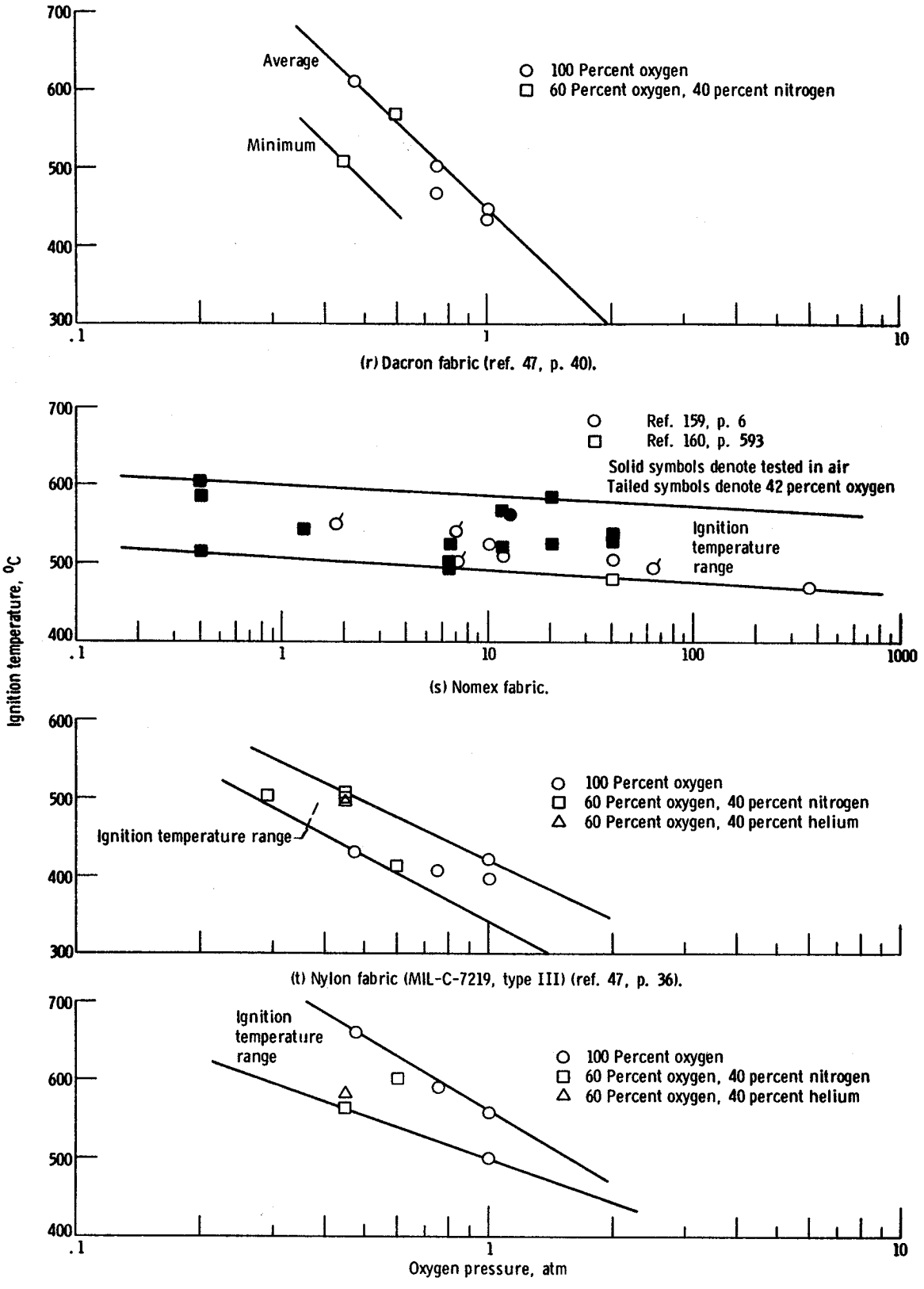


(p) Viton A (ref. 47, p. 31).



(q) Viton and Fluorel (copolymer of vinylidene fluoride and hexafluoropropylene).

Figure E-1. - Continued.



(r) Dacron fabric (ref. 47, p. 40).

(s) Nomex fabric.

(t) Nylon fabric (MIL-C-7219, type III) (ref. 47, p. 36).

(u) Orlon fabric.

Figure E-1. - Concluded.

APPENDIX F

COMBUSTION RATE DATA

This appendix contains figures showing the rate of burning of selected materials as a function of oxygen pressure (or partial pressure). In cases where the test environment was other than 100 percent oxygen, such as air or in mixtures with nitrogen or helium, the pressures plotted are partial pressures (i.e., if the test gas is air at 1 atmosphere pressure, the oxygen pressure plotted is 0.21 atmosphere).

The following table gives the pages on which the combustion rate data for selected materials are shown:

Figure	Material	Page	Figure	Material	Page
F-1(a)	Cotton fabric	194	F-1(k)	Polymethylmethacrylate (rod)	197
F-1(b)	Dacron fabric	194	F-1(l)	Polymethylmethacrylate (sheet)	197
F-1(c)	Epoxy	194	F-1(m)	Polysulfone	198
F-1(d)	Neoprene	195	F-1(n)	Polyurethane	198
F-1(e)	Nomex fabric	195	F-1(o)	Polyvinylchloride	198
F-1(f)	Nomex fabric	195	F-1(p)	Silicone	199
F-1(g)	Nylon	196	F-1(q)	Teflon fabric	199
F-1(h)	Nylon rod	196	F-1(r)	Teflon rod	200
F-1(i)	Poly-benzimidazole	196	F-1(s)	Viton-Fluorel	200
F-1(j)	Polyethylene	197	F-1(t)	Velcro	200

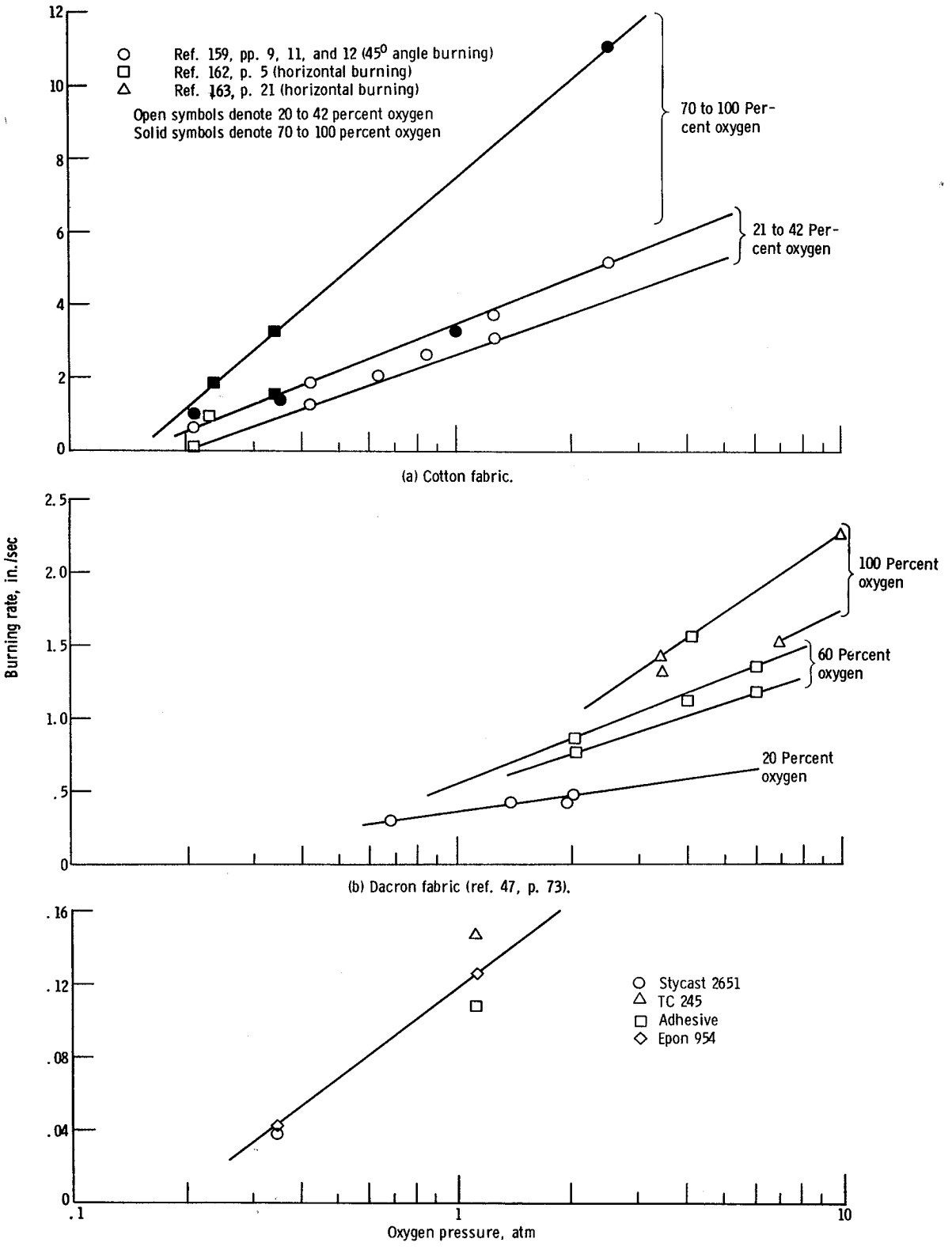
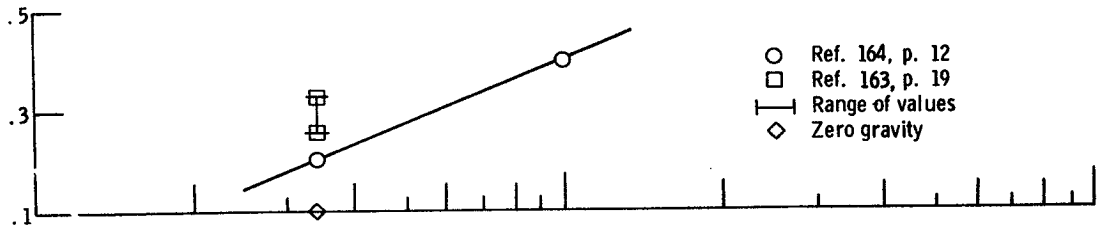
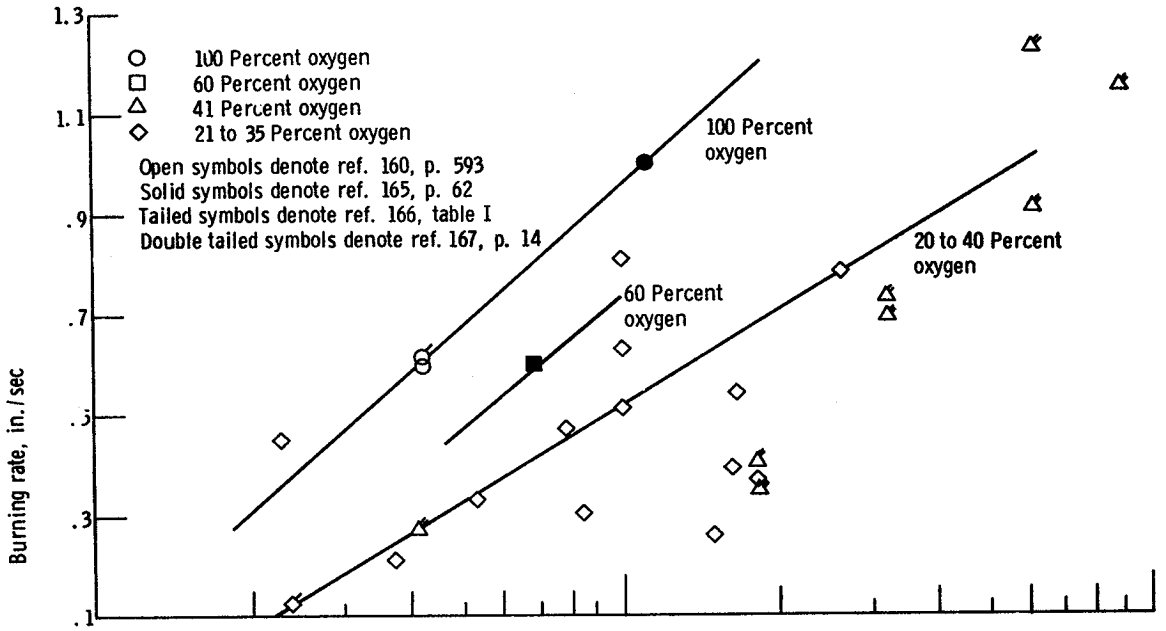


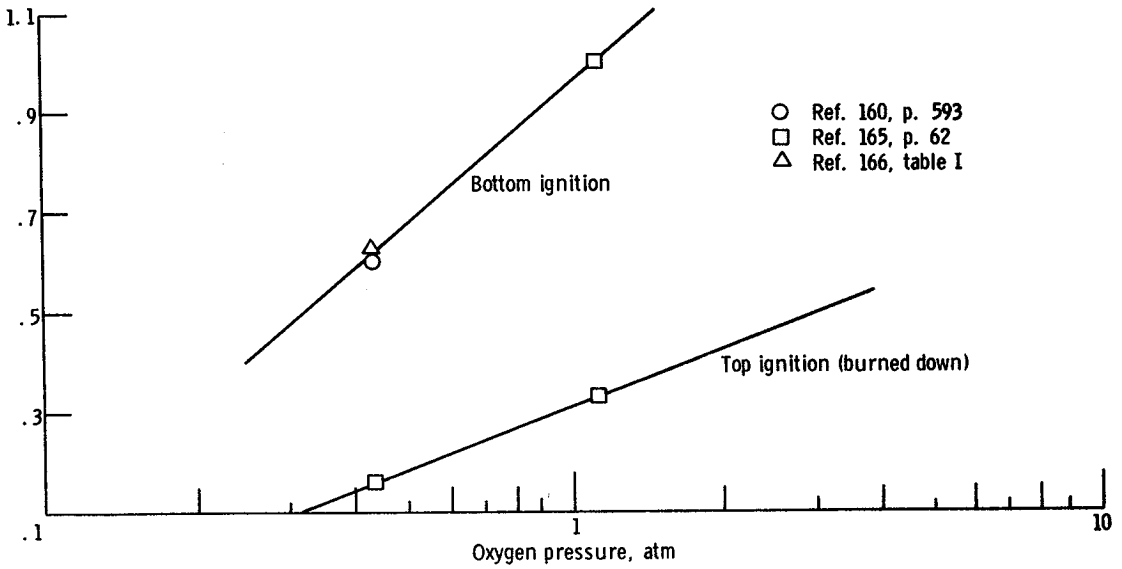
Figure F-1. - Combustion rate data. Lines represent the bestfit of the data based on the authors' interpretation.



(d) Neoprene.

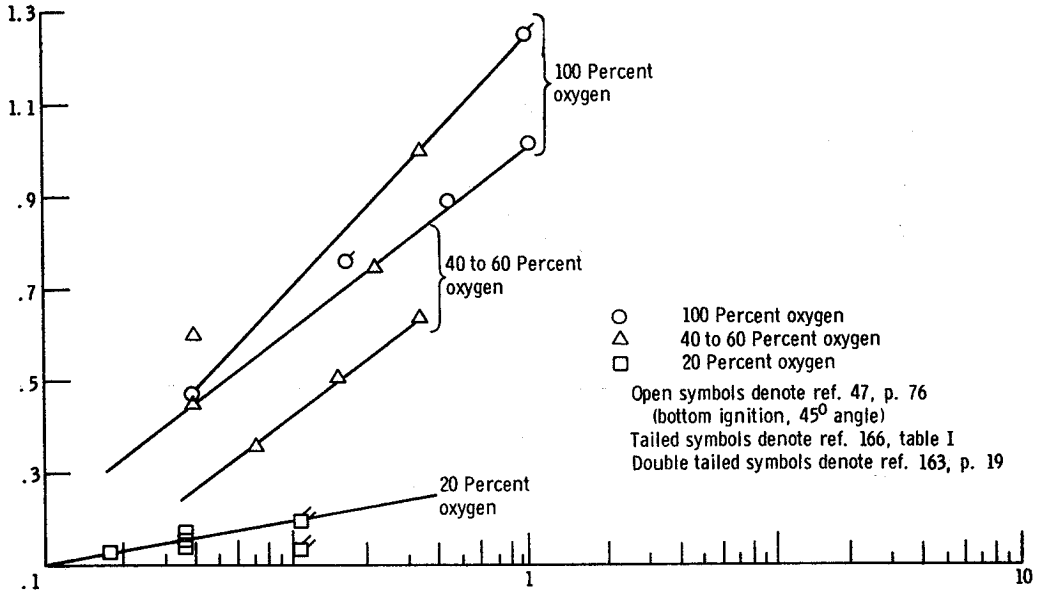


(e) Nomex fabric. Burning at various oxygen concentrations.

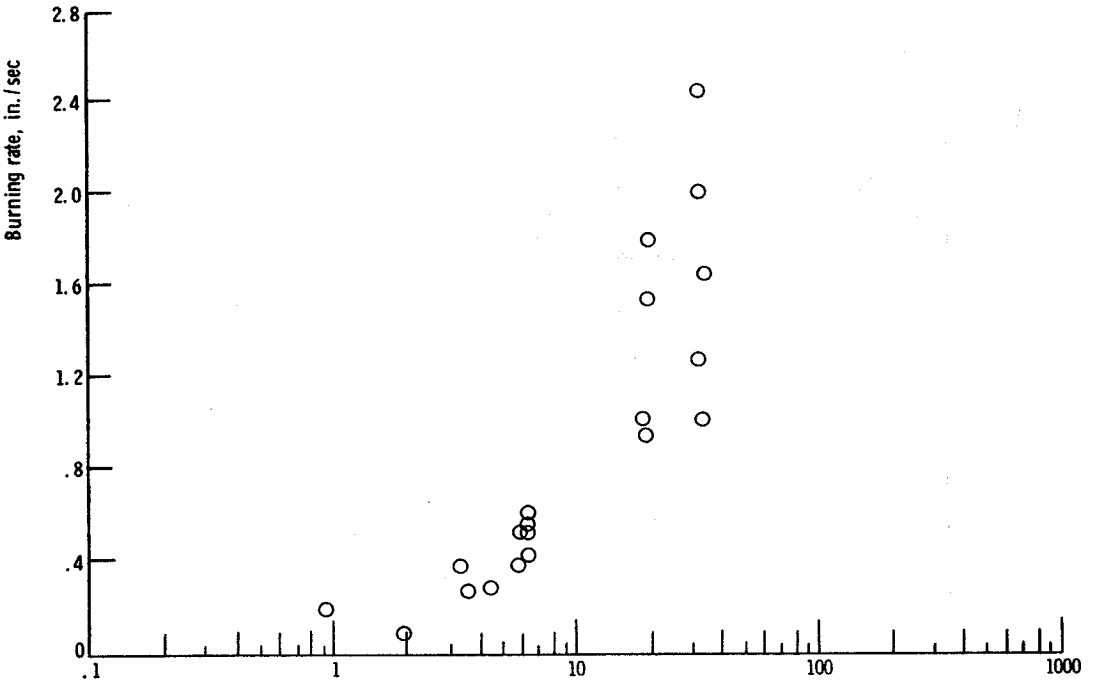


(f) Nomex fabric. Top and bottom ignitions in 100 percent oxygen.

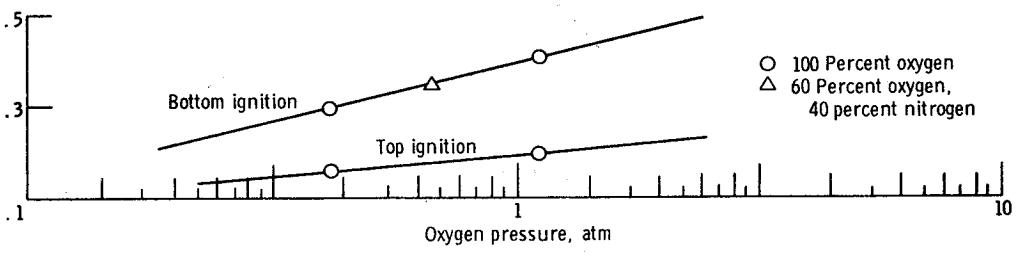
Figure F-1. - Continued.



(g) Nylon.

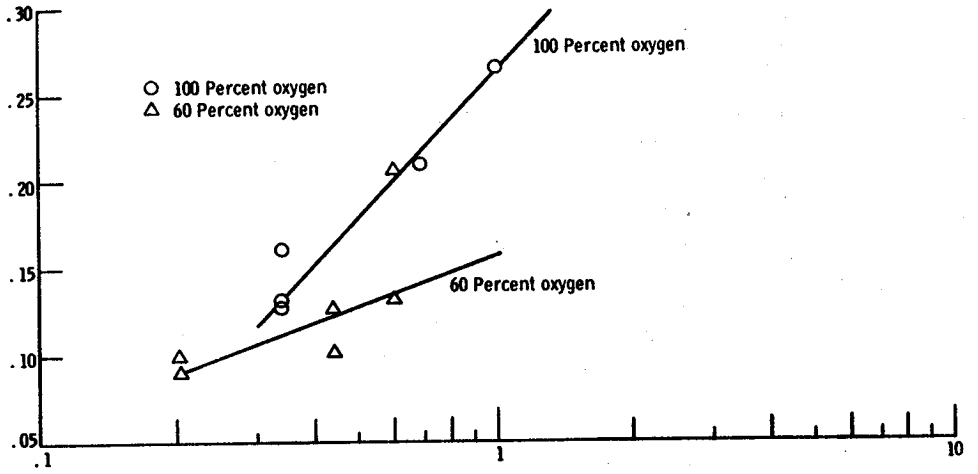


(h) Nylon rod (ref. 168, tables I to III, p. 10).

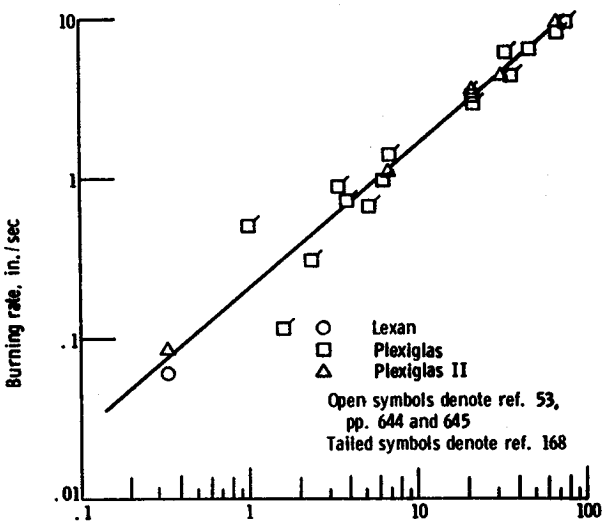


(i) Poly-benzimidazole (ref. 165, p. 62).

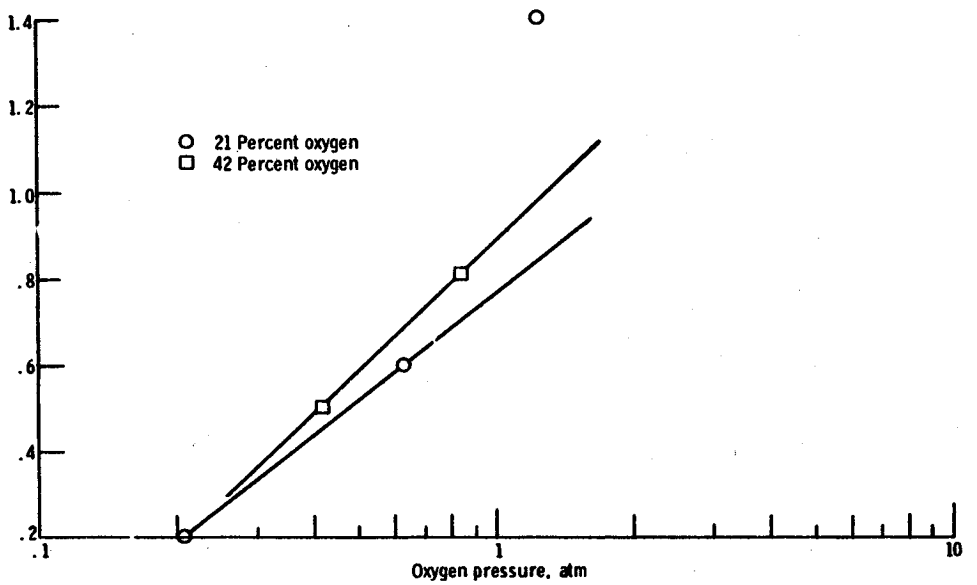
Figure F-1. - Continued.



(j) Polyethylene (ref. 47, p. 70).

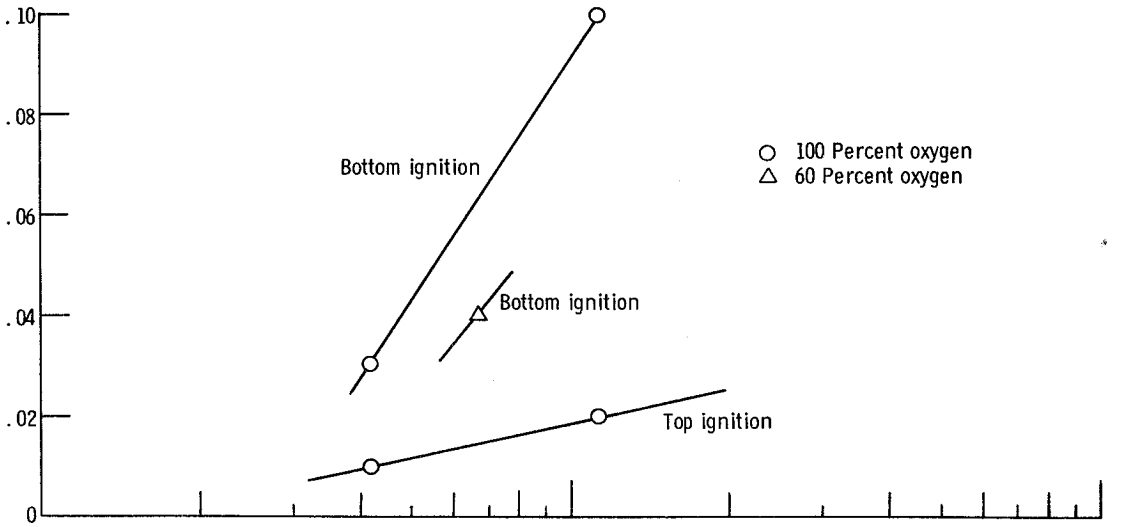


(k) Polymethylmethacrylate (rod).

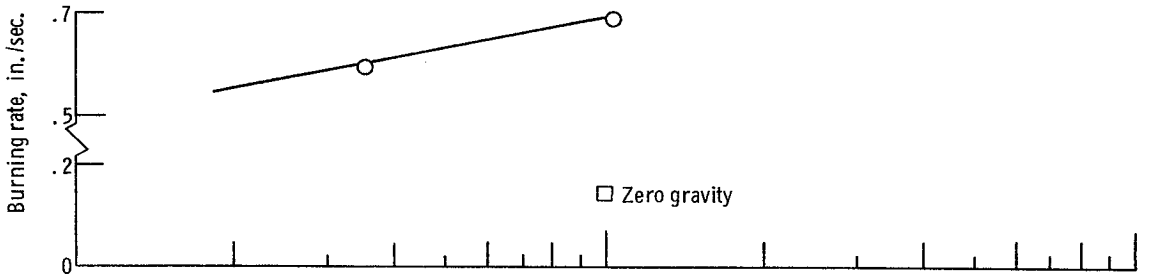


(l) Polymethylmethacrylate (sheet) (ref. 159, p. 11).

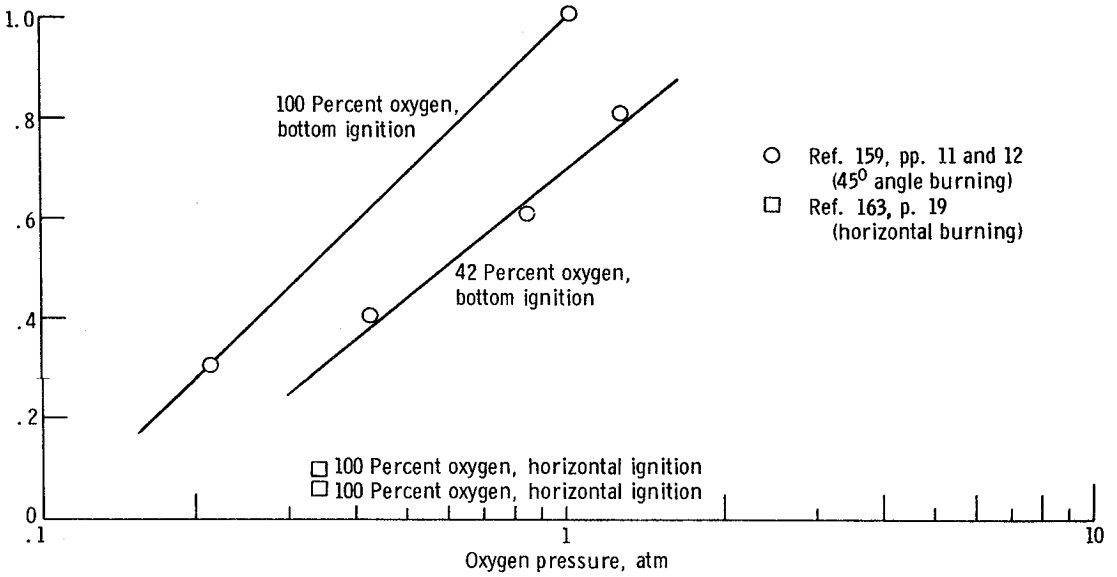
Figure F-1. - Continued.



(m) Polysulfone (ref. 165, p. 63).

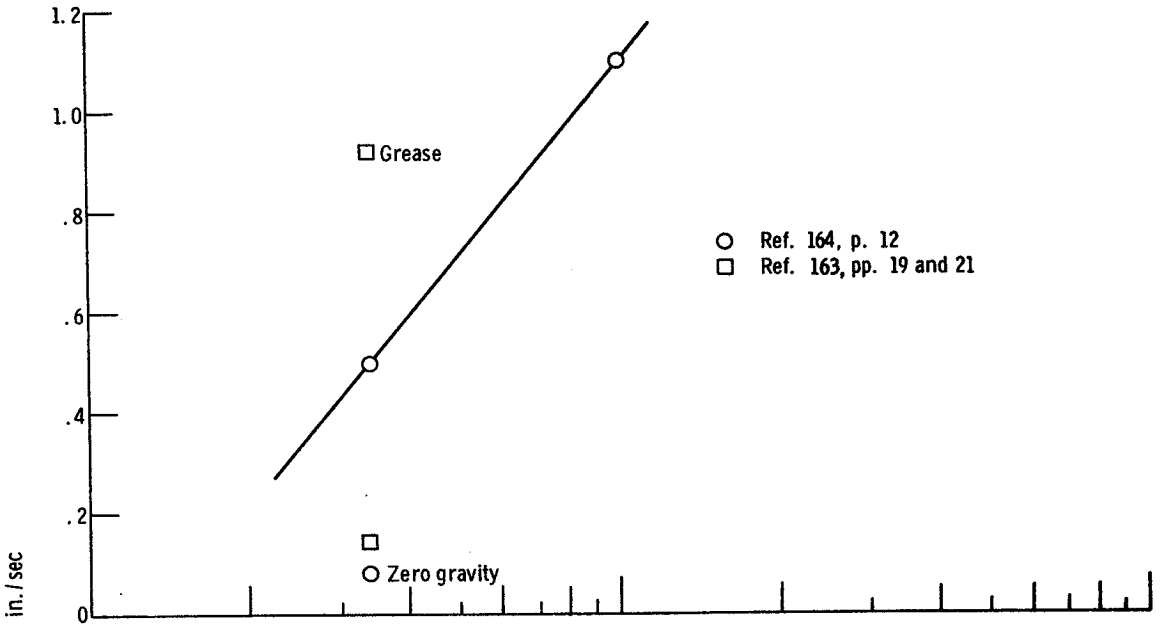


(n) Polyurethane (ref. 164, p. 12). 100 Percent oxygen.

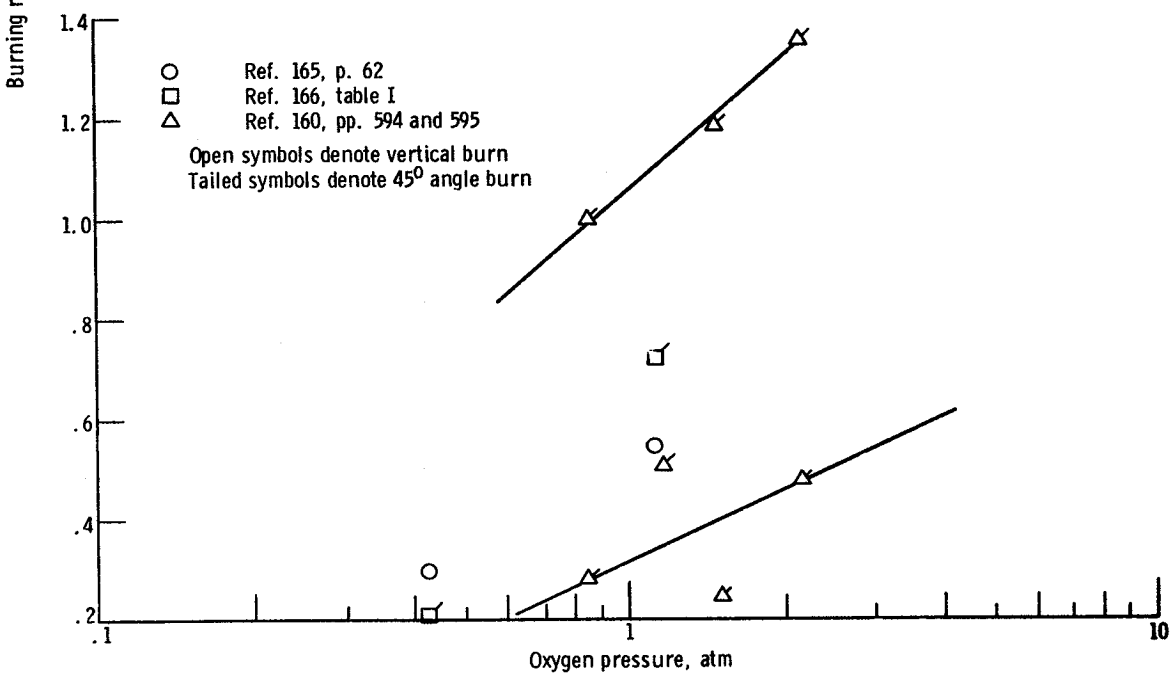


(o) Polyvinylchloride (PVC).

Figure F-1. - Continued.

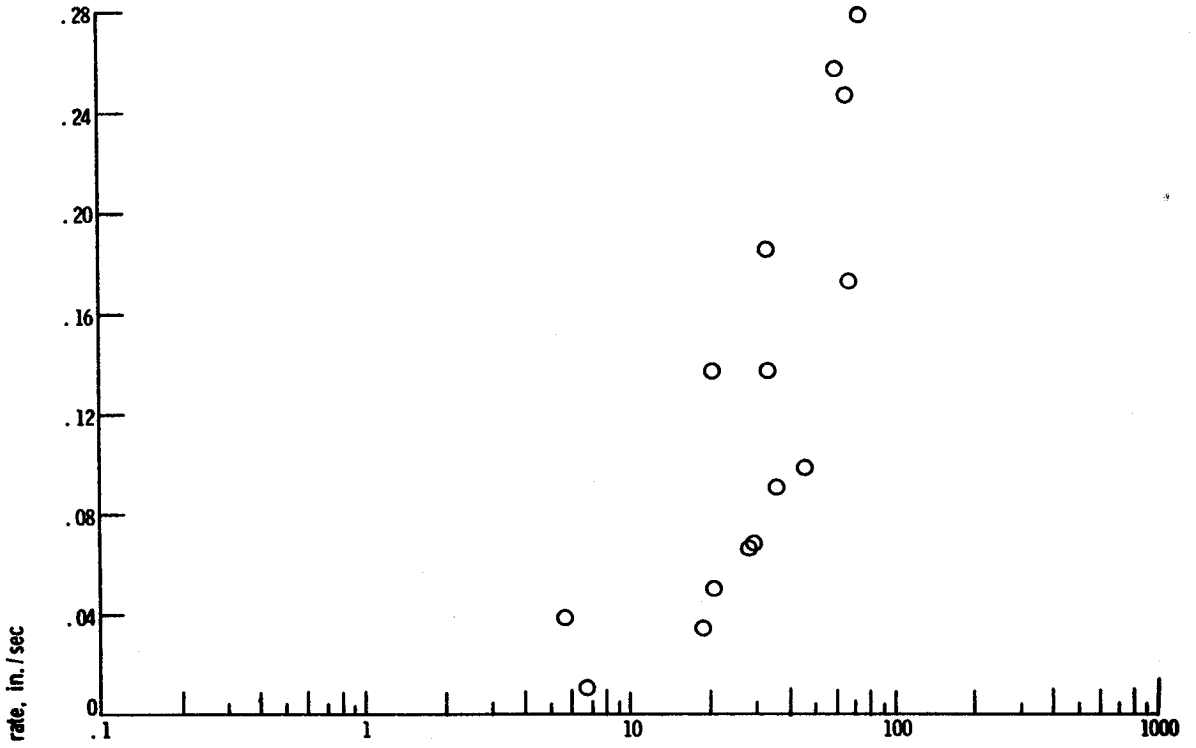


(p) Silicone.

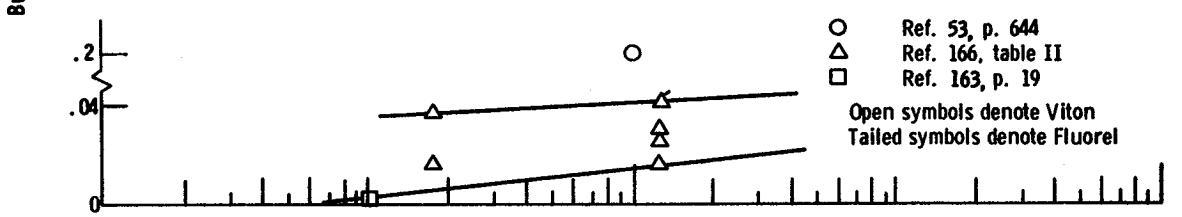


(q) Teflon fabric - bottom ignition (100 percent oxygen).

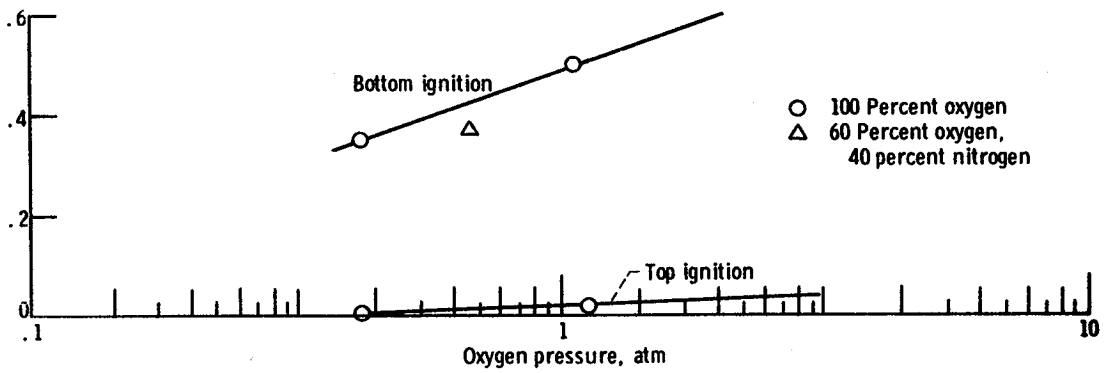
Figure F-1. - Continued.



(r) Teflon rod - top ignition (ref. 168, p. 10).



(s) Viton-Fluorel (copolymer of vinylidene fluoride-hexafluoropropylene).



(t) Velcro (ref. 165, p. 62).

Figure F-1. - Concluded.

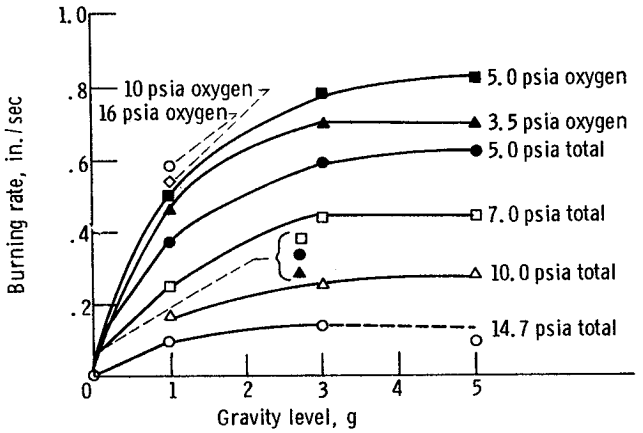


Figure F-2. - Effect of gravity level on burning rate in nitrogen-oxygen mixtures for cotton cloth (ref. 169, p. 26). Oxygen partial pressure in mixtures, 3.5 psia.

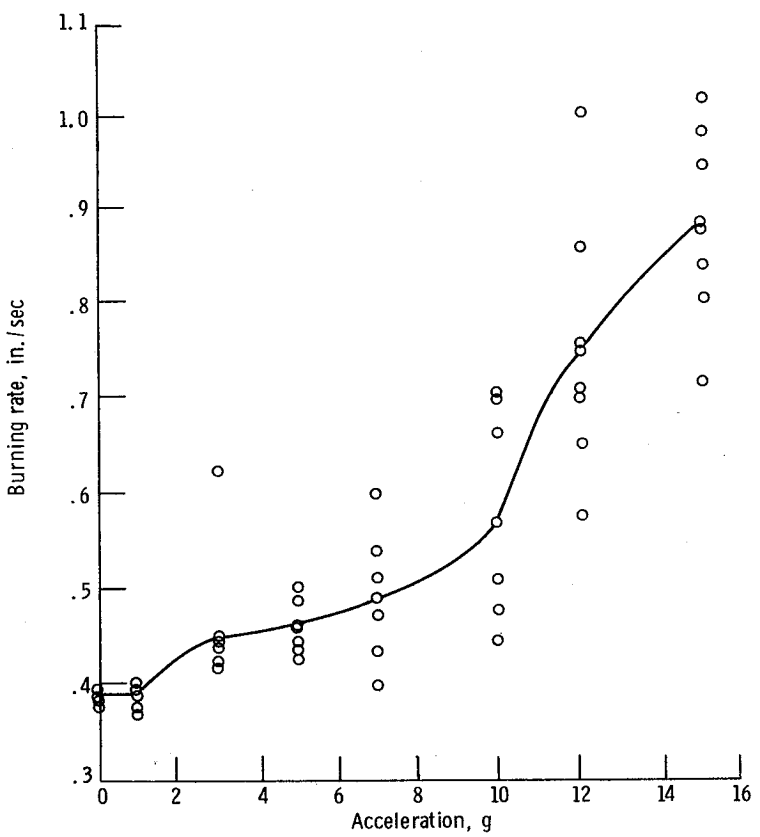


Figure F-3. - Burning rate as function of acceleration for Nomex standard cloth (ref. 170, fig. 1). Burning in direction of acceleration.

REFERENCES

In parentheses after most references are given the Microfiche card numbers denoting the location of the references in the Microfiche supplement and the pages of the references reproduced in the Microfiche supplement.

1. Roder, H. M.; and Weber, L. A., eds.: ASRDI Oxygen Technology Survey. Volume I: Thermophysical Properties. NASA SP-3071, 1972. (Card 1: pp. iii, v, 107-143.)
2. Bailey, B. M.; Sterner, C. J.; and Vignale, V. J.: Study of Liquid Oxygen Contamination, Summary Progress. Rep. 4, Air Products and Chem. Inc. (AD-253231), 1960. (Card 1: 46-59, 60-62.)
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