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Design Guide for High Pressure Oxygen Systems

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16. Abstract

The design of a successful high pressure oxygen system requires special knowledge of materials, design practices, and manufacturing and operational techniques. The current literature on these subject areas is indeed useful in providing a guide to the designer for selection of materials and for determining generalized design approaches for oxygen system and components. However, many of the design subtleties, techniques, and related knowledge, presently in use in aerospace applications, have not been reported in the literature. Consequently, to assure the availability of this important information to designers of future systems, the research, experience, and practical knowledge gained from designing systems for the manned space flight program during the past 20 years is incorporated into this document. The engineers from JSC and White Sands Test Facility have compiled and formatted this document to provide a ready and easy reference for designers of any high pressure oxygen system.

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NOTE

While NASA does not endorse commercial products, this document, in reporting the results of materials testing, of necessity uses specific trade names of the materials tested. This use does not imply that there are no suitable substitutes available; however, the reader is cautioned that substitute materials should be subjected to the same stringent test requirements that the reported materials have undergone. The guidelines in this document are presented in the spirit of responsible communication of the results of research and development. Neither the U.S. Government nor any person acting for the U.S. Government assumes any liability resulting from the use of the information contained in this document.

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1. INTRODUCTION

Oxygen is a relatively energetic reactant at normal ambient conditions and becomes more highly reactive with increases in pressure. At very high pressures it becomes extremely reactive. The successful design, development and operation of high pressure oxygen systems requires special knowledge of materials, design practices, test phenomena, and manufacturing and operational techniques.

During the course of the manned space flight programs, a great deal of research and testing has been conducted by the Government and its contractors to develop high pressure oxygen systems used in the propulsion, power, and life support systems of manned vehicles. To support such varied applications, testing has covered a broad spectrum of environmental and operating conditions. As a result of this research and testing, a wealth of test data and knowledge has been amassed on the reactivity of a wide variety of metallic and nonmetallic materials in high pressure environments. (For example, ref. 3, JSC-02681.) Another current data base on the properties and behavior of oxygen in its various states has been compiled in the nine-volume Oxygen Technology Survey, sponsored by NASA's Aerospace Safety Research and Data Institute (ASRDI), 1972-1975 (ref. 1). Additionally, in reference 2, Clark and Hust have provided a thorough review of a large number of reports on the oxygen compatibility of both metallic and nonmetallic materials. These and other related sources published in the current literature are indeed useful in providing a guide to the designer for the selection of materials and for determining generalized design approaches for oxygen components and systems. However, many of the design subtleties, techniques, and related knowledge, presently in use in aerospace applications, have not been adequately reported in the literature.

Our experiences have proved that a successful high pressure oxygen system is not necessarily achieved merely by selecting the most oxygen compatible materials available. Because, even the best materials have limitations, innovative design features and techniques must be employed to make up for material deficiences. Space program engineers have gained considerable understanding of the effects of geometry on the design of oxygen system components and have developed design features directed at overcoming some of the physical limitations of materials. Much has been learned about unsafe and undesirable design practices. Advancing technology, with the attendant demand for storage and use of oxygen at increasing pressures and flow rates, makes it imperative that this design expertise and knowledge be well understood and documented for application by the future developers of space flight hardware.

Therefore, the primary purpose of this handbook is to document and provide a repository for critical and important detailed design data and information, hitherto unpublished, along with significant data on oxygen reactivity phenomena with metallic and nonmetallic materials in moderate to very high pressure environments. The authors, representing several divisions of the Engineering and Development Directorate of the Johnson Space Center and its White Sands Test Facility, have compiled and formatted this data and information to provide a ready and easy to use reference for the guidance of designers of future propulsion, power and life support

systems for use in space flight. This document, which very clearly illustrates both good and bad design practices, is applicable not only to aerospace designs, but also to designs for industrial and civilian uses of high pressure oxygen systems. The information presented herein are derived from data and design practices involving oxygen usage at pressures ranging from about 20 psia to 8000 psia equal with thermal conditions ranging from room temperatures up to 500° F.

2. IGNITION MECHANISMS

The number of potential ignition sources that could be present in even a simple component intended for high pressure oxygen service is quite large and varied. For example, electrical sensors or heaters can fail and cause arcing, sparking or overheating which lead to ignition. Small contamination particles, both metallic or nonmetallic, can be accelerated to sonic velocities in high flow regions of the component and lead to impact ignition of susceptible materials. Contamination can also collect in stagnant regions of a component and be heated to ignition by pneumatic shock or adiabatic compression.

Actuation can cause impact loading of valve seats or other detail parts resulting in failure of the parts or mechanically induced ignition. Failure to consider material hardness differences can result in galling of rubbing surfaces which can cause both functional failure or ignition. Chatter and subsequent fretting can result from unbalanced airloads.

Cavity resonance leading to ignition of trapped contaminants can occur in blind passages upon system actuation. Flow induced vibration leading to system failure can also occur in bellows and lines where system design of support structure is not adequate. Flow induced cavitation in LO_2 systems may result in formation of ignition susceptible fresh surfaces.

Consideration of ignition mechanisms should include all of those factors listed above and should be covered during design of both components and systems. While this listing covers the most frequently observed ignition sources, it is not considered to be exhaustive. A careful failure modes and effects analysis which includes ignition as a failure mechanism should be conducted as a part of each new design.

3. MATERIAL SELECTION

Materials currently used in high pressure oxygen systems range from ignition-resistant materials like Monel 400 to materials of widely varying ignitability like butyl rubber and the silicones. The range of ignitability as a function of pressure is illustrated in figure 1 for nonmetallics and in figure 2 for metals.

The material selection process has historically been guided by considerations of functional acceptability and light weight, with only secondary consideration being given to the possibility - or ease - of ignition. Many currently used materials appear to work primarily because the design in some way protects the ignition-susceptible material or because no particle with sufficient energy to ignite the system has yet impacted it. While functional performance is obviously a very important requirement in the design of high pressure oxygen systems, the incidence and severity of fires indicates that selection based on ignition resistance is at least equally important.

While material selection alone cannot preclude ignition from these mechanisms, proper choices can markedly reduce the probability of ignition. For example, ignition induced by mechanical impact can be minimized by selecting valve seats and balls that do not shatter under normal loading. Galling can be largely eliminated if potential rubbing surfaces are made from materials with widely differing hardnesses. For all types of ignition mechanisms, selecting materials that have relatively small exothermic heats of combustion (like Monel 400 and Inconel 718) will reduce not only the probability of ignition but also the probability of propagation. Materials with high heats of combustion (stainless steels) or very high heats of combustion (aluminum alloys) should be avoided wherever possible. A summary of typical heats of combustion as well as other properties for some currently used materials is given in table 1.

MATERIAL TESTS

Over the past 20 years a large number of different types of tests (ref. 2 - ASRDI, Vol. IX, 1975) have been developed and evaluated by various groups, both public and private, in an attempt to find test methods that would predict materials behavior in planned applications. For nonmetallic materials, both mechanical and pneumatic impact tests have been studied. For metals, tests studied have included promoted ignition, mechanical and particle impacts, rubbing or rotating friction, and arc or spark ignition, with a number of variations on each type. To date, no single test has been developed that can be applied to all materials, both metals and nonmetals, to produce either consistent relative rankings or absolute ignition limits as a function of oxygen pressure alone. The tests that appear to show the greatest predictive ability are as follows.

1. Nonmetals - Test No. 13 in NHB-8060.1B, "Ambient Liquid Oxygen and Pressurized Liquid and Gaseous Oxygen Mechanical Impact Tests" (ref. 4)

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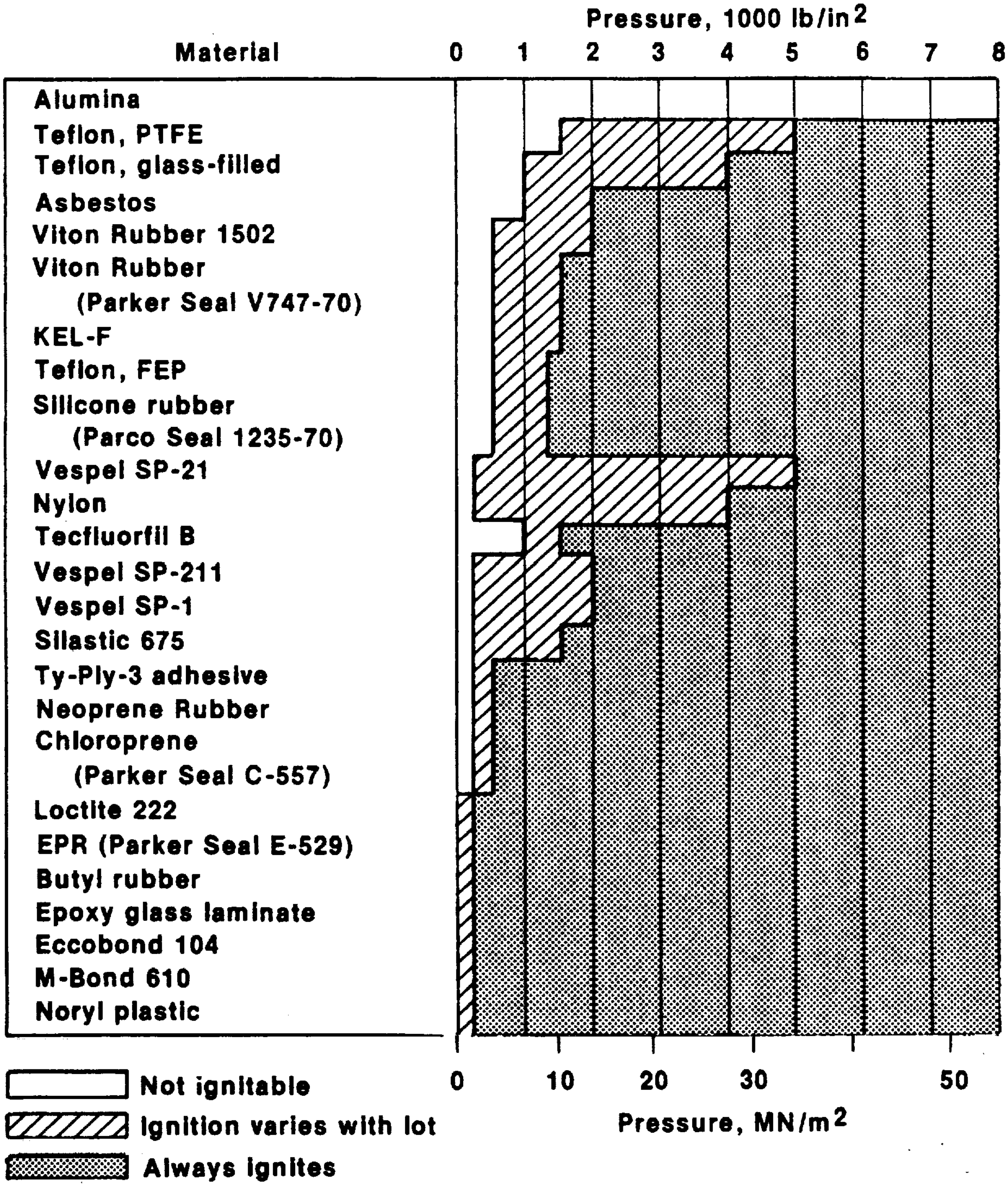

Figure 1.- Range of ignitability for nonmetallics.

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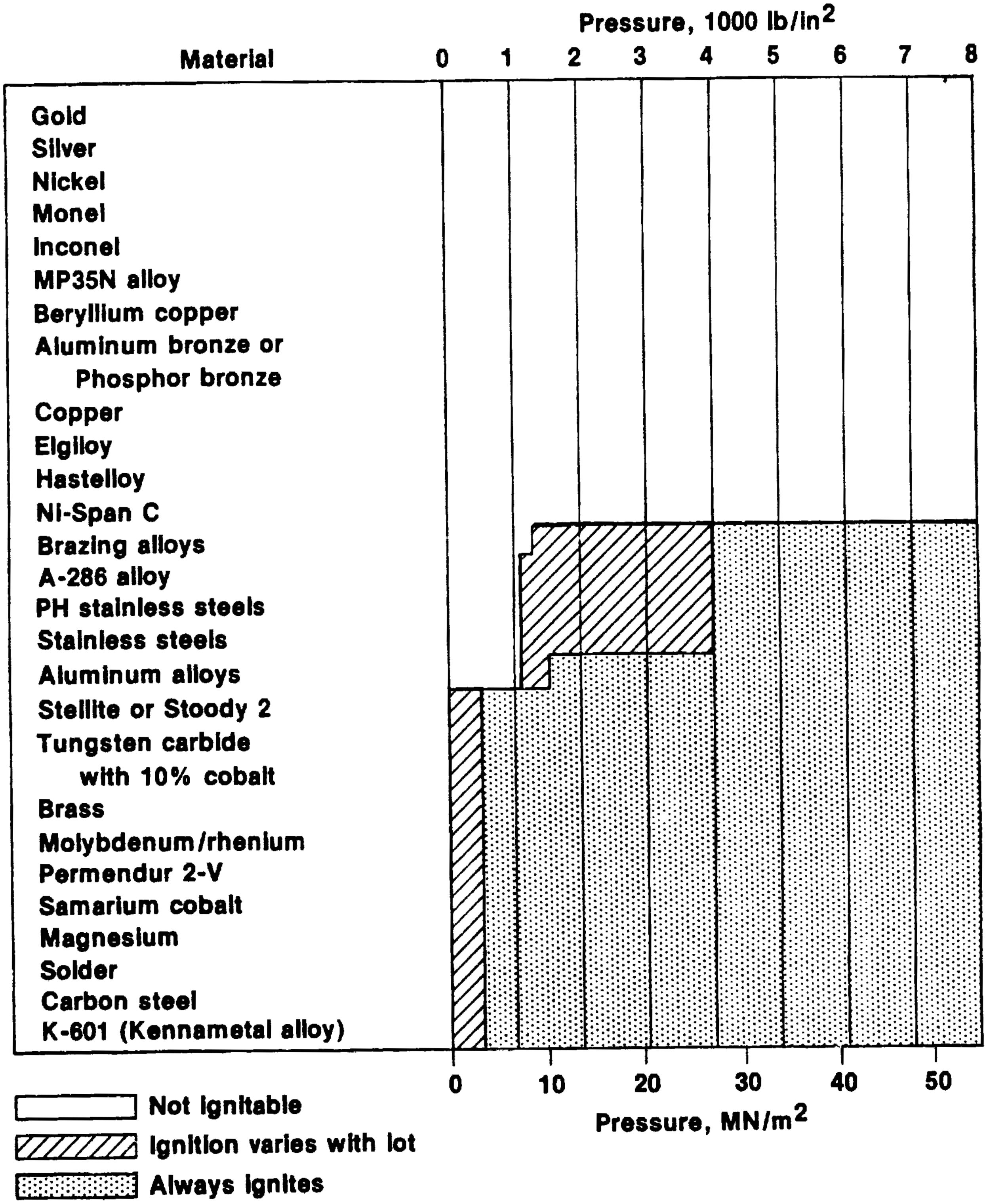

Figure 2.- Range of ignitability for metals.

TABLE 1.- PHYSICAL PROPERTIES OF TYPICAL OXYGEN SYSTEM METALLIC MATERIALS

Material	Density, lb/in^3 (kg/m^3)	Ultimate tensile strength 1000 lb/in^2 (MN/m^2)	Max. use temp., ^oF (K)	Heat of combustion, Btu/lb (MJ/kg)	Impact ignition sensitivity pressure threshold lb/in^2 (N/m^2)
Aluminum alloys	0.10 (2800)	40 (276)	350 (450)	130 000 (302)	1050 (7.24)
Stainless steel	0.28 (7800)	140 (965)	950 (783)	33 500 (77.8)	1050 (7.24)
Inconel 718	0.30 (8300)	180 (1240)	1200 (922)	15 100 (35.1)	8000 (55.2)
Monel 400	0.31 (8600)	145 (1000)	1000 (811)	14 200 (33.1)	8000 (55.2)

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This test is a modified form of the Army Ballistic Missile Agency (ABMA) impact test, which has been in use for over 20 years. A schematic of the test fixture is shown in figure 3. In essence, samples of the material being tested are impacted at 368 ft-lb/in^2 (772 kJ/m^2) with oxygen at the pressure and temperature of intended use. Twenty specimens are tested from each lot of material. If two or more specimens react, the lot is rejected. If only 1 specimen of 20 reacts, an additional 40 specimens are tested and, if no more reactions occur, the lot is accepted. Thousands of materials have been tested and, to date, no component ignitions have been attributable to materials that have passed this test when used within the limits (temperature, impact energy, and pressure) of the test envelope. A comprehensive listing of test results obtained for a wide variety of materials is given in JSC-02681.

2. Metals - White Sands Test Facility (WSTF) Particle Impact - TR-277-001 - "Metals Ignition Study in Gaseous Oxygen"

This recently developed test has demonstrated the ability to discriminate between ignitable and non-ignitable metals at pressures up to 6000 lb/in^2 (41 MN/m^2). The test fixture in figure 4 involves impact of candidate metallic specimens with typical particles in the 100 to 1000 micron range at sonic velocities with oxygen at the temperature and pressure of intended use. Experience to date indicates that this test could be adopted as a meaningful method for selecting metals for use in oxygen systems.

The particle ignition pressure is defined as "the pressure below which the maximum sized particle which can penetrate the components filters and moving at sonic velocity will <u>not</u> ignite the material."

BATCH/LOT TESTING

As is readily apparent from the data shown in figure 1, many nonmetallic materials show a significant range of reaction pressures when different lots of material from the same source are tested using identical methods. The reasons for this variability are not understood in detail and are probably different for each material tested. As a result, prediction of the test behavior of a given lot of material is possible in only a limited number of cases. Except for materials that have been proved acceptable by tests of at least 10 lots of material without a single failure, each new lot of material must be experimentally proved acceptable. Materials that have passed the necessary testing and have been found to be insensitive to batch/lot variation are shown in table 2.

When the materials that will function in a design range from those that do not require batch control to those that always ignite at the design pressure, the selection logic varies with the sensitivity of the material. Figure 5 illustrates the selection and control logic we have developed for high pressure oxygen systems. It should be noted that using batch/lot insensitive and batch/lot tested materials below their ignition pressure significantly simplifies the test requirements, documentation, and review.

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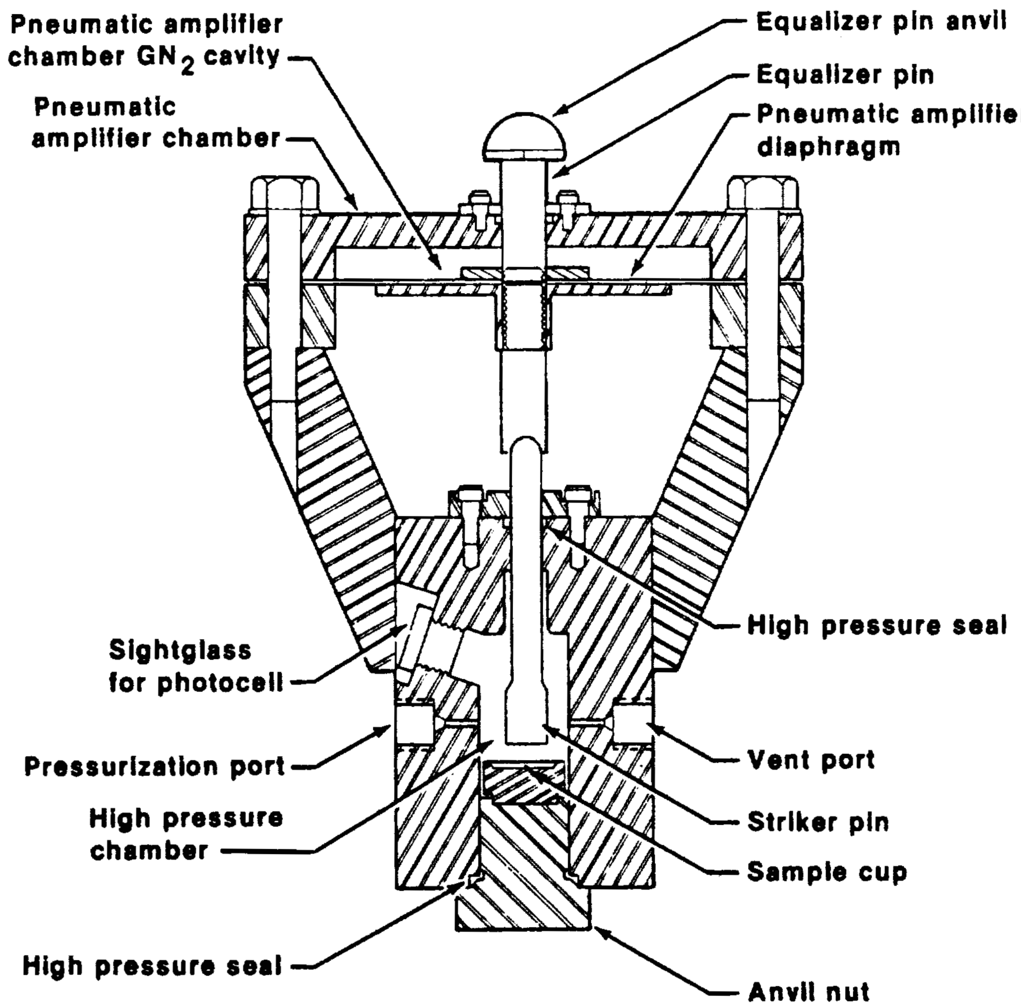

Figure 3.- Pressurized mechanical impact test chamber drawing.

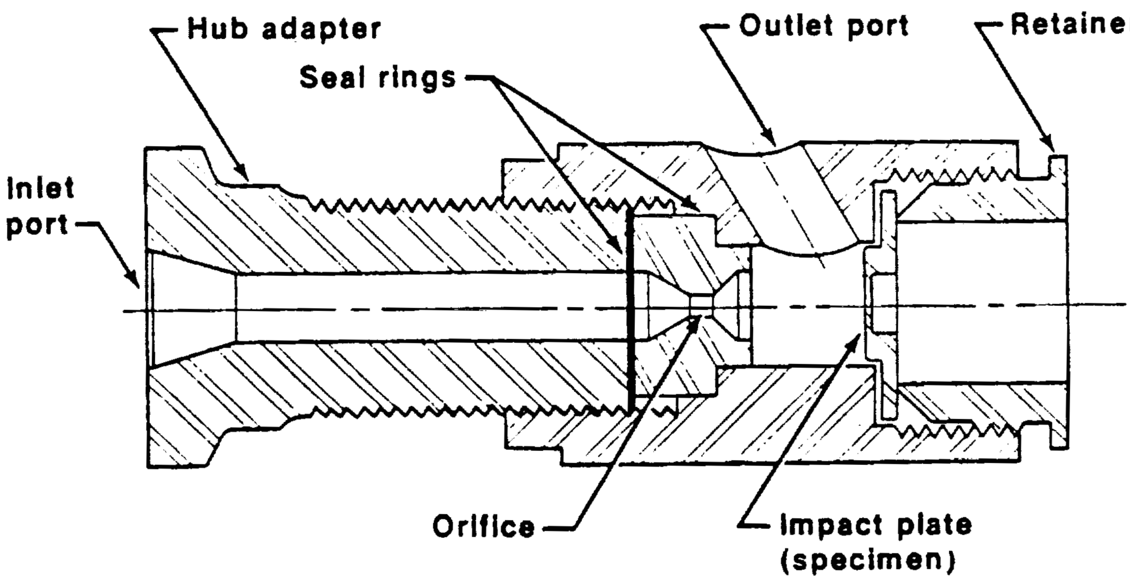

Figure 4.- White Sands Test Facility high velocity (sonic) impact plate test fixture.

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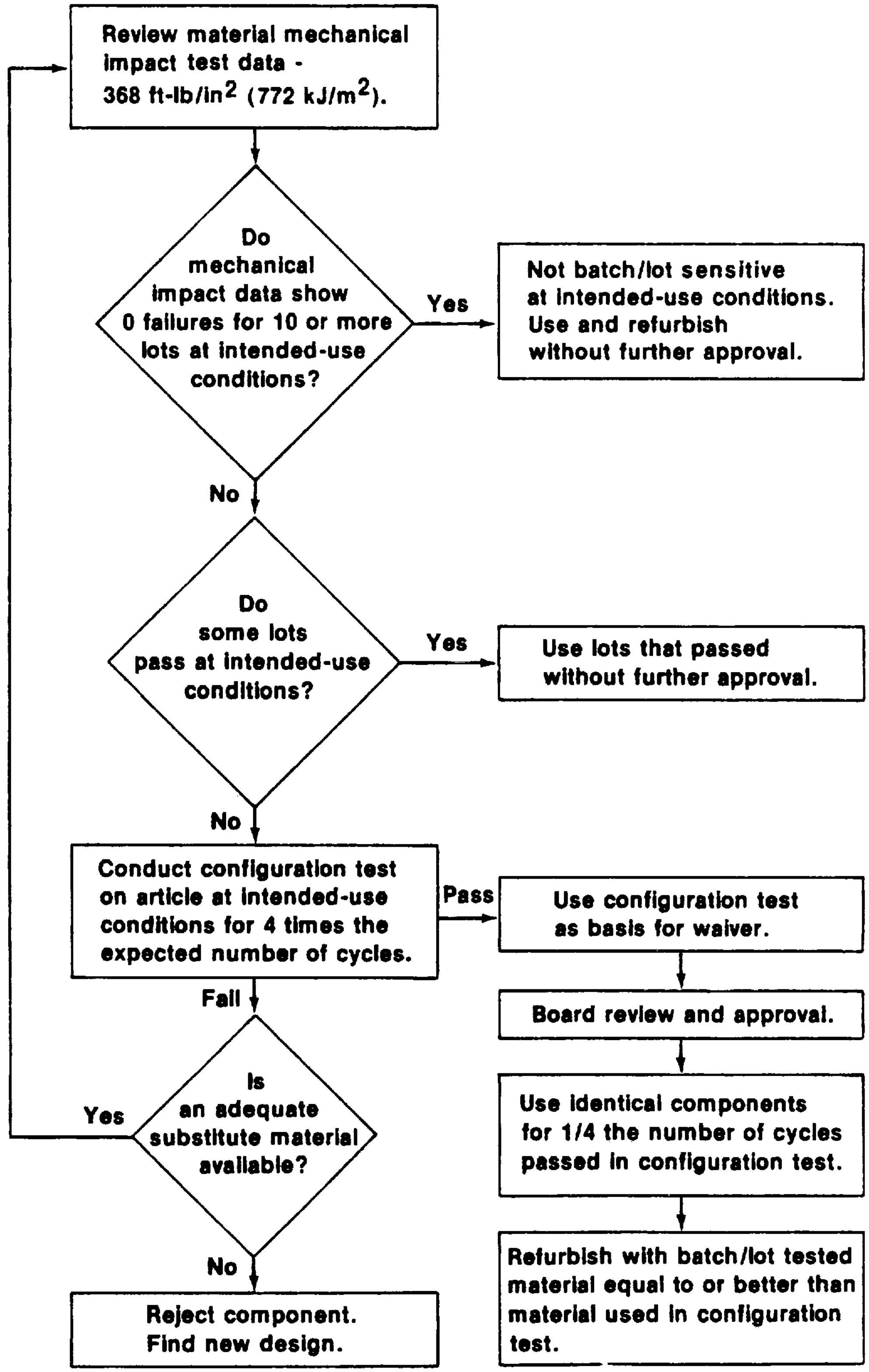

Figure 5.- Nonmetallic materials control logic.

TABLE 2.- MATERIALS THAT DO NOT REQUIRE BATCH CONTROL

Material	Type of Material	Fluid	Max. temp., °F (K)	Max. pressure, lb/in^2 (MN/m^2)
*Everlube 812	Dry film lubricant	GOX LOX	530 (550) -297 (90)	5500 (38) 1000 (6.9)
*Microseal 100-1	Dry film lubricant	GOX LOX	200 (366) -297 (90)	1000 (6.9) Ambient
*Microseal 200-1	Dry film lubricant	GOX LOX	200 (366) -297 (90)	3300 (23) 1000 (6.9)
*Triolube 1175	Dry film lubricant	GOX LOX	350 (450) -297 (90)	3300 (23) 1000 (6.9)
Krytox 240 AB	Grease	GOX LOX	250 (394) -297 (90)	1000 (6.9) 1000 (6.9)
Krytox 240 AC	Grease	GOX	150 (339)	6000 (41)
Braycote 3L-38RP	Grease	GOX	540 (555) -297 (90)	4400 (30) 1000 (6.9)
Teflon, PTFE	Plastic	GOX LOX	250 (394) -297 (90)	1000 (6.9) 1000 (6.9)
25% glass-filled Teflon	Plastic	GOX LOX	150 (339) -297 (90)	1000 (6.9) 1000 (6.9)
Rulon A	Plastic	LOX	-297 (90)	600 (4.1)
KEL-F	Plastic	GOX LOX	150 (339) -297 (90)	500 (3.4) 400 (2.8)
Viton Rubber 1542/1441	Elastomer	GOX	250 (394)	135 (0.93)
Tecfluorfil B	Plastic	GOX LOX	200 (366) -297 (90)	200 (1.4) 275 (1.9)
Vespel SP-1	Plastic	GOX	150 (339)	250 (1.7)
Viton Rubber (Parker Seal V747-70)	Elastomer	GOX	150 (339)	250 (1.7)
Armalon TG-4060	Fabric	GOX	275 (408)	400 (2.8)

*Maximum use pressure on these dry film lubricants is the maximum pressure where 10-batch data are available. These lubricants may be acceptable at higher pressures, but additional testing is required for proof.

CONFIGURATION TESTING

If it is not possible to find, even with batch/lot testing, materials that meet the functional requirements of a design, it may be possible to provide sufficient protection from ignition to permit use of a susceptible material. If this design approach is used, then it is mandatory that the adequacy of the design be demonstrated by configuration testing at conditions more severe than the expected worst-case use environment for the component in question.

For configuration testing to be considered valid, the tests should be conducted on hardware identical to the proposed use hardware. Substitute nonmetallics should be batch/lot tested to provide a replacement baseline even though the material will not pass the standard impact tests in the expected use environment. Only nonmetallics that equal or exceed the batch/lot rating of the original material used in the configuration tests should be used to refurbish the components.

The configuration tests should use oxygen pressures at least 10 percent above the worst-case use condition. Expected temperature limits should be exceeded by at least 50° F (24 K). And, if the material is to be subjected to rapidly changing pressures, the pressure rise rate used in the configuration tests should be at least twice that which the component is expected to experience in operation.

If cycling or multiple reuse of the component is a design requirement, then the configuration testing should exceed by a factor of 4 the expected number of cycles or reuses. Failure of the configuration test article before completion of the required number of cycles would limit the use life of the component to 1/4 the number of cycles actually completed before failure.

MATERIAL RECOMMENDATIONS

The materials listed in table 3 have demonstrated superior resistance to ignition and fire propagation in high pressure oxygen systems. Valve and pressure vessel materials are examples. The stainless steels normally used for valve stems, bodies, and springs are potentially combustible in high pressure oxygen systems. Monel alloys, which are self-extinguishing in oxygen fires, are available in the necessary range of hardnesses. K-Monel can be used for the valve stem and 400-series Monel for the valve body. Springs can be wound from Monel wire. Though small diameter Monel wire is not currently available, miniature springs can be made of Elgiloy. Sapphire poppet balls should replace tungsten carbide or steel balls because sapphire has a lower level of reactivity (and therefore is less combustible) than either tungsten carbide or steel and it is more resistant than tungsten carbide to breakup under a mechanical impact. Titanium and its alloys, normally attractive as candidate materials for pressure vessels because of their high strength-to-weight ratios, cannot be used for oxygen vessels because they are impact sensitive in oxygen. Inconel is a good choice for the vessels to contain high pressure oxygen. Utilization of these materials, particularly when they are used in conjunction

TABLE 3.- RECOMMENDED MATERIALS

Application	Material
Component bodies	Monel Inconel 718
Tubing and fittings	Monel Inconel 718
Internal parts	Monel Inconel 718 Beryllium copper
Springs	Beryllium copper Elgiloy Monel
Valve seats	Gold or silver over Monel or Inconel 718
Valve balls	Sapphire
Lubricants	Batch/lot tested* Braycote 3L-38RP Batch/lot tested* Everlube 812 Krytox 240 AC
O-seals and backup rings	Batch/lot tested* Viton Batch/lot tested* Teflon
Pressure vessels	Inconel 718

*Usage should be limited to temperatures less than or equal to those listed in table 2.

Note: Titanium and its alloys are impact-sensitive in oxygen atmospheres and therefore may not be used in oxygen systems.

with the design, manufacturing, inspection, and test techniques recommended in other sections of this document, should result in components with the lowest risk of fire possible in today's state of the art.

In no case should an alloy be used at an oxygen pressure above its particle ignition pressure. This criterion would limit the use of aluminum alloys and stainless steels to pressures below 1050 lb/in^2 (7.24 MN/m^2) to allow some margin for error in test results and impact predictions.

Only those nonmetallic materials which have been found to be batch/lot insensitive or have been batch/lot tested should be used for original or replacement component parts. Even in cases where the design is justified by configuration testing, only those materials which have been shown by test to be at least as good as those used in the configuration tests should be used.

Off-the-shelf equipment or slightly modified current designs should not be used in high pressure oxygen systems to save money, time, or weight, unless it can be shown that at the operating pressure limit the materials used are "not ignitable" in accordance with the values given (with some margin) in figures 1 and 2.

4. COMPONENT DESIGN

The purpose of this section is to document improved high pressure oxygen component design techniques which have been developed. The examples that follow are drawn from actual oxygen systems. Most of the problems illustrated were discovered in hardware tests or use and the solutions shown are, for the most part, those which we have successfully implemented. In these examples, we offer specific suggestions for the design of component housings and valve parts, for the use of seals and filters, and for the design of ancillary equipment. The major problems addressed include ignition of metallics and nonmetallics, adiabatic compression, mechanical overstress, seal erosion, and contamination generation and control. Some of the guidelines are intended for use in original design, where maximum benefit can be obtained. Others are examples of less-than-ideal configurations, each of which proved to be the best achievable fix to a problem that occurred in an existing component.

The designer is cautioned that in addition to the standard analyses relating to component or system function (stress, throughput, etc.) there are certain additional special analyses that are considered mandatory to the proper design of oxygen systems and which must be considered in the design process. These are as follows.

1. Examination of regions for the generation of potential acoustic resonant conditions and also where particulate contamination could be accelerated to high velocities.

2. Calculation of mechanical impact energies for moving parts, particularly valve seats and poppets. The impact energies should be kept as low as possible, with values less than 10 ft-lb/in^2 clearly being safe.

3. Pressure rise rates caused by actuation should be determined. Values below 2000 psi/second are considered acceptable.

4. Resonant frequencies of lines and components should be compared to flow induced component frequencies to insure that flow conditions do not generate destructive vibrations.

5. Failure modes and effects analyses should consider not only the known and potential ignition mechanisms but also the effects of component functional failures.

6. Single barrier failure analyses should be conducted to determine whether barrier failures or leaks can expose susceptible materials to high pressure oxygen.

7. To prevent cavitation in liquid oxygen (LO_2) systems an analysis should be conducted to insure that the system pressures exceed the LO_2 vapor pressure by at least 2 psi for all flow conditions which the system is expected to see.

COMPONENT HOUSINGS

The housing generally contributes the greatest proportion of weight and combustible matter to the component assembly. This mass is due to its function as the enveloping structure and as a pressure containment vessel, which requires substantial material thickness to keep stresses acceptably low. Since housings do constitute so much of the mass, the selection of housing material is especially important in fire-sensitive oxygen systems.

High pressure oxygen system components for portable or flight use must be lightweight, so it may appear to be desirable to build their housings from such lightweight metals as aluminum. Such metals, however, have limited fire resistance and their use results in an increased combustion hazard. Aluminum may be used for an oxygen system only when pressure, flow velocity, and pressurization rates are low. In such applications, an analysis of adiabatic heating should be performed to assure acceptability. For higher pressures, higher flow velocities, or higher pressurization rates, Monel and similar alloys, which have much greater fire tolerance, must be used and the additional weight penalty accepted as necessary for system safety.

To offset this additional weight, some weight reduction techniques can be used, such as trimming the exterior surfaces in areas where stress levels are low. However, the designer should use caution. Some guidelines on using this technique and on avoiding hazardous thin walls, blind passages, feathered edges, burrs, and flow impingements are included in the following discussion of component housing problems and solutions to them.

Thin Walls

Problem:

The walls between inner cavities or passageways and the outer surface of component housings may become so thin that stress concentrations result when pressure is introduced. Since geometries both inside and outside can be complex, it may not be obvious from drawings or even from direct inspection that such thin, highly stressed areas exist. If such walls become too thin, they may rupture under pressure loading. This sudden rupture results in an energy conversion that raises the temperature in the rupture zone. The failed section can expose bare, jagged metal which oxidizes rapidly and hence initiates and supports combustion. Figures 6a and 6b illustrate a thin wall condition.

Solution:

An extremely valuable technique for locating such stressed areas is to machine a clear plastic model of the housing. This model permits viewing inner and outer surfaces simultaneously. While exact wall thicknesses cannot be measured directly, the thin areas do become obvious. Such an indication should prompt more detailed layout analysis and tolerance study followed by stress analysis of the local area to determine whether a problem actually exists. Tolerances then called out on the manufacturing drawing should be tight enough to preclude stress concentrations.

The thin wall in the figure is primarily the result of an overdrill due to lack of attention during design or to an overtolerance. The dimensions of a drilled intersection should be planned more carefully or the tolerances set more tightly. It may even be possible to eliminate the intersection altogether as shown in figure 6c. All intersections should be examined by X-ray or borescope to ensure that the drilling was accomplished in an acceptable manner.

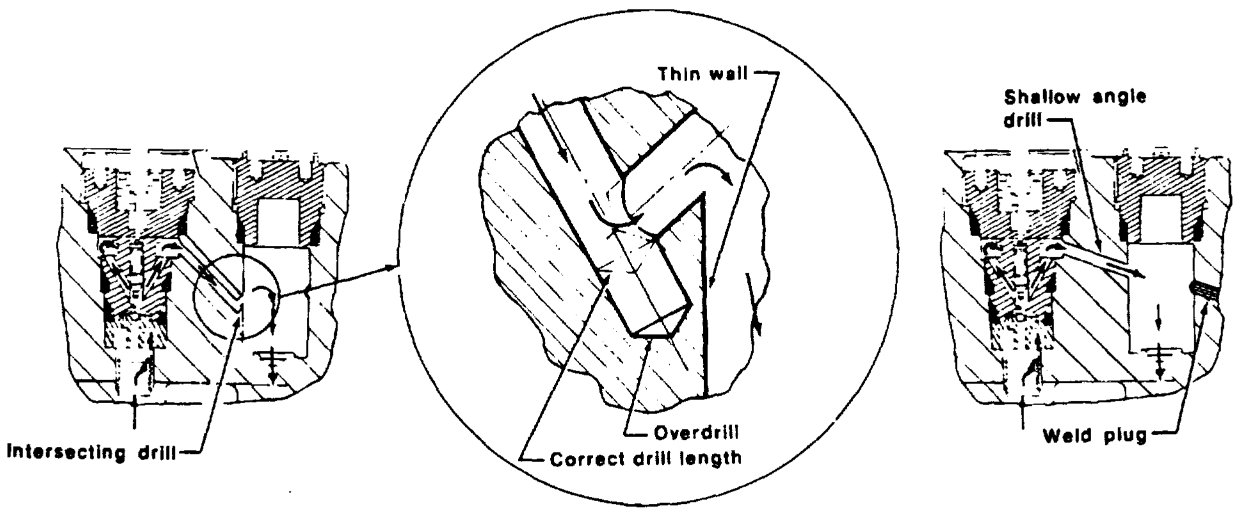

Figure 6.- Component housings - Thin walls.

Blind Passages or Dead End Cavities

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Problem:

A stagnant area at the end of a drilled passage tends to collect debris either from manufacture or from normal use. During rapid pressurization of gaseous oxygen and its attendant compression heating, the debris becomes fuel for ignition. When an underexpanded jet impinges on (or flows across) a stagnant cavity, a periodic pressure wave may be formed that oscillates in the cavity, heating the gas within it. If particles are present, hot gaseous oxygen could ignite them. Blind passages and dead end cavities also present increased difficulty during cleaning. They require that the part be turned during soaking to eliminate air pockets. And special nozzles or extensions must be used to flush such difficult-to-reach areas. Figure 7a depicts a blind passage created by plugging a drilled passage. Figure 7b depicts a dead end cavity created by overdrilling an intersecting passage.

Solution:

Gaseous oxygen components should be designed so that a jet will not impinge on or flow across a stagnant cavity. Jets should be gradually expanded and stagnant cavities should be eliminated or kept as shallow as possible. In figure 7a the blind passage can be eliminated by making the counterbore for the plug much deeper and installing the plug closer to the regulator stem. The cavity may not be completely eliminated, but the total dead volume is significantly reduced. The cavity shown in figure 7b can be eliminated by paying careful attention to dimensions and tolerances or, preferably, by redesigning to eliminate the intersecting holes. Inspection with a borescope can be done to verify that passageway lengths are within tolerance.

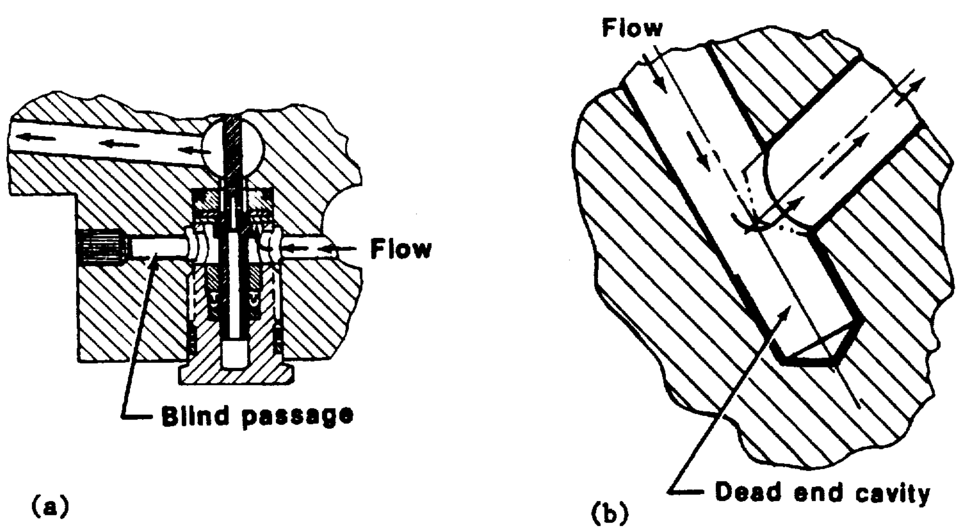

Figure 7.- Component housings - Blind passages or dead end cavities.

Sharp Feathered Edges

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Problem:

Sharp feathered edges are surfaces with large areas but little mass. In an environment where compression heating, shock heating, or flow friction is present, there may be insufficient mass of metal to conduct heat away. Thus, heat can concentrate in such an edge and it can become an ignition point. Any two intersecting passages that are drilled off center or at an angle other than 90 degrees will produce an edge feathered to some degree. Other machining situations may also cause a feathered edge. Figure 8 depicts a feathered edge caused by an offcenter drill intersection, with the smaller drill stopping at the cavity edge and allowing the 120-degree cone angle of the holes to produce a pronounced feathered edge.

Solution:

The problem shown can be alleviated either by drilling through or by stopping short of the original position, as illustrated by figures 8b and 8c. During design, it is a simple task to find potential feathered edges. All intersecting drills should be examined for feathered edges.

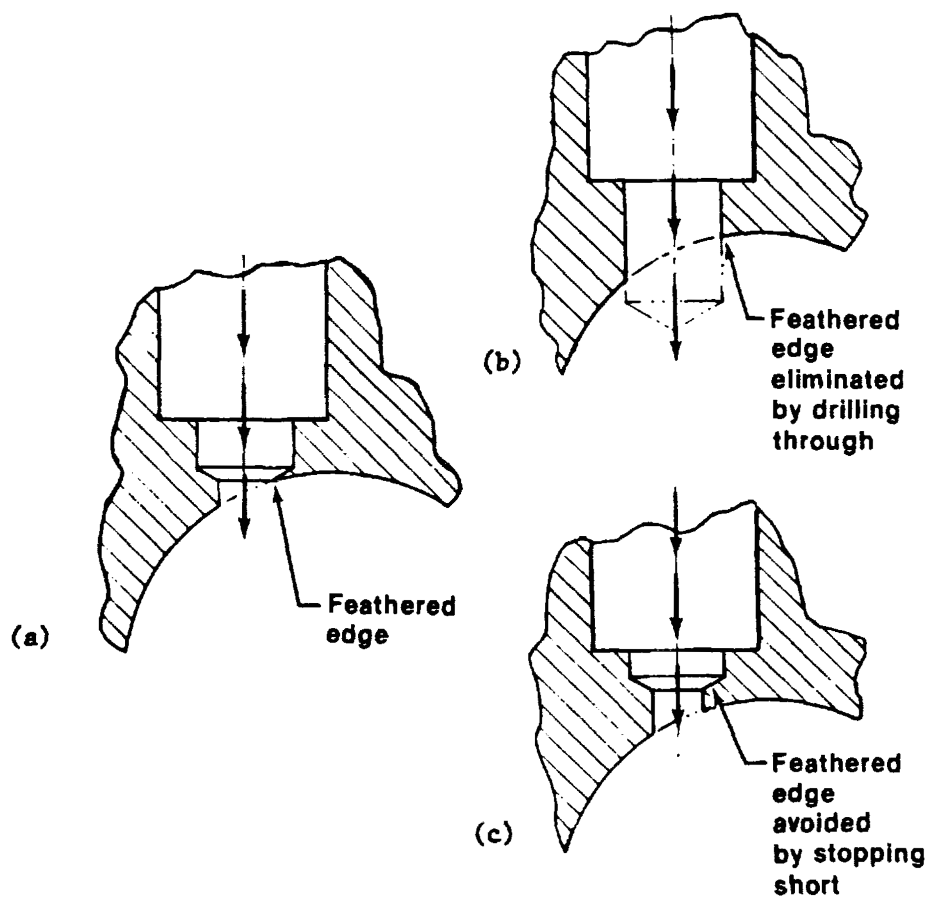

Figure 8.- Component housings - Sharp feathered edges.

Burr Removal

Problem:

Small attached splinters of metal created during machining are called burrs (fig. 9). These burrs are usually removed during manufacturing; however, if the burr is in an inaccessible passage, it may not be detected. The problem is that the burr (much like the feathered edge just discussed) is a thin piece of metal with little mass and large area which can by localized heat generation easily become an ignition point or a source of fuel. The burr also has impact potential because it could be dislodged during operation. It is a fixed contaminant which cannot be flushed away or even detected with certainty.

Solution:

Detection and correction must come early in the design cycle. When a possible burr location is identified, the area should be redesigned. If it is not possible to eliminate the condition, then special inspection tools such as borescopes should be specified and deburring procedures developed.

Burrs and sharp edges are so critical in high pressure oxygen systems that their removal should be emphasized during the design phase by specific drawing callouts to every edge and corner that will be exposed to the flow stream. In addition, specific inspection procedures should be defined by procedural document also called out on individual drawings. Such emphasis is necessary since burr removal on most other hardware is usually called for by general note, poorly considered in design, often neglected in manufacturing, and ignored in inspection. This has been found by spot inspection to be the case even in crucial high pressure oxygen systems when such emphasis was not made.

Burr removal in small diameter internal passageways at the intersection of cross drills has been one of the most difficult techniques to develop. Best results have been obtained with small motorized grinding tools and with electrical discharge machining (EDM).

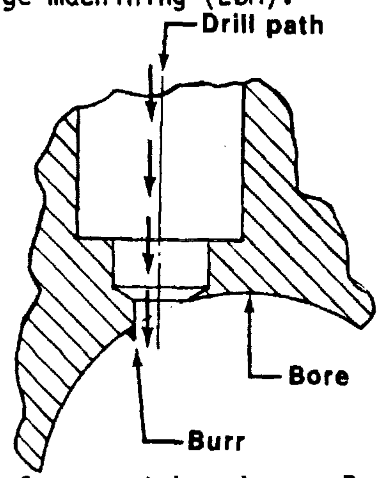

Figure 9.- Component housings - Burr Removal.

Flow Impingement on Aluminum Housings

Problem:

Since aluminum constitutes a fuel in an oxygen fire and since the oxygen flow might contain particulate matter that could ignite this fuel on impact, the flow should not be allowed to impinge directly on an aluminum housing wall (figure 10a).

Solution:

The housings of newly manufactured hardware should be made of fire-resistant material such as Monel or some other high-nickel alloy. To correct for impingement in existing hardware, critical areas of high pressure and high flow can be shielded with fire-resistant metals. Rerouting and diffusing flow can also slow or block impacting particles (figure 10b).

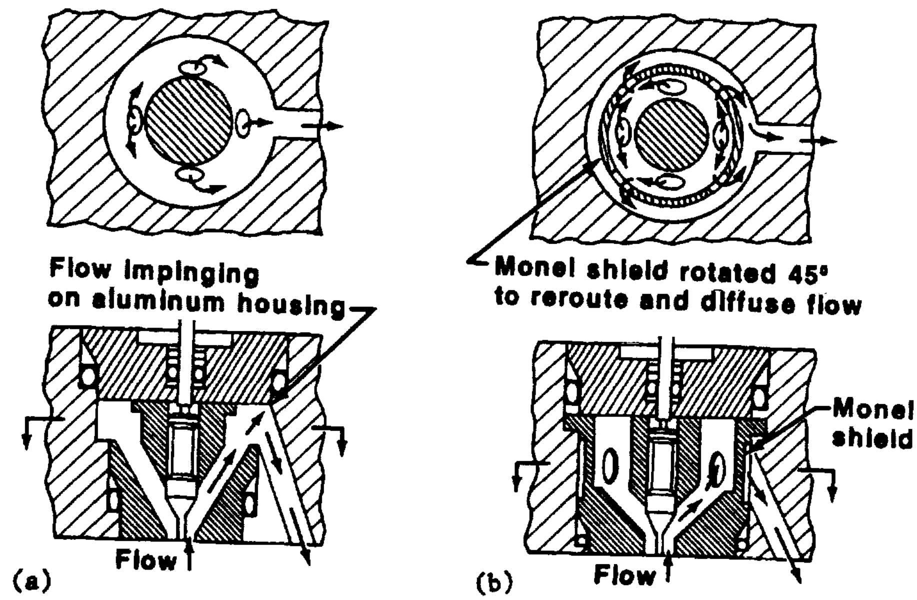

Figure 10.- Component housings - Flow impingement on aluminum housings.

VALVES

Conventional valve parts are designed to preclude galling and to withstand the high stresses of elevated pressure and spring forces. Monel alloys are fire-resistant and the range of hardnesses in which they are produced can be used to minimize galling problems. The harder, stronger alloys such as K-Monel can be used for highly stressed, small diameter, moving parts such as valve stems. 400-series Monel can then be used for the valve body. Springs can be wound from Monel wire. Miniature springs can be made of Elgiloy or beryllium copper if small diameter Monel wire is not available. Tungsten carbide and steel poppet balls should be replaced with sapphire balls since sapphire has a lower level of reactivity (and therefore is less combustible) than either tungsten carbide or steel. It is also more resistant than tungsten carbide to breakup under a mechanical impact in oxygen. Lock rings and retainer nuts that are not exposed to oxygen can still be made of lightweight aluminum since they are not subject to the oxygen ignition hazard (although galvanic corrosion of dissimilar metals must still be considered).

The working parts, if made of combustible materials, can contribute significant mass to fuel a fire. Friction between moving parts can initiate combustion within the valve. Static or impact loads on subminiature, highly stressed parts can cause fracture or heating of these parts, which can then initiate combustion. Flow-induced oscillation or chattering of a poppet within a valve can result in fretting and highly localized heat generation, which can lead to ignition.

Volumes upstream of a valve may be affected by high valve actuation rates. The fast closing of the valve could produce a water hammer effect, sending a pressure pulse upstream, which could then cause a temperature rise by adiabatic compression. Such a pulse could also cause structural failure in an upstream component or container.

Volumes downstream of a valve may also be affected by high valve actuation rates. The fast opening of the valve could subject passageways or components to adiabatic compression, which could result in hot spots and possible ignition of nonmetallics or particulate contaminants.

These problems and suggested solutions are presented in the following valve design articles.

Static and Impact Loads on Subminiature Parts

Problem:

Valves for high pressure oxygen systems may be designed with subminiature parts to reduce pressure forces so that regulating springs can be kept a reasonable size. If these parts get too small, then they may be highly stressed by the ordinary static and impact loads. If the high stresses are applied quickly, the local energy transfer rates can be high enough to fracture a miniature part or heat it enough to ignite it or any contaminant present (fig. 11).

Solution:

High pressure oxygen systems should be designed so that working loads on valves with subminiature parts are low. Fast actuation which could apply impact loads to such subminiature parts should be avoided, and the parts should be made of materials that are not impact sensitive. Furthermore, each system should be designed for cleanliness and isolation of contaminants.

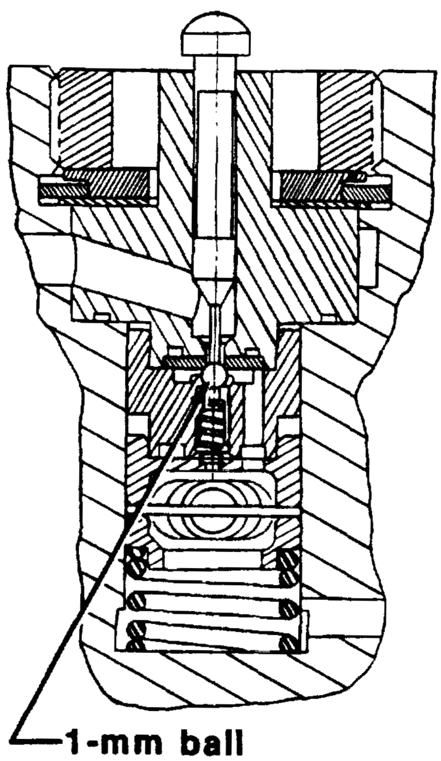

Figure 11.- Valves - Static and impact loads on subminiature parts.

Check Valve Chatter

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Problem:

Under some flow rate conditions, check valves in oxygen service may "chatter" as a result of a resonant coupling of the dynamically induced flow forces (which are dependent on check valve geometry, system geometry, flow rate, and oxygen pressure and temperature) with the check valve seating spring forces. Chattering results in the poppet's hitting the seat at a high frequency and can cause an ignition at the seat due to the high localized heat generation. Furthermore, the chattering can generate particulate matter which can inhibit the function of downstream components or act as a fuel for ignition farther downstream.

Solution:

Check valves are available in a broad variety of configurations. Figure 12 shows the cross-section of a typical check valve. Successful check valve design includes selection of appropriate materials; selection of tolerances to avoid galling of moving parts; and control of tolerances to avoid lateral instability (chatter) of the poppet in its guide. To control axial chatter, a variety of techniques are available. The use of a soft-seating spring can minimize cracking pressure so that only a minimal flow holds the valve open. Or the valve may be designed so that the poppet must move substantially off its seat before the flow ports are uncovered.

Close attention should be given to dynamic analysis of the check valve design across its entire flow range and for the entire spectrum of expected oxygen temperatures and pressures to show its dynamic stability. Because of the difficulty of such analyses, the valve must be also tested as a component and in a complete system configuration (see section 7).

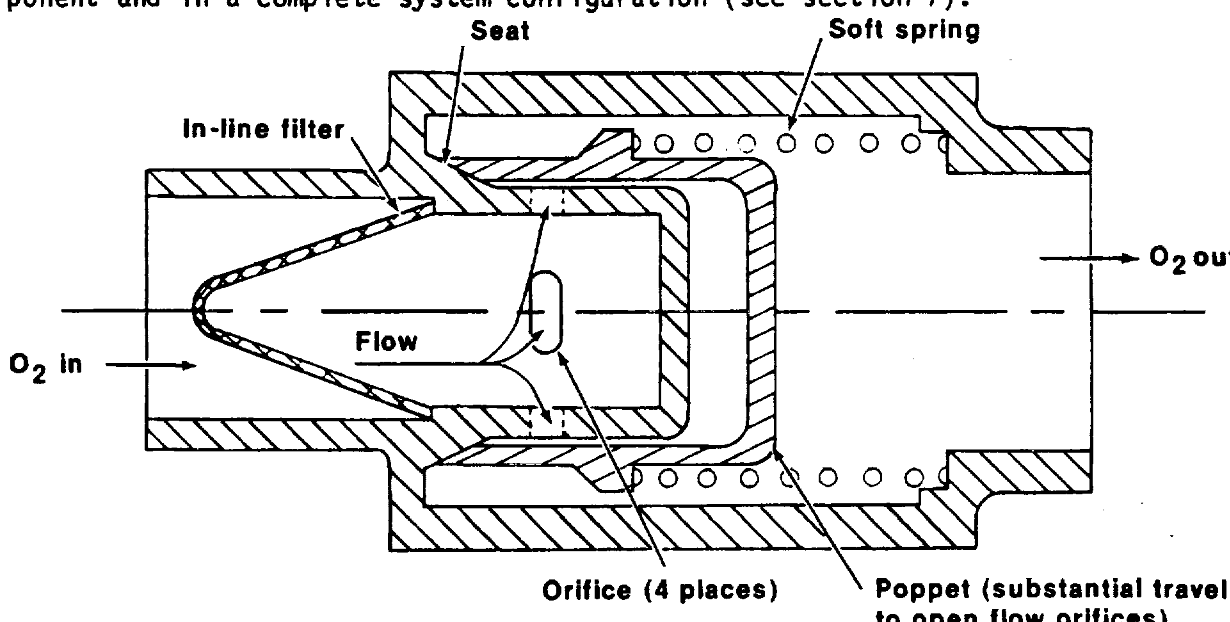

Figure 12.- Valves - Check valve chatter.

Poppet Oscillation (Asymmetrical Flow)

Problem:

Asymmetric flow across a valve poppet creates a dynamic imbalance of flow forces on the poppet, causing it to oscillate transversely against its bore. This transverse oscillation results in the poppet's hitting the bore at a high frequency and can cause an ignition due to the high localized heat generation. Furthermore, the transverse oscillation can generate particulate matter which can inhibit the function of downstream components or act as a fuel for ignition farther downstream, figure 13a.

Solution:

Where possible, the internal flow geometry within valves should provide symmetrical flow across the poppet. An effective alternate approach is to mount the poppet in the bore by means of flexure assemblies, which are very flexible in the longitudinal direction (and thus do not inhibit the valve's open/close action) but which restrict the transverse motion of the poppet. The flexure assemblies act to center the poppet in the bore at all times and thus prevent any transverse contact. Bore and poppet materials should be selected to minimize the possibility of ignition. Both surfaces may be metallurgically hardened to minimize deterioration due to fretting, figure 13b.

(a) Asymmetrical flow

(b) Symmetrical flow

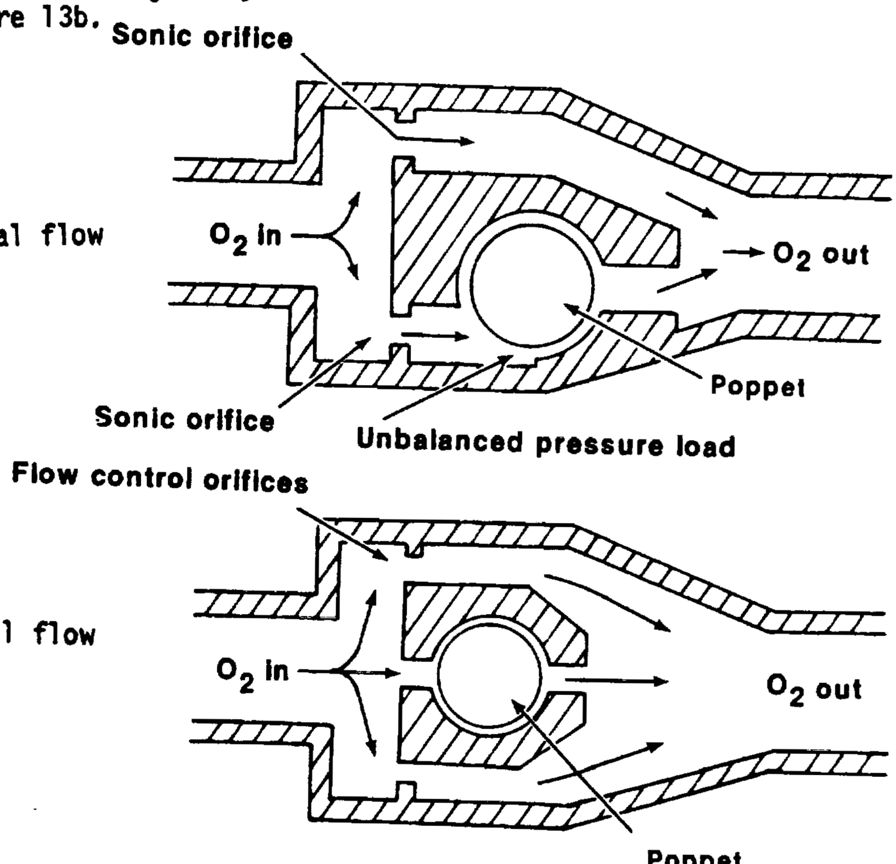

Figure 13.- Valves - Poppet Oscillation.

Actuation Rates

Problem:

Actuation of a fast-opening shutoff valve subjects the first stage regulator and passageways immediately upstream of the regulator to a sudden increase in pressure as shown schematically in figure 14a. This sudden pressure rise can cause adiabatic compression resulting in localized temperatures high enough to ignite nonmetallic seals or particulate contamination.

Fast closing allows bottle pressures to put high impact loads on the valve seat. Energy transferred in the impact can ignite contamination on the seat.

Solution:

The system requirements should be evaluated with the goal of establishing as slow an actuation rate as feasible. Once the minimum actuation rate requirement is established, the actuating valve can be designed specifically to achieve this rate. Orifices or restrictions may be required to limit pressurization rates. For components already existing, thermodynamic analysis techniques should be used to identify areas of concern. The rate can then be decreased by converting a fast-working pushbutton actuator to a slower threaded-type actuator.

Another method, shown schematically in figure 14b, is to incorporate the shutoff function into a regulator stage using the regulator valve as the shutoff seal. No separate shutoff valve is then required. Before the regulator is actuated, the first stage is closed with high pressure upstream of the valve seat and medium pressure downstream. The second stage is also closed with medium pressure upstream of its valve seat and no pressure downstream. After the regulator is actuated, downstream pressure increases over a relatively small differential. No sudden increases occur, so no heat-producing compression takes place. This method of decreasing the actuation rate is useful even when long term storage is a factor. If the first stage slowly leaks, it may in time increase the interstage pressure to the level of the supply pressure (7400 lb/in^2 or 51 MN/m^2 in the illustration). When the second stage regulator (functioning also as a shutoff valve) is opened, there will be a surge of flow. But the regulator will quickly close again since its desired downstream pressure will be immediately reached. If the interstage volume is small - and it should be small by design - then there will not be much oxygen to support a sustained surge.

The definitions of "fast" and "slow" depend on the situation. Factors that should be considered in establishing actuation rates include the ignition temperatures of the nonmetallics and metallics downstream of the valve, the total volume immediately downstream of the valve, the operating temperature, the operating pressure, the pressure rise rates in volumes downstream of the valve, and the heat transfer characteristics of the oxygen and the passageway walls. Since all these factors will vary from system to system,

it is difficult to establish valving rates or pressure rise rates that would be acceptable for each case. But extensive pneumatic impact testing with oxygen has indicated that an actuation rate of 50 milliseconds or less to bring downstream pressure to 95 percent of upstream pressure does routinely cause ignition. This rate and any faster rate should definitely be considered "fast." Ball valves are very fast; their actuation rate has been measured at less than 2 milliseconds. At the other extreme, a rate of 0.5 second to achieve the same downstream-to-upstream pressure ratio has been found to cause no ignitions in extensive testing up to 2000 lb/in^2 (14 MN/m^2). This rate and any slower should be acceptably "slow" from the standpoint of adiabatic compression ignition.

There may be a limit, however, to the "slowness" that should be designed into a particular system. If a valve opens too slowly, it presents in effect a slowly expanding orifice to the flow stream. If the upstream and downstream pressures and orifice characteristics are such that the flow becomes supersonic, then particulate contamination may be accelerated to a high velocity. Such a velocity can be much higher than would be experienced in a "fast" opening (and slower flowing) valve. With the increased kinetic energy, particle impacts are more capable of causing ignition. Evidence of this phenomenon exists in oxygen test program experience. To determine the best trade-off, a thorough analysis of the actuation, considering all the factors listed above, should be performed for each individual shutoff valve.

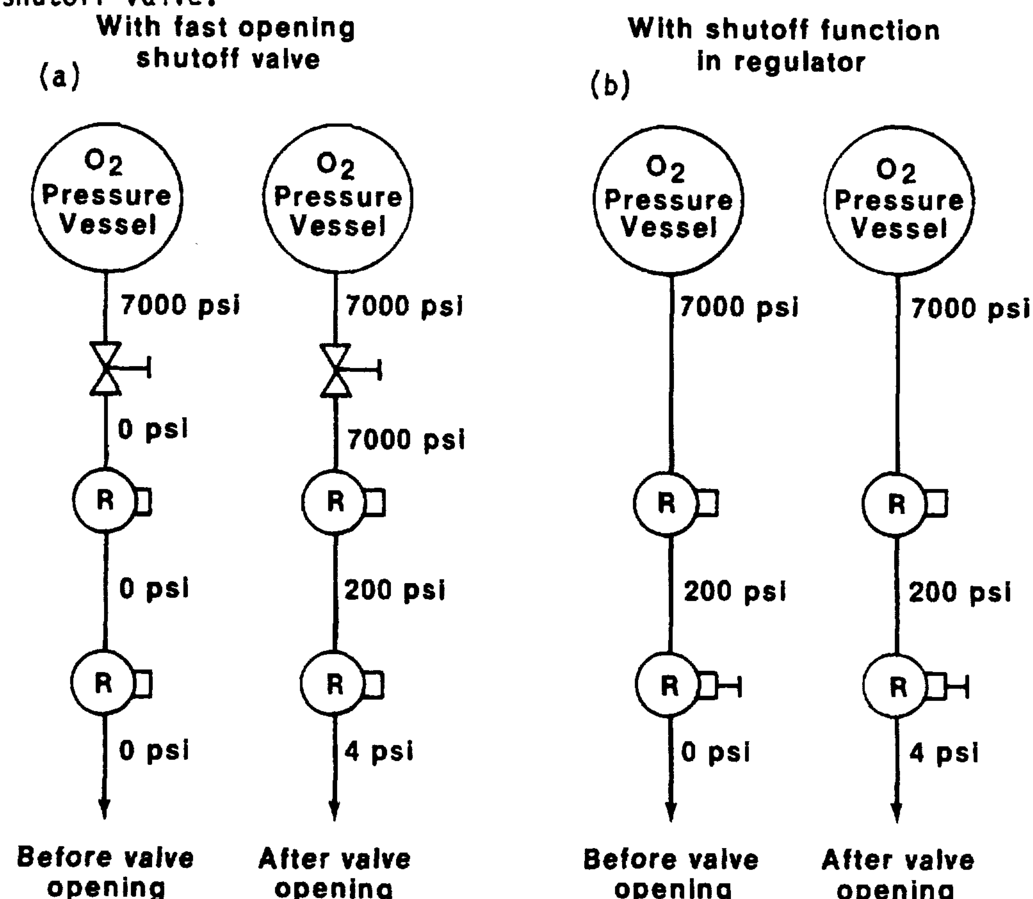

Figure 14.- Valves - Actuation rates.

Single Barrier Failure

Problem:

A leak in which only the primary containment structure is breached is defined as a single barrier failure. Such a leak introduces oxygen into a region which is not normally exposed to oxygen. In this region, the materials or configuration of parts may not be compatible with high pressure oxygen. In the pressure transducer shown in figure 15, rupture of the bourdon tube would constitute a single barrier failure since oxygen would leak into the surrounding cavity.

Solution:

Any situation in which there is a single barrier that may fail should be analyzed during the design phase. Such single barrier failure analysis can consist of an engineering evaluation of the configuration, including analysis of materials, or a configuration test may be performed. In the case of the pressure transducer shown below, a configuration test was performed by drilling a hole in the bourdon tube, then pressurizing it with oxygen. A spark from the resistance wiper arm caused ignition and the resulting explosion destroyed the transducer. The configuration was subsequently changed by adding an oxygen-compatible oil to the cavity to prevent sparking.

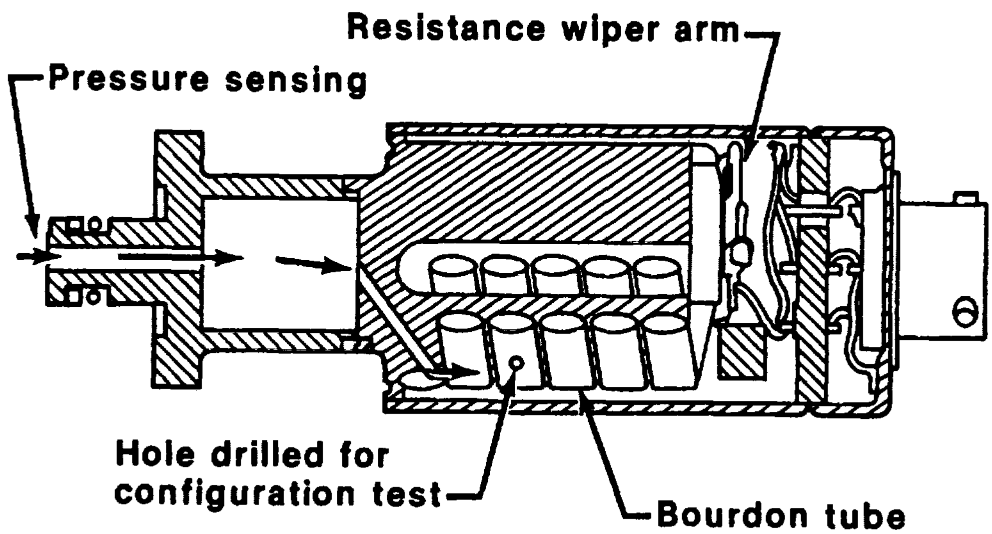

Figure 15.- Valves - Single barrier failure.

Rotating Stem Valves

Problem:

A manual, screw-type valve with a rotating stem, figure 16a, might seem desirable in a high pressure oxygen system because such a valve can provide a slow actuation rate. However, a rotating stem valve presents contamination problems especially when combined with a nonmetallic seat. Such a seat can easily be damaged by excessive closing torque or by shredding or gas erosion during both opening and closing. Furthermore, solid contaminants can become embedded in such soft seat material. If the seat is made of metal, it must be hardened to prevent galling by the rotating stem. Such hardened materials can fracture or even fragment as a result of excessive closing torque or closure onto hard contaminants (like silicon dioxide). Also, seat galling is still possible when the valve stem rotates against a metallic seat.

Solution:

A manual valve with a nonrotating stem, figure 16b, and a metallic seat can be chosen to achieve the desired slow actuation rate. In this case, the metal seat can be made of a much softer material and the seat can be formed by "coining" (pressure molding by the stem itself to create a perfect match). Contaminants will not cause fragmentation of such a seat. Galling cannot occur unless the nonrotating feature is compromised. The seat and body of such a valve can be fabricated from such metals as Inconel or Monel, which have been shown to be comparatively unreactive with oxygen.

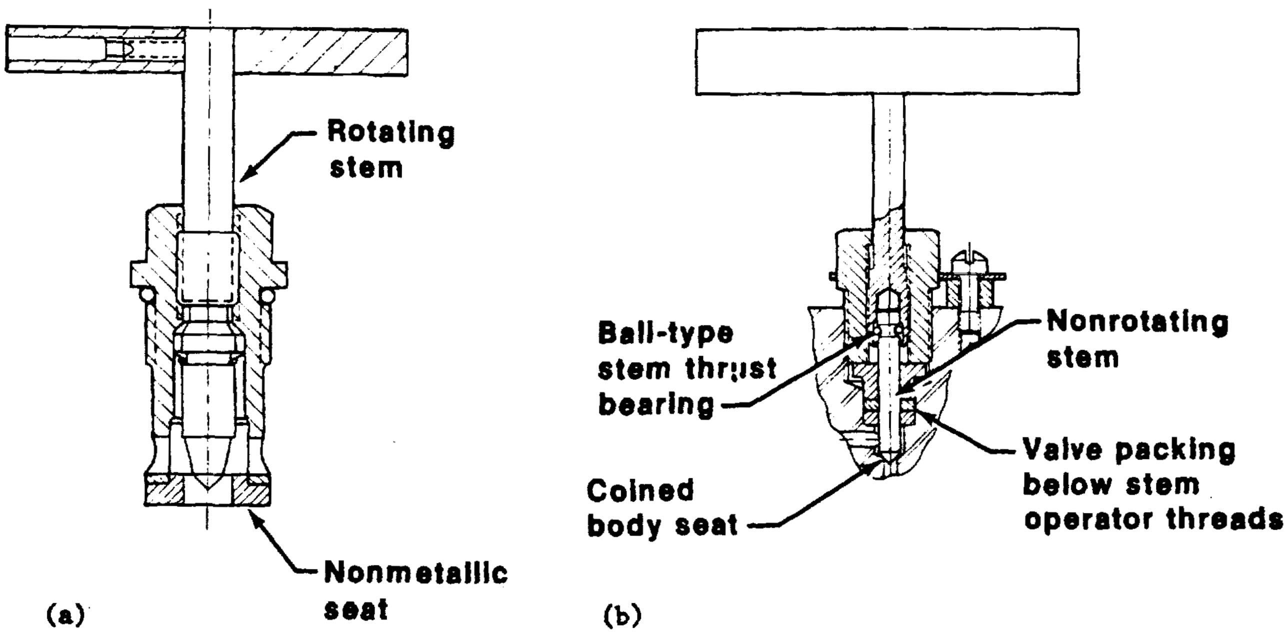

Figure 16.- Valves - Rotation stem valves.

SEALS

Seals used in valves and fittings are made of relatively soft nonmetallic materials. All such materials with adequate mechanical properties are ignitable at relatively low temperatures compared to the ignition temperatures of the surrounding metal parts. Seal locations are therefore among the most likely combustion sites. To decrease the risk created by these locations, the number of seals used should be minimized. Where they are used, they should be shielded or removed from the flow stream.

The following articles discuss not only some techniques of shielding seals from flow impingement but also some methods of avoiding such seal-eroding conditions as alternating pressure, seal extrusion, seal squeeze, seal rotation, and the effects of poor seat shape. Also presented are some considerations on using dynamic seals and metal-to-metal rubbing seals.

Flow Impingement

Problem:

If the oxygen flow stream impinges directly on an exposed nonmetallic of low ignition temperature such as O-ring material, there is a risk of ignition due to impact by contaminants carried along in the flow stream (figure 17a).

Solution:

This problem can be solved by shielding the O-ring from the flow stream with a backup ring of a material with a higher ignition temperature or by designing the housing bore and sealed component so that metal is bottomed on metal, creating a flow barrier to protect the O-ring (figures 17b and 17c).

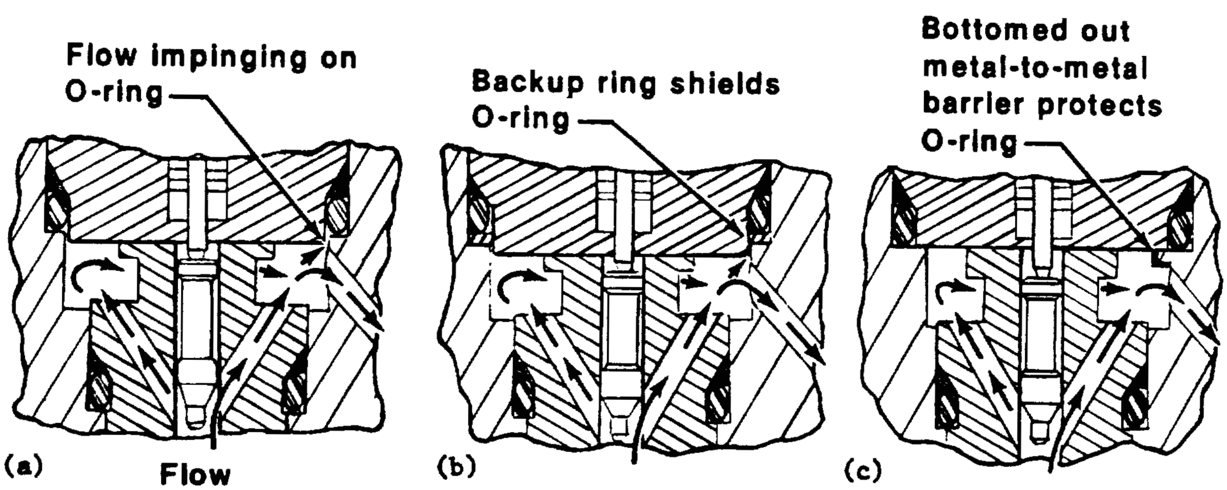

Figure 17.- Seals - Flow impingement.

Alternating Pressure (Redundant Seal)

Problem:

When two sets of seals are used at the same location in a long term pressurized storage application, eventual permeation of the first seal produces a pressurized volume between the seals. The pressure in this zone would be greater than that on the low pressure side of the component but less than operating pressure. When the valve is opened and the low pressure side is raised to operating pressure, the second seal is exposed to pressure on its downstream side which is now greater than that in the intermediate zone. As the component goes through several use cycles, the direction of the pressure force alternates from one side to the other. This alternating pressure can cause seal working and erosion or blowback of contaminants (figure 18a).

Solution:

The solution is to eliminate the second "redundant" set of seals and ensure that the first set of seals is adequate in oxygen compatibility, Shore hardness, and proper use of backup rings to perform the sealing task alone (figure 18b).

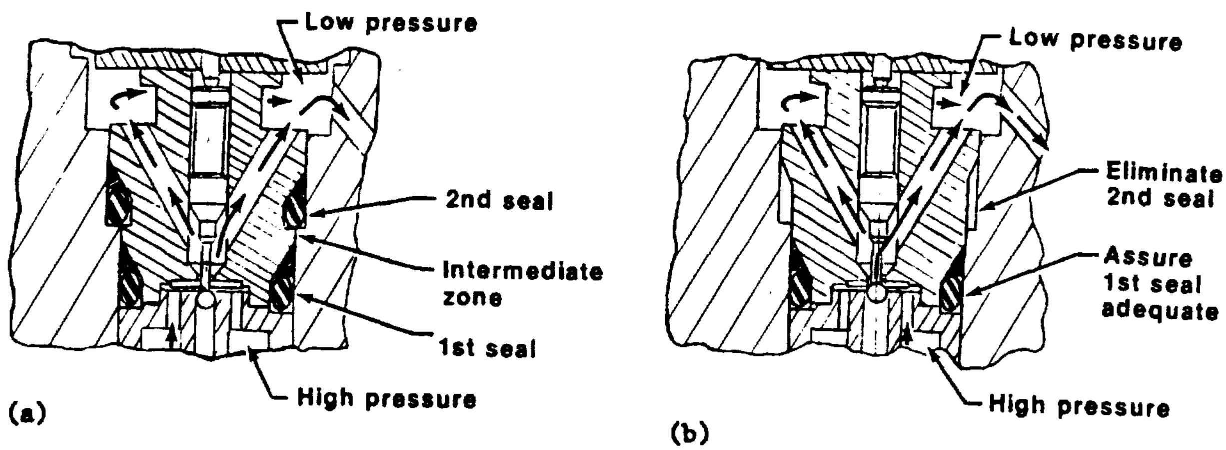

Figure 18.- Seals - Alternating pressure (redundant seal).

Seal Extrusion (Backup Rings)

Problem:

In high pressure oxygen systems, it is critical to minimize both seal erosion and contaminant generation. Without backup rings, O-rings can be partially extruded into the radial gap between parts. Even though the O-ring may still seal, such extrusion over a number of cycles may wear off material, thus degrading the seal and contaminating the system with nonmetallic particulates. In systems with very high pressures, ordinary backup rings may also be partially extruded, causing the same problems (figures 19a and 19c).

Solution:

For safety in high pressure oxygen systems, one should use backup rings on the low pressure side of O-rings even at pressures where standard O-ring practice does not dictate such use for gases in general. At pressures greater than 1000 lb/in^2 (7 MN/m^2), more sophisticated backup ring shapes such as delta rings should be used (figures 19b and 19d).

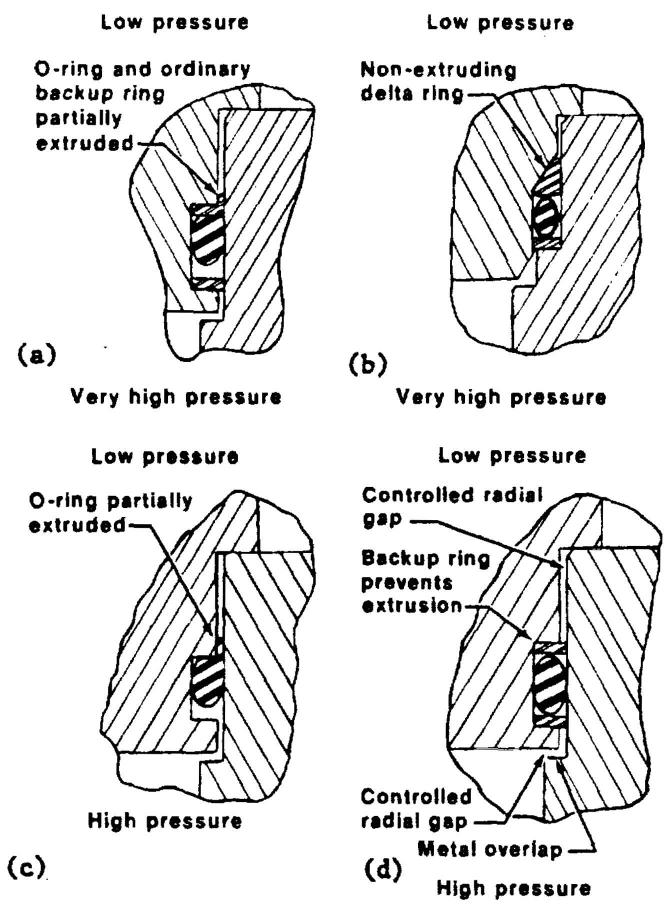

Figure 19.- Seals - Seal extrusion (backup rings).

Seal Squeeze

Problem:

Buildup of tolerances on valve parts or an unfavorable configuration in which to machine a gland may result in a gland too small for its O-ring seal. Since a certain amount of compression or squeeze in the axial direction is necessary to achieve the proper sealing load, there must be space for the O-ring to expand radially. If this radial space cannot be provided, the O-ring will be partially extruded from the gland and this extrusion will result in particualte pieces being shaved off.

Solution:

Careful attention should be given to dimensions and tolerances of all parts in the valve assembly. Ideally, adequate gland size should be provided in the initial design. When adequate gland size cannot be achieved, a special seal with an oval cross section may be used. This seal retains the required dimension axially but has a reduced cross-sectional width. Thus, the seal will occupy less space side to side even when compressed (fig. 20).

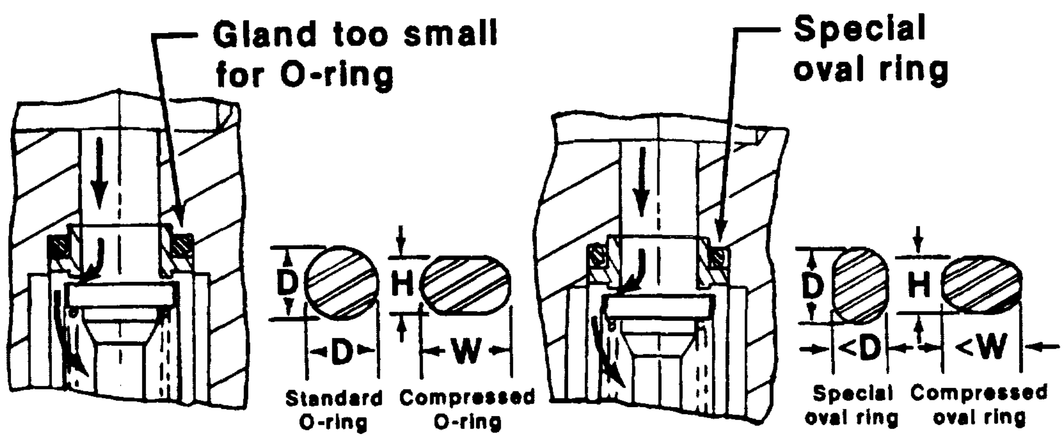

Figure 20.- Seals - Seal squeeze.

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Rotation of Seals

Problem:

Sealed parts that require rotation at assembly (such as O-rings on threaded shafts) can generate particles which may migrate into the flow stream as shown in the first illustration. Particulate generation also occurs in ball valves where operation of the valve rotates a ball on a nonmetallic seat.

A related phenomenon which may be described as "feathering" occurs when valve stems are rotated against some nonmetallic seats such as KEL-F. Because of the mechanical properties of some nonmetallics, a thin, feather-like projection of material is extruded from the seat. The feathered feature is more ignitable than the seat itself would have been (figure 21a).

Solution:

Instead of a rotating sealed part, the sealed part could be designed as a push-in plug locked in place by a second part which is threaded but not sealed as shown in figure 21b. Alternately the sealed threads could be replaced with a flanged and bolted connection. Kel-F seals should not be used in rotating configurations at all and ball valves are not recommended for for oxygen systems not only because of particle generation but also because of fast actuation rates.

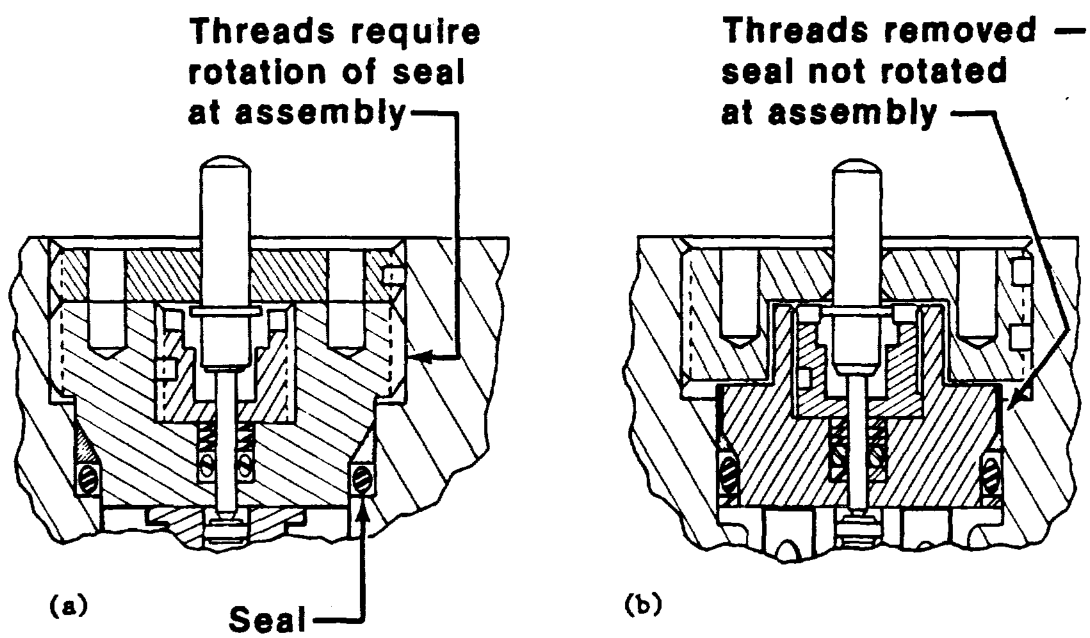


Figure 21.- Seals - Rotation of seals.

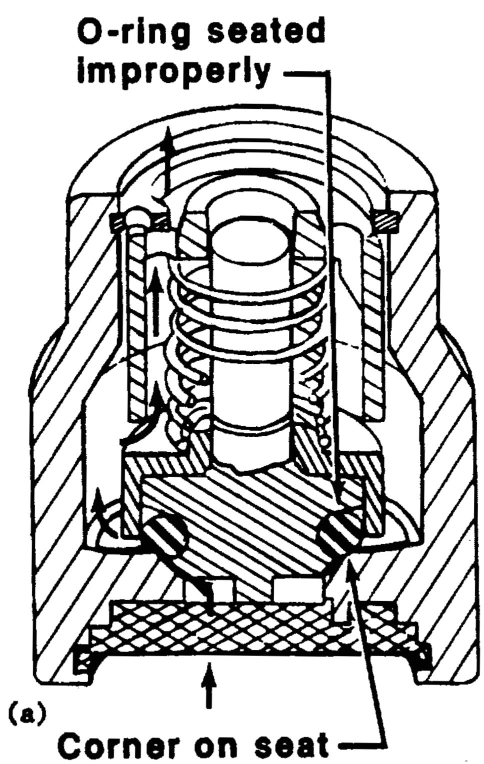
Seat Shape

Problem:

Designs which seal an O-ring on an unusual seat shape may set the stage for increased wear problems or unduly accelerated extrusion of the nonmetallic. Such effects can generate particulate contamination which will increase the risk of combustion. An example of such a design is seen in figure 22a wherein a face-type O-ring seal is seated on the edge of the sealing surface.

Solution:

Nonmetallic sealing interfaces are a necessary compromise; however, the designs can be optimized. The example is objectionable because it utilizes an O-ring improperly. The most reliable valve and regulator configurations have been found to be a metallic or sapphire ball in a washer-shaped Vespel seat, as shown in figure 22b.



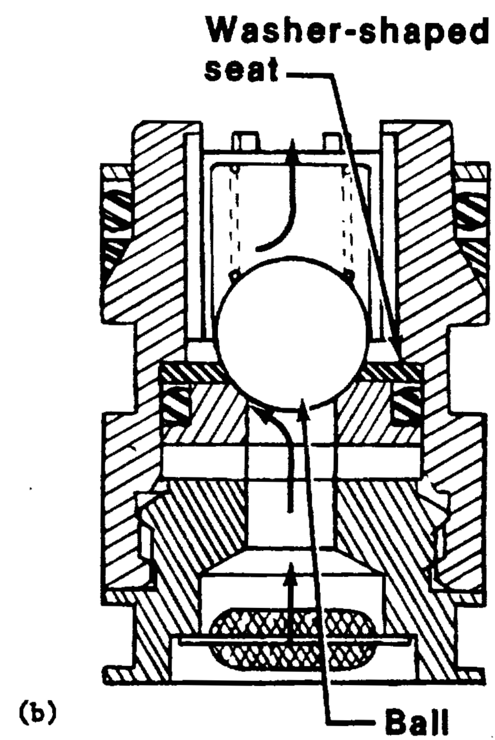


Figure 22.- Seals - Seat shape.

Dynamic Seals

Problem:

When a portion of a valve or fitting moves in relation to a sealing surface, friction can generate particles at the interface. The amount of particulate matter depends on the load and coefficient of friction between the metallic part and the nonmetallic seal and on the strength of the nonmetallic seal material. Unfortunately, even the best nonmetallic materials for O-rings in high pressure oxygen service have a fairly substantial friction coefficient and a relatively low strength (figure 23a).

Solution:

For applications up to about 1200 lb/in^2 (8.3 MN/m^2), the O-ring may be replaced by a spring-loaded Teflon seal. The Teflon has both a lower coefficient of friction and a higher strength. Such seals may require modification of the seal groove in radial seal applications since they cannot be stretched as much as elastomeric O-rings for assembly. Spring-loaded Teflon seals may not be adequate for use as rotating shaft seals or other continuous-motion applications since frictional heat buildup becomes a problem. In such applications, special configurations may be required to provide heat rejection.

For valves and fittings used at pressures above 1200 lb/in^2 (8.3 MN/m^2), seals made of pure Teflon (PTFE) may be acceptable if the reduced sealing capability due to cold flow can be tolerated. Also, batch-certified Viton or KEL-F 81 may be used, although Viton may harden and permit leakage at temperatures of -40° F (23 K) and lower (figure 23b).

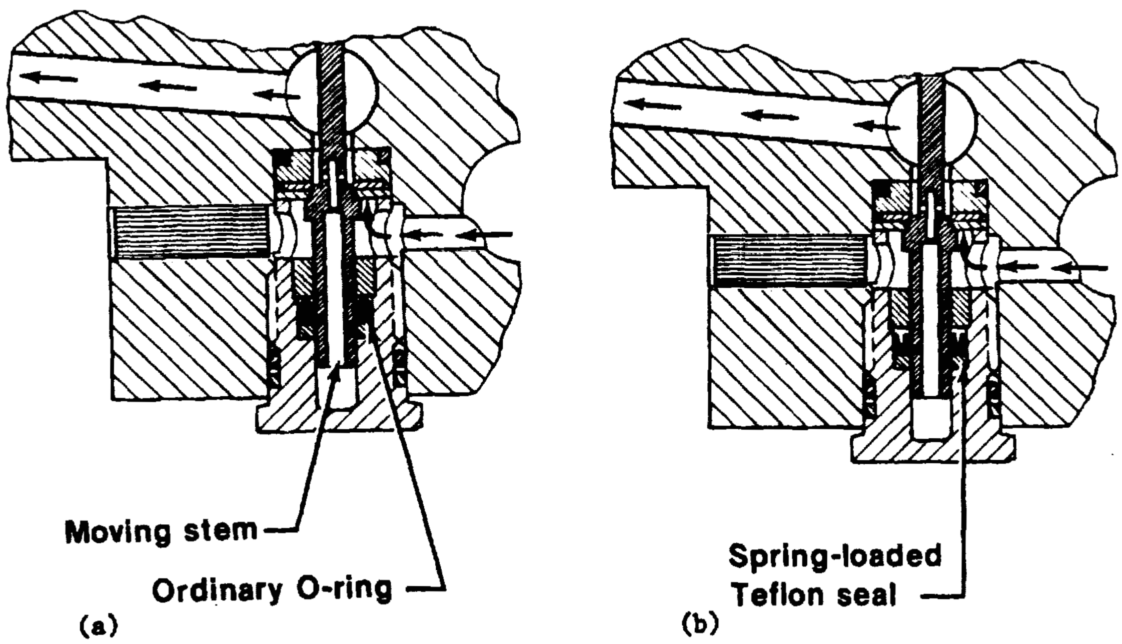


Figure 23.- Seals - Dynamic seals.

Metal-to-Metal Rubbing Seals

Problem:

Design requirements for valves that control the flow of hot oxygen at high pressure rule out soft seals. In this situation, soft seals are replaced by metal-to-metal rubbing seals. High pressure and high flow rates can produce side loads and oscillations on the poppet seal; these side loads and oscillations can cause fretting or galling. Fretting, in this case, means metal deterioration caused by repetitive high frequency vibration at the interface between two surfaces. Galling is a more severe condition involving smearing and transfer of material from one surface to the other. Both occurrences are problems in oxygen systems. The valve poppet could seize, resulting in loss of function; the frictional heat of the fretting or galling could lead to ignition of the valve; or the particles generated by the fretting or galling could cause malfunction or ignition of another component downstream, figure 24a.

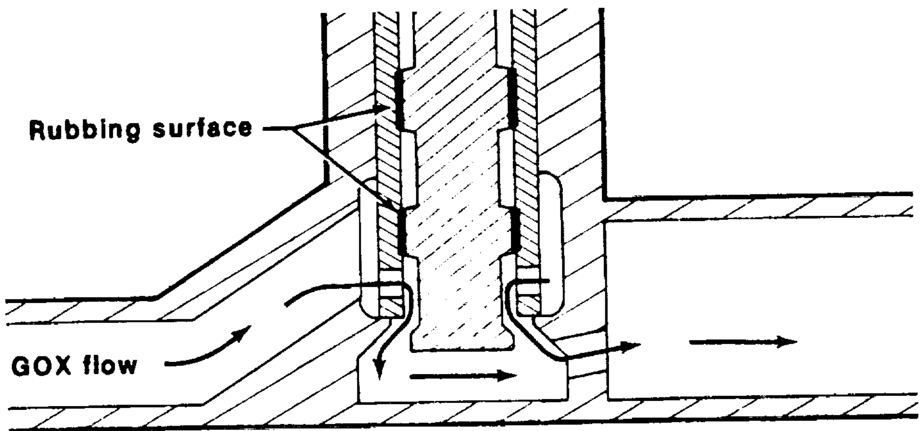
Solution:

Where possible, the valve poppet should be designed for symmetrical flow so that no oscillatory side loads are created. The symmetrical flow will center the poppet in the bore and maintain design clearances between the poppet and bore surfaces.

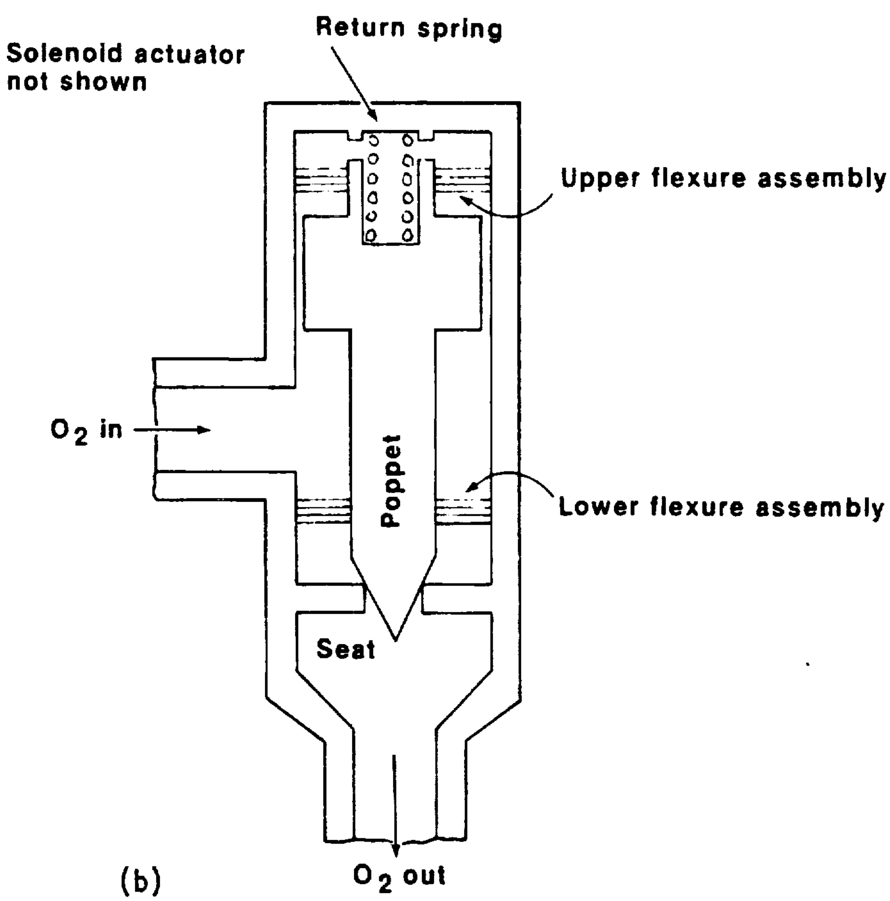
For gaseous systems it may be possible to reduce the volumetric flow rate (and thus the magnitude of oscillations and side loads) by installing an orifice downstream of the poppet to minimize the pressure differential occurring across the poppet.

It is also possible to flexure mount the poppet in the bore and to increase the clearance between the poppet and the bore by incorporating labyrinth seal grooves in the poppet surface.

Poppet and bore materials should be selected to minimize the chance of ignition. Both may be hardened by a process like nitriding to minimize material loss due to fretting or galling, figure 24b.



(a)



(b)

Figure 24.- Seals - Metal-to-metal rubbing seals.

FILTERS

Contamination can never be completely eliminated from a fluid system since it is always being generated to some degree by moving parts. It is therefore usually necessary to control and remove particulates from the flow stream continuously. Filters are the devices most commonly used to control particulates. While they do trap most contaminants above a specific size, there are concerns associated with their use. One is that after some use the filter becomes a potential combustion site just because of the high combustibility of its collection of fine particles. Another concern is that filters are made of very small diameter metallic wire, so small that a very slight addition of heat can cause hot spots in the wire.

Proper design of filters must include a careful trade-off study to ensure that ignition potential is reduced rather than increased. Use of fire-resistant materials such as pure nickel or Monel can ease some of the concern. A maintenance plan that calls for frequent cleaning or replacement of filters can also help.

Other techniques are discussed in the following articles on the use of filters at the inlets and outlets of modules, upstream of valve seats, and around difficult-to-clean passageways.

Problem:

Modular pressure system components, such as regulator assemblies, which are manufactured, tested, shipped, and handled as independent units, are subject to the introduction of contaminants through their inlet and outlet ports. These ports are sealed off by fittings and tubes during normal operation, but these openings may be unprotected before the module is installed in the system.

Solution:

Install at inlet and outlet ports filters that remain in place whether connecting fittings are in or out. The typical installation is shown in figure 25.

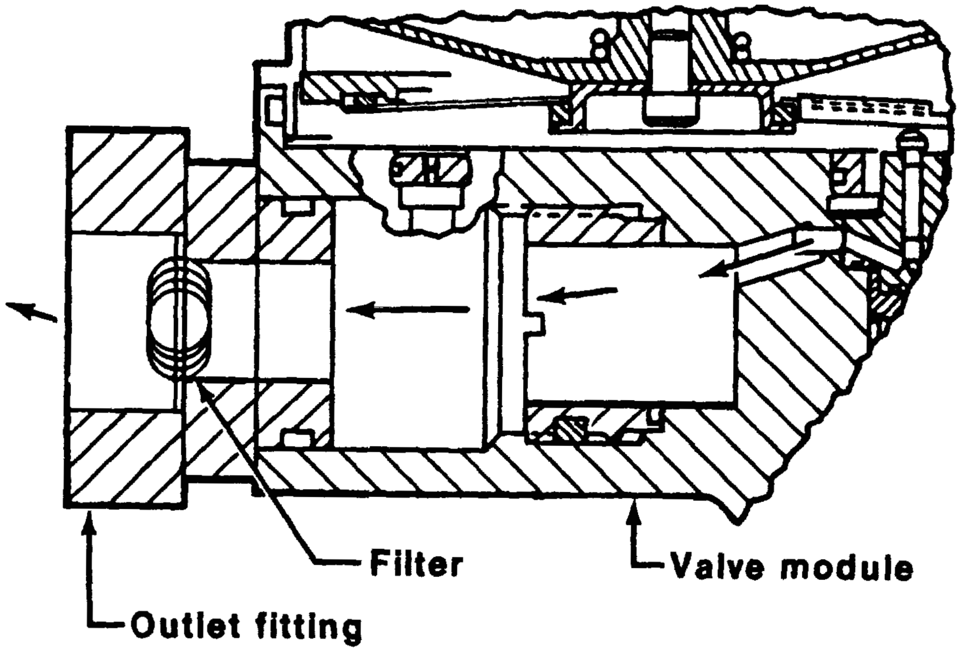


Figure 25.- Filters - Filters at inlets and outlets of modules.

Filters Upstream of Valve Seats

Problem:

Valve seats in high pressure oxygen systems are critical sealing points which must be carefully designed and manufactured to provide leakproof, reliable pressure control. Proper material selection and seat-forming techniques are crucial if an adequate seal is to be achieved for long term storage at high pressure and for thousands of cycles of use. The performance of such a seal is degraded by the trapping of contaminant particles at its sealing interface (figure 26a).

Solution:

Install very fine mesh (e.g., 10-micron) filters immediately upstream of valve seats (figure 26b).

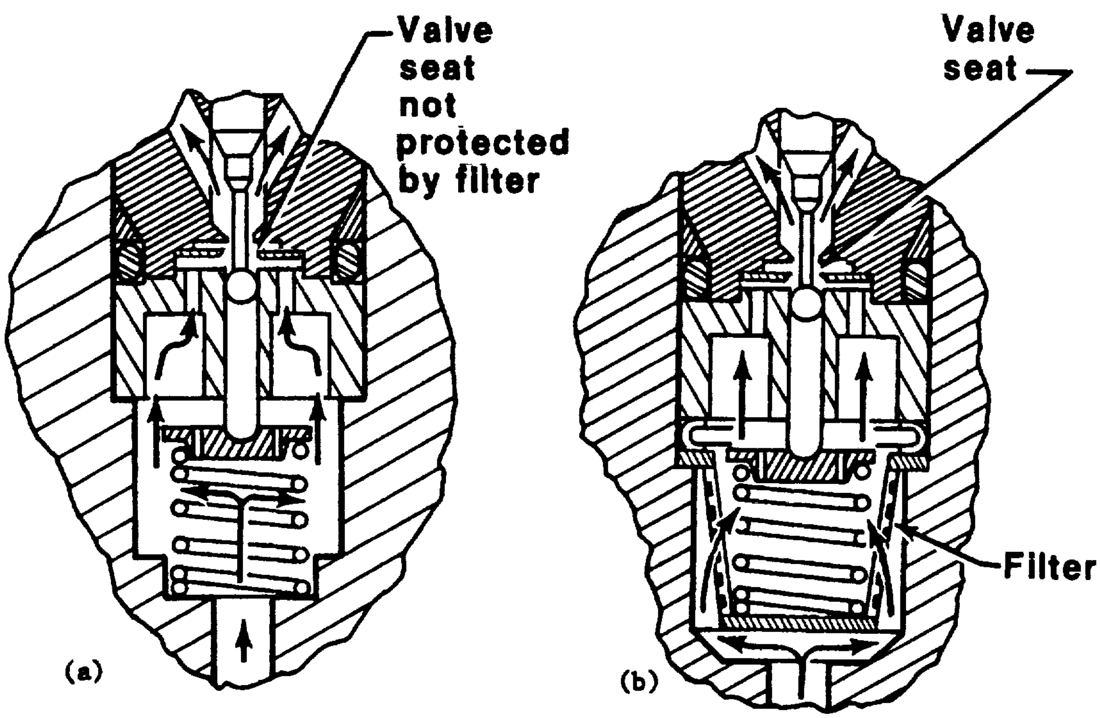


Figure 26.- Filters - Filters upstream of valve seats.

Filters Isolating Unavoidably "Dirty" Passageways

Problem:

Some portions of the flow stream in an oxygen system may be extremely difficult to clean during manufacturing. The pressure bottle shown in figure 27a has tubing brazed to the inside of the wall which is difficult to clean adequately. The long passageway with a small diameter, shown in figure 27b, could not be satisfactorily cleaned once the plug was welded in place. Welds and soldered and brazed joints, if left in the as-formed condition, may leave slag, roughness, porosity, or cracks which can generate or trap contaminants.

Solution:

Fine mesh filters should be added immediately outside the unavoidably "dirty" passageways to contain and control contamination that cannot be eliminated. Welds should be specified as full penetration so that all contacting surface area is joined together to prevent entrapment of particulates and eliminate uncleanable blind surfaces. Exposed weld surfaces should then be ground to a smooth finish to enhance cleaning.

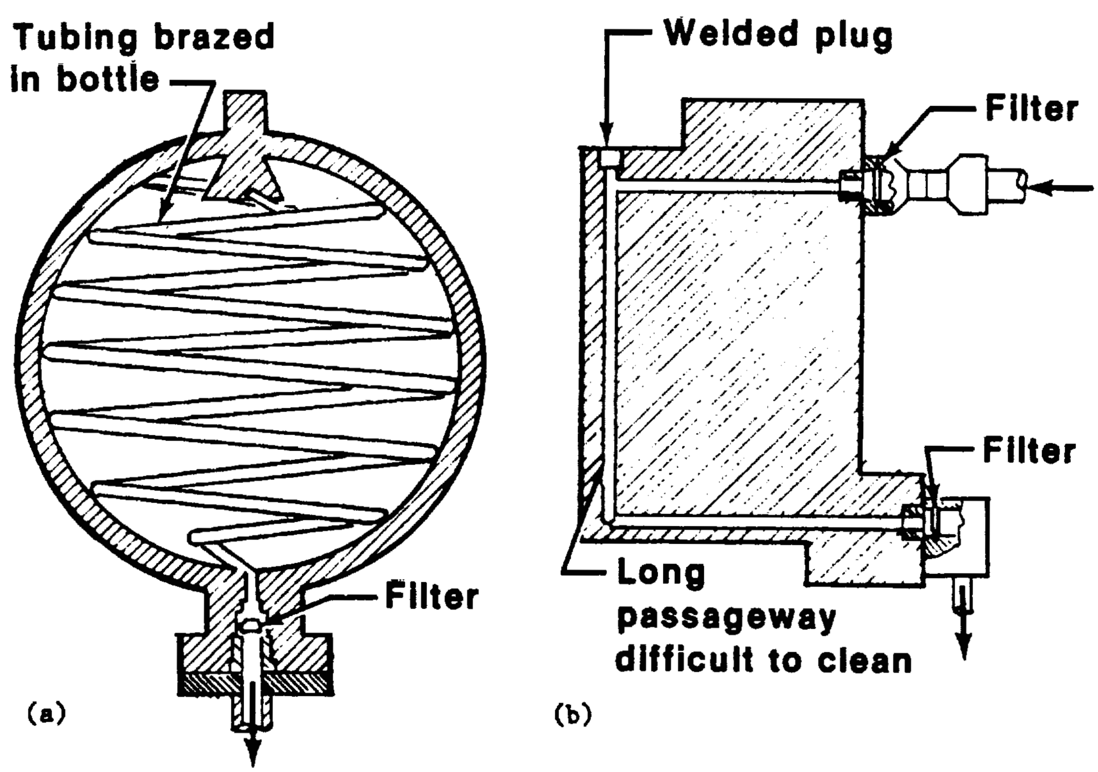


Figure 27.- Filters - Filters isolating unavoidably "Dirty" passageways.

ANCILLARY EQUIPMENT

In addition to housings, valves, seals, and filters, high pressure oxygen systems typically contain a varied collection of ancillary components such as tanks, pumps, heaters, and sensors. These components should be designed just as carefully as the other components we have discussed. They have their own unique set of design considerations.

Tanks for high pressure oxygen systems, for instance, may not be made of titanium and its alloys despite the high strength-to-weight ratios which normally make them so attractive. Titanium and its alloys are impact sensitive in oxygen atmospheres.

Pumps, compressors, fans, and blowers in oxygen service must be carefully designed to avoid rotational friction, or rubbing, which can quickly lead to an ignition. Bootstrap pumps, in which a fuel-rich gas drives a turbine on a common shaft with the oxygen pump, present the special problem of avoiding fluid contact along the common shaft.

Heaters and sensors in oxygen systems present a special set of problems because they introduce electrical current into an environment where a short circuit or an arc would cause an ignition.

The following pages discuss some of the design problems and solutions related to ancillary components.

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Bootstrap Oxygen Turbopump

Problem:

Bootstrap oxygen turbopumps, such as are employed in boost propulsion systems, utilize hot fuel-rich combustion gases to drive a turbine which also drives the oxygen turbopump on the common shaft. Mixing along the common shaft of the fuel-rich combustion gases with the high pressure oxygen being pumped will produce high temperature combustion that will destroy the turbopump.

Solution:

Use of an additional, intermediate set of seals along the shaft creates a separation area which is then continuously purged with an inert gas to avoid the development of a hazardous gas mixture (fig. 28).

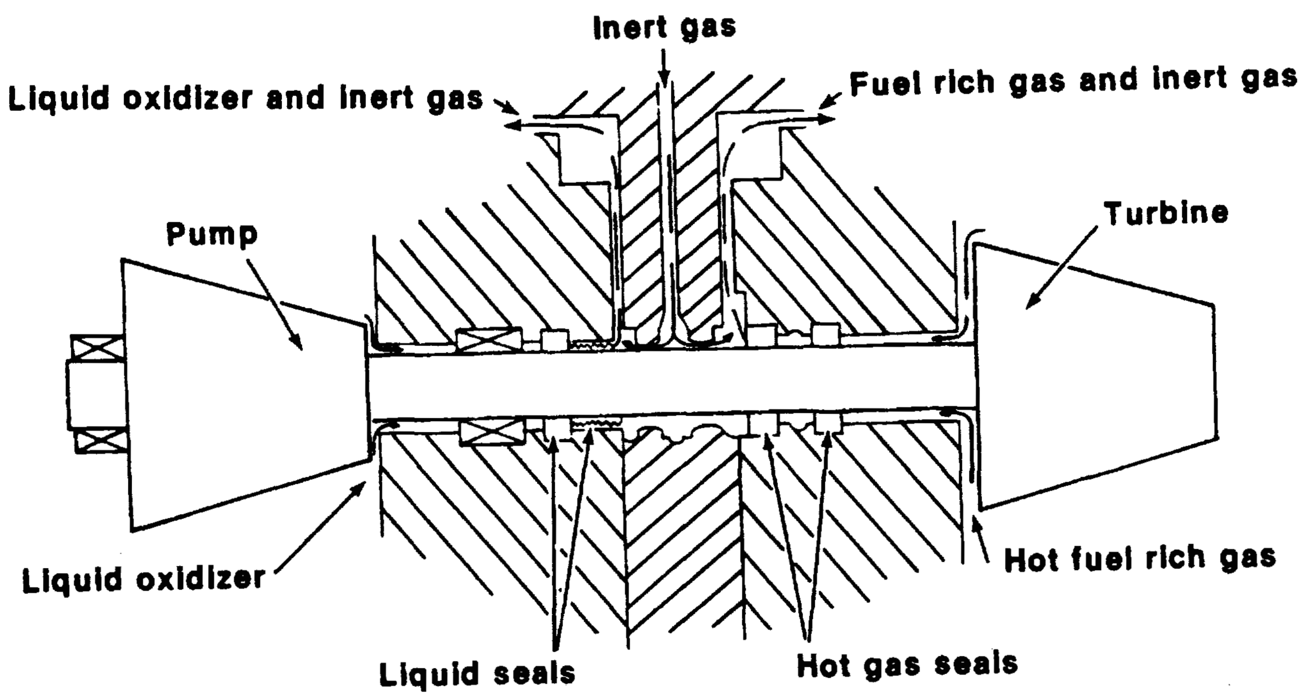

Figure 28.- Ancillary equipment - Bootstrap oxygen turbopump.

Heaters

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Problem:

In certain cases heaters are required to function within the high pressure oxygen environment. A malfunction in the heater or its control circuitry could result in overheating, a short circuit, or arcing, which would ignite system materials.

Solution:

Heater temperatures should be controlled to values substantially below the temperature at which ignition of the heater surface material or any adjacent material could occur. This margin should be at least 200^{o} F (111 K). In establishing it, the designer should consider the possible temperature difference between the thermal sensor and the hottest heater surface location, the uncertainty in sensor reading, and the uncertainty in ignition temperature. Redundant thermal sensors should be used if indicated by a failure modes and effects analysis.

Ignition due to electrical malfunction of the heater may be prevented by using double-insulated heater wire. An additional safety feature that can be used is the differential current sensor, which monitors heater current in both the inlet and the outlet wire and turns the heater power off if a predetermined imbalance develops (such as from a short or an arc from the heater to another element in the system). Materials, both metallic and nonmetallic, should be chosen to minimize the chance of ignition should a short or arc occur.

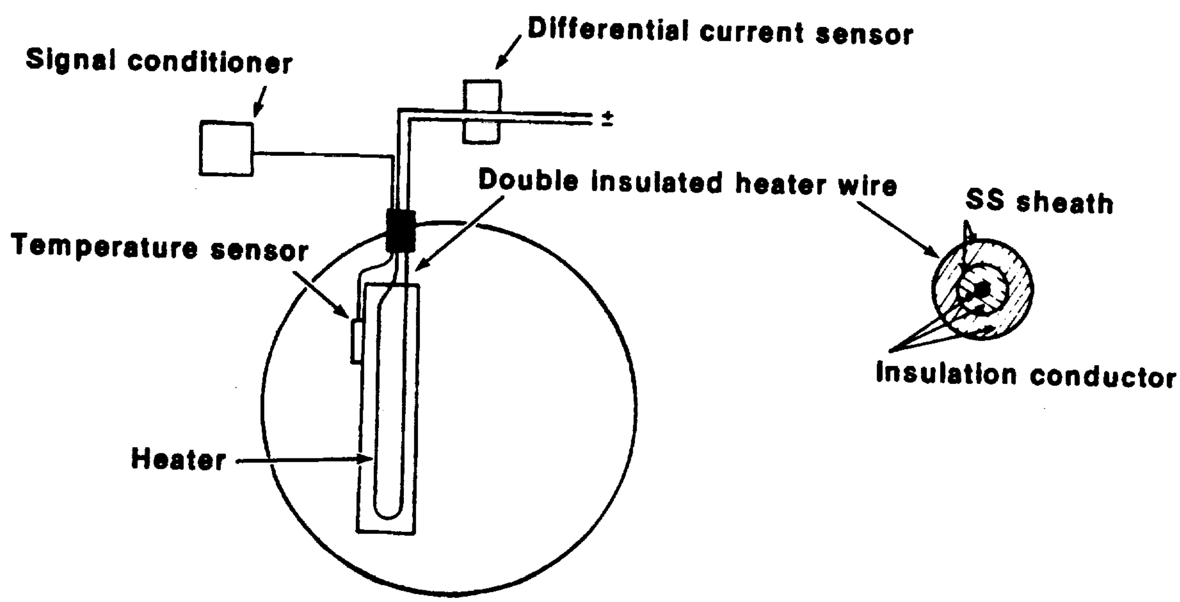

Figure 29.- Ancillary equipment - Heaters.

Sensors

Problem:

Sensors are required in oxygen systems to measure such parameters as temperature, pressure, density, liquid level, and flow rate. A malfunction in the sensor or its signal conditioner could result in high current flow, overheating, a short circuit, or arcing, which should ignite system materials.

Solution:

Sensor and signal conditioner circuitry should be designed to minimize the current flow and thus the overheating and arcing that might result from a short in the sensor system. Materials, both metallic and nonmetallic, should be chosen to minimize the chance of ignition should a short occur. In situations where arcing can occur, testing should verify that the maximum possible spark energy is insufficient to cause ignition of adjacent materials.

No figure is used to illustrate this item.

5. SYSTEMS DESIGN

It is our purpose in this section of the handbook to build on the guidelines for material selection and component design given in sections 3 and 4 and to extend these guidelines to the systems design level. These added guidelines are not exhaustive but focus on those special considerations required in the design of an oxygen system.

It is assumed that the designer will adequately handle those standard analyses related to system flow capacity, dynamic and static structural loads, thermally induced loads, heat transfer, etc. These routine analyses are not unique to high pressure oxygen systems, but inadequate attention to them can result in system failures whose results are magnified because of the extreme reactivity of oxygen.

Many of the special analyses required in the design of oxygen systems, as well as many of the potential design problems and the design practices for overcoming them that were presented in section 4 at the component level also apply at the system level. These areas have already been adequately discussed in section 4 and the information will not be repeated here.

Two areas of importance in the design of high pressure oxygen systems that should be noted are as follows:

1. In the performance of the fracture mechanics and flaw growth analyses, which should be a part of any system design, the designer should be aware that the presence of oxygen increases the fatigue crack growth rate in metals as compared to the rate in an inert atmosphere. Also, in gaseous oxygen systems, the presence of water vapor can further accelerate fatigue crack growth.

2. The selected architecture of high pressure oxygen systems imposes certain constraints on system operations such as the sequence and timing of commanded component functions. As an example, during shutdown of a cryogenic boost propulsion system, the engine's liquid oxygen prevalves must be closed and the LO_2 inlet line to the oxygen turbopump pressurized with inert gas within a closely specified time to avoid cavitation and a dangerous overspeed condition in the liquid oxygen turbopump. As part of the standard failure modes and effects analyses (FMEA) a comprehensive system operating analysis should be performed to understand the constraints imposed by a particular architecture on both normal and failure-mode operations.

In this section, we present design considerations for the use of high pressure oxygen which require special attention at the system level. We have grouped these design guidelines and special considerations into the following categories for discussion:

System architecture
System flow dynamics
System thermal design
System cleanliness

We will distinguish between cryogenic liquid, supercritical, and gaseous oxygen systems when the distinction is important.

SYSTEM ARCHITECTURE

System architecture considerations include identifying the components required to perform the function, defining redundancy requirements, and locating components within the vehicle and in relation to one another. Failure modes and effects analysis (FMEA) is an effective tool in the initial process of designing system architecture and should be used in selecting components, establishing redundancy levels, and evaluating specific system geometries, rather than as an after-the-fact justification of a system architecture that was derived by less disciplined means. There are system geometry considerations related to flow dynamics, thermal design, and cleanliness which will be discussed subsequently under those headings. The following two items are important system architecture considerations for oxygen systems.

Protection of System Redundancy

Problem:

A component or system-level failure can initiate a fire within the system. Oxygen fires, once started, spread rapidly using any exposed nonmetallics and even some metals as fuel. The fire may not only engulf the affected components but also spread to adjacent components and destroy system redundancy.

Solution:

Containment of a fire to as small an area as possible is desired. If the fire can be limited to a single component or to a small area, redundant components should be able to carry on the system function. Not only should all system materials be selected with an eye to their combustibility, but, wherever practicable, they should be selected to provide firebreaks between system components. Nickel and Monel are candidate fire-resistant materials. Furthermore, redundant system components should not be located in a common assembly or adjacent to one another because the failure of one of the components could then lead to failure of the others. The redundant components should be separated geometrically and also by firebreaks wherever possible. Figure 30 illustrates the use of firebreak application in systems architecture.

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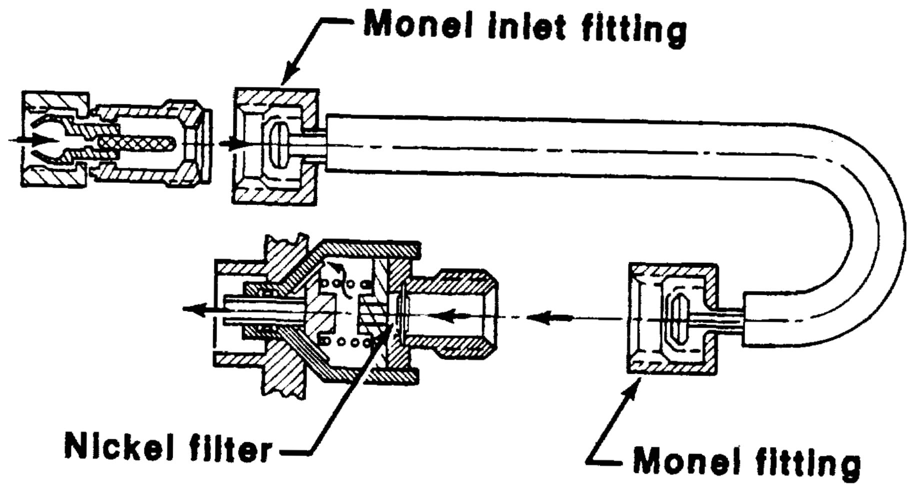

Figure 30.- System architecture - Protection of system redundancy.

Location of Oxygen System Relief Ports

Problem:

All high pressure oxygen systems are provided with pressure relief ports to prevent structural failure due to overpressure. Improperly located oxygen vents can damage adjacent components or cause an ignition.

Solution:

The designer must evaluate all system relief port locations to ensure that oxygen will not be vented overboard near a fuel or internally into an area containing a fuel and an ignition source. If oxygen is vented into internal vehicle cavities, a cavity analysis should be done to verify that no hazardous situation will develop as a result of the vent. As part of the system-level FMEA, a similar compartment hazard analysis should be done to determine the effects of any system leaks. Where cryogenic oxygen is vented, the potential to freeze adjacent components of other systems should be evaluated.

No figure is used to illustrate this item.

SYSTEM FLOW DYNAMICS

Considerations of system flow dynamics include flow velocity effects, particle impact, erosion, cavitation, induced vibration, geysering, water hammer, and pressure spikes. Particle impact effects, water hammer, and adiabatic compression effects have been discussed in section 4. The following four items deal with aspects of flow dynamics as they affect oxygen systems.

Because of the complexity and the variability of system design, no attempt was made to illustrate the items discussed in the rest of this section. We believe the problem statement and solutions are adequate for clear understanding.

System Erosion

Problem:

Erosion of system components due to flow phenomena such as particle impacts, impacts of droplets entrained in a gas flow, and cavitation can expose fresh, reactive surfaces to oxygen and provide the localized heat generation necessary to cause ignition.

Solution:

Good design practice to prevent erosion, as in the case of particle impact, includes velocity control, a flow geometry that minimizes impact angle, adequate filtration, selection of ignition-resistant materials, and control of localized system pressure drop and heat input to minimize cavitation potential.

Cavitation in Rotating Equipment

Problem:

Cavitation (creation of localized areas in the fluid having pressures below the vapor pressure) in liquid oxygen feed systems upstream of oxygen turbopumps can result in a variety of turbopump hazards. These hazards include erosion of the impeller and localized burning of the impeller due to bubble collapse. Extensive cavitation may cause turbopump overspeed leading to critical rotor dynamics problems, including rubbing of the impeller on the housing with resultant frictional ignition.

Solution:

The system design must provide adequate net positive suction pressure (NPSP) to oxygen turbopumps by establishing adequate supply tank pressure

and carefully calculating and controlling flow system thermal inputs or by using a boost pump upstream of the turbopump.

Flow-Induced Vibration in Bellows and Flexible Joints

Problem:

Oxygen flow through bellows and flexible joints can induce high-level pressure fluctuations in these components which can lead to rapid failure due to structural fatigue.

Solution:

Flow velocity through these components should be minimized. Where possible, bellows should be lined. Where lined bellows cannot be used, the system should be analyzed for susceptibility to flow-induced vibration.

Geysering in Cryogenic Liquid Oxygen Propulsion Feed Systems

Problem:

Geysering occurs in vertical systems with a tank and a long feedline from it filled with cryogenic oxygen. Heat transfer into the line causes gas bubbles to form and begin rising in the line. As the bubbles rise, they coalesce to form larger bubbles. In a line that is long with respect to its diameter, the result is an expanding vapor bubble of sufficient size to expel the liquid above it into the tank with a force large enough at times to rupture the tank or to damage internal tank components such as baffles, screens, or level sensors. When the liquid subsequently reenters the line, it can cause large water hammer forces with accompanying system damage.

Solution:

Geysering can be controlled by controlling tank pressure, choosing appropriate feedline geometry, insulating the feedline, and recirculating the fluid from the low point in the line back to the tank. Control consists of keeping the oxygen in the line from reaching its vaporization temperature and providing adequate line diameter to handle the vapor bubble percolation that still occurs.

SYSTEM THERMAL DESIGN

System thermal design considerations include startup thermal conditioning, insulating to prevent external system condensation, and avoiding the lockup of cryogenic oxygen in a system segment.

Startup Malfunctions in Rotating Equipment and Dynamic System Components

Problem:

In cryogenic oxygen turbopump systems, it is necessary to bring components to thermal equilibrium before starting up the system to avoid hazardous component thermal transients which may affect fits and clearances, cause rotor dynamic instabilities, or lead to high speed rubbing friction. Any of these problems may result in an ignition.

Solution:

Provide thermal conditioning of the cryogenic system and components by gradually bleeding through cryogenic gas, then liquid. Once approximate thermal equilibrium is achieved, maintain it by using pumps to circulate properly conditioned fluid through the system before startup.

Condensation on External System Surfaces

Problem:

Exposed cryogenic surfaces in oxygen systems can form large amounts of ice. The falling ice can damage the vehicle or its components during ground operations or launch.

Solution:

Exposed cryogenic surfaces should be insulated. Any of the various insulation schemes (sprayed-on foam, wrap-around closed-cell segments, vacuum jackets) used to control heat input to cryogenic oxygen systems can be used to preclude the formation of ice or liquid air on surfaces. The designer should ensure that there are no uninsulated system areas or exposed gaps between insulated areas which permit the buildup of ice.

Lockup of Cryogenic Oxygen in System Segments

Problem:

Cryogenic oxygen hydraulically locked up between two valves or flow control components can absorb heat and through the increase of pressure cause structural failure.

Solution:

The system and components should be designed to provide appropriate pressure relief and thereby preclude unacceptable pressure buildup. Either a separate relief system may be incorporated into the system or back-relief valves may be built into the components. System relief devices should be protected by insulation and perhaps by purging with nitrogen or helium to prevent ice blockage of the relief port.

Condensation of Contaminants Within Cryogenic Systems During Loading

Problem:

Loading cryogenic oxygen can result in condensation water or any other condensable vapor inside the system. In large systems, even contaminant levels measured in parts per million can produce a sizable frozen mass that could impede flow or system function.

Solution:

Before a cryogenic system is loaded, all air, water, and condensable vapors should be purged or evacuated from the system. Experimentation may be required to define the degree of purge or the number of evacuation cycles required.

SYSTEM CLEANLINESS

System cleanliness is extremely important in oxygen. Metallic and nonmetallic contaminants and nonvolatile residues may be left in components and systems after fabrication and assembly. The component design practices identified in section 4 concerning contaminant generation and control are also applicable to system design as are the clean assembly techniques discussed in section 6 and the cleaning techniques discussed in section 8.

The designer should recognize, however, that component filters alone may not be adequate to handle contaminants built into the system or generated at the system/level. Separate system-level filters may be required to control particulate contamination, and appropriate system flush and purge ports should be designed into the system.

System Level Filters

Problem:

The most rigorous attention to designing a system for clean assembly and clean operation and to minimizing contaminant collection areas cannot totally eliminate contamination built into the system and generated by the system during operation. If system-level contamination control and removal features are not provided, performance and safety may be severely degraded.

Solution:

Adequate system-level filters should be provided (filtration rating, dirt-holding capacity) to handle built-in contaminants and system-generated contaminants. The system filters should be located so as to protect component filters from contamination overload.

System Flush and Purge Fittings

Problem:

The most rigorous attention to designing a system for clean assembly and clean operation and to minimizing contaminant collection areas cannot totally eliminate contamination built into the system, generated by the system during operation, or introduced into the system during maintenance operations. If system-level contamination control and removal features are not provided, performance and safety may be severely degraded.

Solution:

System flush and purge fittings should be located at appropriate high and low points to allow effective flush or purge of the system in all expected attitudes.

6. CLEAN ASSEMBLY AND INSPECTION

CLEAN ASSEMBLY TECHNIQUES

An area of foremost concern in high pressure oxygen systems is contamination control. Contaminants are the most likely source of readily ignitable material. If they are nonmetallic, then they have relatively low ignition temperatures. If they are metallic, they have been abraded off metal surfaces. Such a product of metallic abrasion will have bare, unoxidized metal as a portion if not all of its exposed surface area. This surface is readily ignitable when heat from impact, shock, or compression raises the local temperature to a critical value. Elimination of all contaminants is highly desirable but not totally achievable in complex assemblies which include nonmetallic seals, threads, screw lock plugs, press fits, welds, soldered and brazed joints, and lubricants. Fortunately, there are some beneficial techniques that can be used to minimize the bad side effects of these sometimes necessary features.

Assembling Seals

Designs that allow or cause harmful cuts or abrasions to the in-place seals during assembly can create contaminants and can set up future contaminant generation, as the seal will continue to shed particles during its functional life. A typical example figure 31 is the assembly of a shaft into a bore containing an O-ring. The shaft could cut the O-ring because of a nonexistent or inadequate chamfer on the end of the shaft. Perhaps even more common is the forcing of an O-ring over screw threads to position the seal on a threaded shaft or bolt. The crest of the threads will cut and chip the seal, and, if the assembled components are not recleaned, then the contaminated item is left in the system.

Seals should not be forced into bores or over shafts without generous chamfers. These parts must be inspected for burrs and sharp edges before they are assembled. It is important to note that a chamfer will have a sharp edge unless it is specifically removed. Hardened steel may have a very pronounced sharp edge at the intersection of the chamfer cut and the outer diameter of the shaft.

Installation of an O-ring over threads whose major diameter exceeds the inside diameter of the O-ring should be avoided if possible. If this danger of cutting into the O-ring cannot be avoided, then the assembly specifications should allow for additional cleaning after the O-ring and the threaded part have been assembled and before the components are installed in the next level of assembly. A light coating of seal lubricant should be used to ease the assembly.

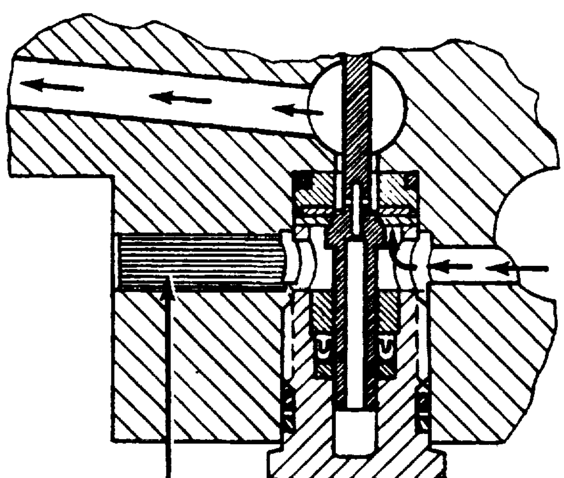

Figure 31.- Contamination generation during assembly.
NOTE: Care must be exercised in the installation of O-rings into bore.

Threaded Assembly

Threaded connections occurring in fluid systems can generate contaminants as the threads are engaged and tightened, as shown in the first illustration of figure 32. One way to avoid this problem is to redesign the threaded members as shown in the second illustration, wherein the smooth portion of the plug interfaces with the seal before the threads engage. This solution, however, does involve rotating a part against its seal causing real damage. Alternately, the in-line threaded feature could be replaced with a flanged and bolted connection, which places the threaded portions outside the fluid stream, as shown in the third figure. Using another method, the function of the threaded member can be carried out by a separate nut device that is not inserted until the sealing has been accomplished with a push-in plug, as shown in the fourth figure. And finally, another option is to install a barrier ring to block the migration of particulate matter, as shown in figure 32e.

Deformable Parts

Parts such as screw locking devices, usually nonmetallic inserts, which function by allowing other parts to deform them are contaminant generators. Their use should be limited as much as possible and their installation should be sequenced so that they are driven in one time only. Successive assembly and disassembly only compounds the amount of particulate created.

Press Fits

Press fits generate particles during their assembly from the relative motion of the two highly loaded surfaces. These particles can be partially removed by cleaning the joined parts immediately after pressing them together, and this step should be called for on the subassembly drawing. Direction should be given in the assembly procedure document that the installation of press fit, push fit, and threaded valve parts into housing bores should be performed with the housing inverted (bore opening pointing down) so that assembly-generated contaminants fall away from the component rather than into critical flow paths.

Welded, Soldered, and Brazed Joints

Welded, soldered, and brazed joints, if left in the as-formed condition, may leave slag, roughness, porosity, or cracks which can generate or trap contaminants. The use of such joints should be minimized in high pressure oxygen components. When the use of welds cannot be avoided, they should at least be specified as full penetration so that all contacting surface area is joined to prevent entrapment of particulates and eliminate uncleanable blind surfaces. Exposed weld surfaces should then be ground to a smooth finish to enhance cleaning.

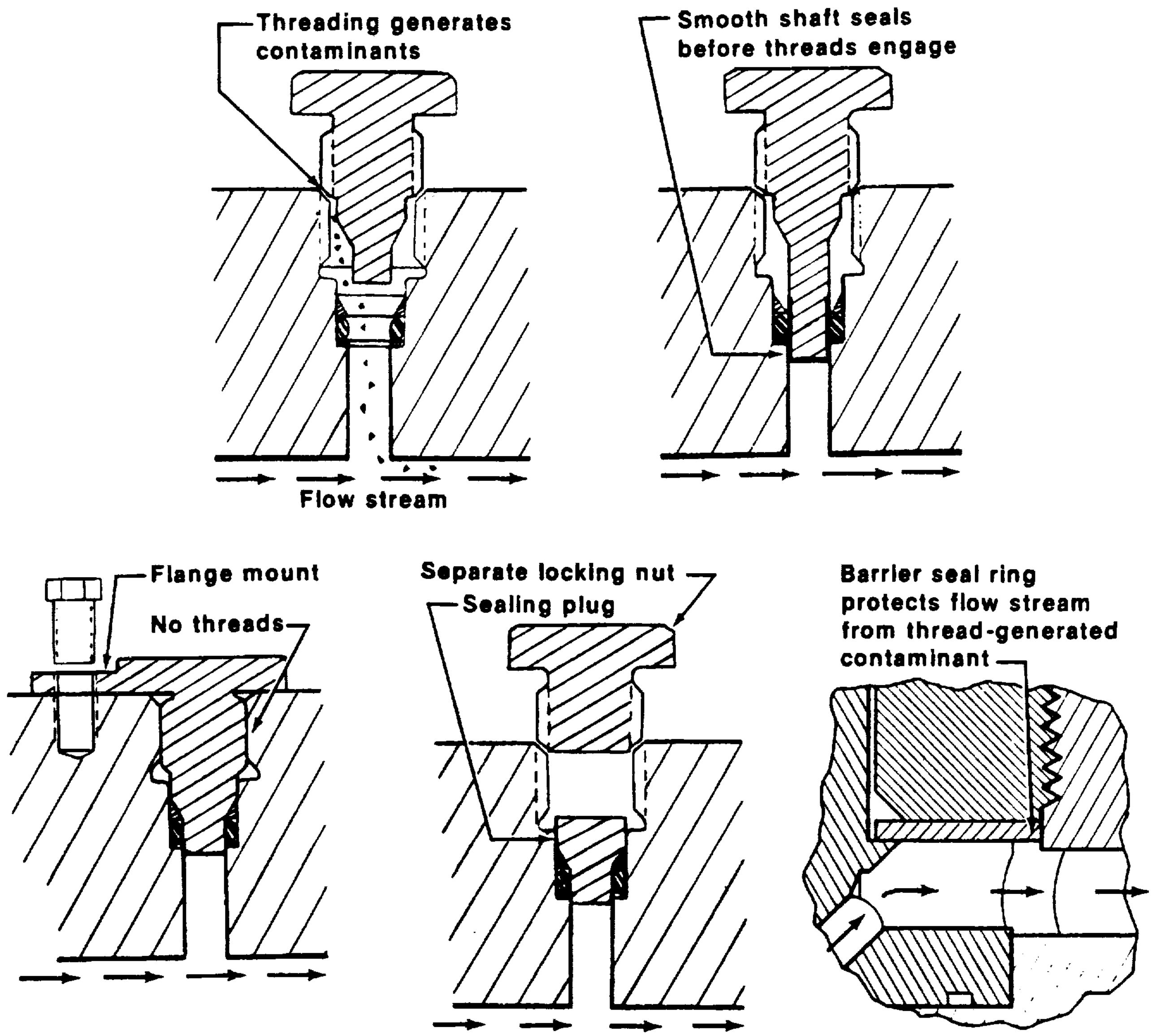

Figure 32.- Threaded assembly generates contaminant.

Burrs

Removal of burrs and sharp edges is critical in high pressure oxygen systems. Accomplishing this in small-diameter internal passageways at the intersection of cross drills is a common problem. The best results have been obtained with small, motorized grinding tools and with electrical discharge machining (EDM).

Lubricants

Lubricants should be used wherever necessary to reduce abrasion and damage to seals during assembly and to enhance the sealing or sliding of parts operationally. Care should be taken, however, to apply lubricants lightly and to remove excess to prevent future migration. Only approved batch/lot tested lubricants should be used, such as batch-certified Krytox 240 AC or Braycote 3L-38RP. It should be noted that, although such approved lubricants are identified as oxygen compatible, they can react with oxygen when system design limits on temperature, pressure, or pressure rise rates are exceeded.

INSPECTION REQUIREMENTS

This design guide points out design, assembly, and contamination problems that should be avoided in high pressure oxygen systems. The problems, their causes, and the means of avoiding them are treated in considerable detail in the sections on design requirements. The design guidelines recommended in this document should be reviewed and applicable features incorporated whenever possible. However, even incorporation of as many as possible is no guarantee against errors. Therefore, special inspection procedures should be used to identify certain problems that are potentially dangerous to oxygen systems.

The problems that tend to increase the ignition hazard in high pressure oxygen systems and, at the same time, lend themselves to inspection are listed below, along with the recommended inspection methods. These additional inspection requirements will increase the overall reliability of the system and should be imposed whenever feasible. These additional inspection procedures should be used in conjunction with, not in place of, inspection procedures normally used to verify component integrity, cleanliness, and conformance to specifications.

Thin Walls

Radiography (X-ray) is a most effective inspection method for imaging and measuring thin walls. Preparation of a clear plastic block figure containing all the passageways is a useful inspection aid for visualizing distances and tolerances between passageways. An example of a machined plastic block is shown in figure 33. Such a block would also aid in visualizing the X-ray view required.

Blind Passages or Dead End Cavities

Often a dead end cavity is the unintended result of an overdrill. X-ray is an excellent inspection method for imaging and measuring dead end cavities. There is also some potential for imaging metallic debris in the cavity using the X-ray method. Visual examination is another excellent method for finding dead end cavities where holes are large enough for a borescope to be inserted.

Feathered Edges and Machine Burrs

Visual inspection is the most effective means of detecting feathered edges and machine burrs when a borescope can be inserted. X-ray has some potential for detecting these conditions, but it is limited by orientation considerations and the generally large overall thickness of the part compared to that of feathered edges or burrs.

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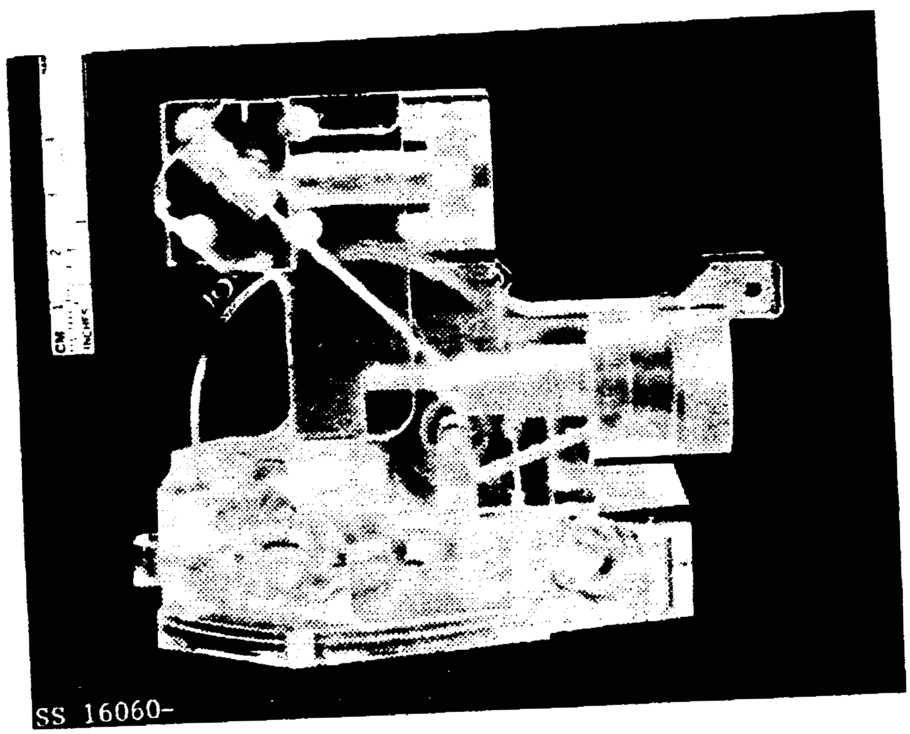

Figure 33.- Machined plastic block.

Seal and Filter Placement

Improper placement of seals, such as reversing the position of seals and backup rings, can result in extrusion of the seal or particulate matter into the oxygen flow. X-ray is quite effective in imaging metallic seals, backup rings, and filters, while neutron radiography is excellent for imaging hydrogen-bearing nonmetallic seals and backup rings.

Debris

Debris is particulate matter that can cause impact heating when carried by a high velocity gas stream or friction heating when entrapped between sliding surfaces. Where a borescope can be inserted, visual inspection is the most effective means of detecting debris. X-ray has some potential for detecting larger metallic particles, although overall part thickness is a limiting factor. Neutron radiography can be used to detect hydrogen-bearing nonmetallic debris, but again overall part thickness is a limiting factor, although not as pronounced as for X-ray detection of metallic debris. Neutron rays are not absorbed by the metal housing as readily as X-rays. A third means of detecting debris or loose particles is to vibrate the part with acoustic sensors attached to the housing. Inspections for debris should be performed after cleaning and could even be considered after assembly as a final verification of system cleanliness.

REINSPECTION RECOMMENDATIONS

Oxygen components and systems should be periodically reinspected to ensure that safety and component integrity are maintained during the life of the system. Determination of system and component reinspection intervals has proved to be a complex task. Detailed knowledge of construction materials, pressure levels, the use environment, and the service the system is performing must be applied. For example, a system that supplies high pressure oxygen to flight hardware is reinspected with greater frequency and in greater detail than is a low pressure oxygen system in a facility welding shop.

In establishing the reinspection intervals, the following items should be considered.

a) Routine disassembly and reassembly of piping systems invariably increases the level of system contamination because particulates are generated.

b) Sampling of an assembled system or component for gasborne contaminants yields only limited data on the internal cleanliness of the overall system because the ability of flowing gases to entrain particulates is a function of particulate mass and identity, gas flow velocity, gas viscosity, system configuration, and other factors. We must emphasize that this method of system sampling cannot be directly correlated with the cleanliness or contamination of internal component or system surfaces.

c) The reinspection plan must address the design service life of components. It must identify problems associated with anomalous component behavior (such as chatter in check or relief valves, valve internal leakage, and regulator pressure control instabilities) and address the disposition of these problems.

d) Additional insight regarding system contamination levels can be gained through systematic inspection of components (e.g., transducers, flex hoses, relief valves, filters) removed for calibration, proof-testing, or periodic maintenance.

Reverification of cleanliness levels in components and systems that have been in service is the subject of Section 8, Cleaning Requirements.

7. COMPONENT AND SYSTEM-LEVEL TEST REQUIREMENTS

OBJECTIVES

The main objectives of individual component and system-level testing are to investigate the performance and operating characteristics of the individual components, and to then investigate the effects of their interaction when assembled and operated as a system. Component testing evaluates and verifies that the specified functional performance, life, reliability and safety are satisfied; while system-level testing satisfies the same purpose at the higher assembly level. Some system components such as lines, connectors, flanges, and sensors are tested for the first time at the system level. A further objective of system-level testing is to define the range of conditions encountered by each component as the system is operated over its full specified operating range, and to verify that the individual component specifications meet these conditions satisfactorily.

TYPES OF TESTING

Three types of component and system-level testing are of interest - engineering development tests, qualification tests, and acceptance tests.

Engineering Development Tests

The complete range of functional requirements, the entire spectrum of imposed environmental conditions, and the full life capability of the components and system should be demonstrated in engineering development tests. Hardware of the highest fidelity possible should be used and the tests should be done with oxygen. The purpose of these tests is to come to a full understanding of the performance of the component and system over the full specification range while it is still possible to change the hardware. Engineering development tests are not burdened with the rigorous discipline of full quality control coverage. Satisfactory engineering development tests of adequate scope can help to guarantee a successful formal qualification program.

Consideration should be given to running selected off-limits tests to determine the real limits of the components and system. Such testing may be particularly valuable where hardware performance margins are not known, where single point failures may exist, or where uncertainty exists in the specifications.

Qualification Tests

These components and systems must demonstrate under full quality control discipline their functional performance enabling them to withstand the possible stresses and to meet the environmental conditions of their application, their life expectancy, and their safety and reliability. Qualification tests are performed on hardware of the highest possible fidelity

with the test system arranged as close to the actual configuration as possible. These tests must be run with oxygen. The component or system is always subjected to a formal acceptance test as the initial portion of the qualification test.

Higher level qualification testing, often called verification testing, is frequently done on an oxygen system to verify that it integrates satisfactorily with other vehicle systems. An example is an integrated vehicle test in which the system software is verified to operate the system satisfactorily. Other examples are large-scale vibro-acoustic and thermal tests.

Acceptance Tests

In acceptance testing, the component or the as-built system must demonstrate that it meets functional requirements, is safe, and is compatible with oxygen as its working fluid.

GENERAL SYSTEM TEST REQUIREMENTS

Several considerations are common to all three types of component and system-level testing.

The fidelity of both the hardware and the test system geometry should be at the highest level possible for all tests.

Cleanliness is crucial in oxygen components and systems. Extreme care must be taken to ensure that all components have been cleaned by approved procedures, that the system has been assembled following approved procedures, and that its cleanliness has subsequently been verified as meeting the standards for gaseous and liquid oxygen usage. See sections 6 and 8 of this handbook for recommended inspection and cleaning standards and procedures.

All fluids to be put into the test system must first be sampled from the ground service equipment and analyzed to verify acceptable quality. All fluids introduced into the test system for system-level tests must be filtered to an appropriate level at the system-loading interface. The ground system filters must be as fine as or finer than the finest onboard filter to keep from loading into the system particulates that would reduce the capacity and life of the flight system filters. After the test, samples of fluids should be removed from the test system for analysis and filtration. These tests should detect any change in fluid properties or degradation in fluid quality. They should also detect any particles picked up by the fluid which may indicate failure, incipient failure, or design problems within the system.

As a cryogenic liquid is loaded into a test system, care must be taken to avoid excessive thermal shock and to prevent pressure vessel implosion due to pressure collapse.

Care must also be taken to verify that insulation is properly installed on cryogenic areas to prevent excessive ice buildup on the test system.

All ground service equipment should be carefully assessed to verify its adequacy to support the test requirements under both normal and contingency operations.

Test designers must verify that any nonflight hardware or instrumentation used in component or systems testing does not compromise the test objectives or system safety. In particular, if any instrumentation such as a pressure transducer is connected into the system by a tube stub, the test director should ensure that the orientation of the tube does not cause it to act as a contaminant collection point, that the tube stub does not become an acoustic heating cavity source, that the potential for cavity compression heating is minimized, and that the instrument is supported to avoid vibration failure.

TEST PROGRAM CONTENT

Much of the recommended test program content for engineering development tests, qualification tests, and acceptance tests is the same for both individual components and for system-level tests.

Engineering development tests should include the following as a minimum.

1. Pretest flow and functional validation tests, including tests of instrumentation operation. These tests to verify that the test system and components are operating correctly should be performed with a clean inert fluid.

2. Stress testing. These tests exercise the system over the entire combined range of test parameters (pressure, temperature, flow), concentrating on those combinations of parameters which produce the worst system stress. Stress testing can be accomplished by operating the component at test pressures that exceed the highest pressure and temperature expected in operation by at least 10 percent. Facility and ground support equipment should be chosen so that its maximum allowable working pressure (MAWP) is sufficiently above planned use levels to allow a 25-percent test pressure margin and still be below the MAWP. In addition, flight equipment should be exposed to a pneumatic surge (gaseous impact) at least twice the rate it is expected to experience in use. Pressure rise rates from 20,000 to 100,000 lb per in^2 per second (140 to 690 MN per m^2 per second) are commonly used. A rapid pressure surge can, by the process of adiabatic compression of the oxygen, heat internal soft goods or assembly-generated contaminants to their ignition temperatures. If a component passes this test phase, user confidence should be significantly enhanced. Stress tests must be performed using oxygen. These tests demonstrate the ability of the component or system to operate over the required range of parameters satisfactorily, and with some safety margin.

3. Environmental testing. These tests expose the component or system, both operating and nonoperating, to the application's expected range of environmental conditions (temperature, pressure (or vacuum), humidity, sand and dust, rain, acoustics, vibration). Environmental tests must be performed with oxygen in the system. These tests demonstrate the ability of the component or system to operate satisfactorily in the expected environment.

4. Life cycle tests. These tests to assure that the system will last the planned lifetime may include mechanical cycles, thermal cycles, pressure cycles, and load cycles. These tests must be performed with oxygen. The number of cycles to be performed is determined from the anticipated use. For flight equipment, the number of test cycles is typically specified to be 4 times the expected life cycles for each operational mode. For facility and ground support equipment, which is usually designed and constructed for longer life and a greater factor of safety than flight equipment, the number of cycles is typically limited to that required to demonstrate functionality and oxygen compatibility; however, a statistically significant number of cycles should be performed in each operational mode. Experience indicates that 50 cycles in each mode should identify inherent operational problems.

5. Posttest flow and functional validation tests. These tests to identify any changes in component or system performance resulting from the test program or from exposure to oxygen should follow the same procedures used for the pretest flow and functional validation.

6. Disassembly and inspection. After the engineering development tests have been completed, system components should be examined in detail to identify evidence of damage, wear, failure, or incipient failure. Special attention should be directed to the condition of soft goods and the presence of contamination. Sources of any observed contamination should be thoroughly investigated. In this manner, anomalies such as fretting, overstressing, and other functionally introduced failures can be identified and corrected before the component is put into use.

Qualification tests should always begin with the approved acceptance test. Thereafter, the qualification test program should be as described for the engineering development tests. Qualification tests, of course, are conducted under the discipline of full configuration control, detailed test procedures, and specified pass/fail criteria. All qualification tests (except the pretest flow and functional validation) must be performed using oxygen.

Acceptance tests should include the following as a minimum.

1. Pretest flow and functional evaluation to verify that the component or system is operating correctly, meets specifications, and has the same performance characteristics as the qualification component or system. This evaluation should be conducted with an inert fluid that meets cleanliness standards.

2. Flow and functional tests, including limited cycle testing, using oxygen to verify system compatibility. Cycle testing should be an abbreviated version of the qualification test procedure. To ensure safety and functionality, pressure and temperature levels should exceed the maximum anticipated use levels. The number of cycles should be only that needed to demonstrate oxygen compatibility. During cycle testing, each component should be evaluated for functional anomalies.

3. Posttest flow and functional evaluation using oxygen.

TEST PROGRAM EVALUATION

In all tests, special attention should be paid to the detection of potentially dangerous characteristics--pressure surges, sustained pressure oscillations, standing acoustic waves in cavities or blind passages, valve or regulator chatter, frictional contact of component parts, etc.

Any time an anomaly is detected, the system or component should be disassembled and inspected to determine the corrective action that must be taken.

Any discrepant or anomalous hardware must be subjected to an established system of controlled review, rework, and reinspection before it is considered for reuse.

8. CLEANING REQUIREMENTS

Cleanliness (contamination control) is critical in oxygen components and systems. There are two obvious reasons. First, contamination levels may be sufficient to cause functional anomalies such as leaking valves or regulators. Second, the presence of contamination can cause ignition of components or systems by a variety of mechanisms such as particle impact, mechanical or pneumatic impact, or spontaneous ignition. These mechanisms are discussed more thoroughly in other parts of this handbook.

The cleaning of an oxygen system should begin with disassembly to the elemental or piece part level. If cleaning is attempted by flowing solutions through a component, vulnerable internal elements may be damaged by the solutions required to clean the major elements of the component. Also contaminants and cleaning solutions may become entrapped in component recesses and may ultimately react with oxygen. When the component has been disassembled, the parts should be grouped according to the method of cleaning. Special cleaning procedures must be developed to remove entrapped contaminants. Disassembly also allows assessment of the serviceability of the component elements. If sealing surfaces are damaged or cracks are observed in the metallic parts, the component must be repaired or replaced. Special attention should be directed to the component soft goods. Damaged or worn soft goods should be replaced with soft goods from the same batch if possible. If soft goods of the same batch are not available, requalification of each component with the new batch of soft goods is recommended unless oxygen compatibility can be established by other means.

Each system and component element must be subjected to cleaning processes which employ the following general techniques.

Precleaning of individual parts must be performed to remove contaminants from readily accessible surfaces. The first step should be a degreasing of the surfaces. Nonmetallics and used metallic parts can be adequately degreased by rinsing with trichlorotrifluoroethane (Freon PCA, MIL-C-81302B, amendment 1, type II); newly machined parts and unusually dirty parts should be vapor-degreased using trichloroethylene or 1,1,1-trichloroethane. Caution must be exercised in the use of vapor degreasing since some metals, such as magnesium, could react with the degreasing solvent. Various cleaning solutions can then be employed in conjunction with ultrasonics. Commonly used cleaning solutions include the following.

Alkaline cleaning solution, typically contains sodium hydroxide, sodium carbonate, sodium metasilicate, sodium phosphates, and surface-active (wetting) agents. Such solutions may be used at temperatures up to 180° F (355 K). An example is Oakite HD126.

Acid cleaning solution, which typically contains phosphoric acid, ethylene glycol monobutyl ether, and wetting agents. These solutions may be used at temperatures up to 150° F (338 K). Oakite 33 is an example.

Mild alkaline liquid detergent, which typically contains anionic and nonionic surface-active agents, chelating agents, and sodium metasilicate.

Such a detergent may be used at temperatures up to 180° F (355 K). Example: Oakite Liqui-Det 2.

Rust and scale remover, which typically contains sodium hydroxide (at much higher levels than in an alkaline cleaning solution), sodium carbonate, surface-active agents, and chelating agents. Such solutions are used from 160° F (344 K) to boiling. Oakite Rustripper is an example.

The sequence of cleaning solutions to be used depends on the material to be cleaned. Stainless steels (300 series), Monel, and Inconel normally are cleaned in alkaline solution and then in acid solution. Carbon steel is cleaned by rust and scale remover, if required, followed by alkaline solution. Copper and brass are cleaned in alkaline solution and briefly in acid. Aluminum is cleaned in liquid detergent. Soft goods are cleaned in liquid detergent except for Teflon, which may be cleaned in alkaline solution followed by acid. Other specialized materials may require different sequences, and consideration must be given to metals' reactivity. Other specialized solutions such as pickling or metal-brightening (chromic acid) solutions may also be employed. A thorough water rinse between cleaning solutions is mandatory. Following the last water rinse, the parts should be flushed with isopropyl alcohol, then Freon PCA. During the entire cleaning process, the parts should be visually inspected and mechanically cleaned when necessary. Visual inspection should be required before final cleaning since gross chemical contamination cannot be removed in final cleaning.

The precleaned parts should then be moved to a clean room. We have found that a Class 100 laminar flow environment, as defined in Federal Standard 209B, is adequate. Final cleaning, sampling, and analysis is performed by rinsing each part with Freon PCA, then sampling the rinse fluid. Soaking in an ultrasonic Freon PCA bath may be necessary to remove particulates. The volume of rinse fluid retained for sampling and analysis is directly related to the rinsed part surface area; e.g., 100 ml/ft^2 (1080 ml/m^2). The rinse fluid is filtered to ascertain the particulate contaminant levels; then the fluid is subjected to chemical analysis for determination of total hydrocarbon content.

Additional information may be obtained from applicable sections of JSCM-5322B, 1982, "JSC Contamination Control Requirements Manual."

A typical particulate specification that has been found to be adequate for oxygen systems is shown in the following table.

MAXIMUM ALLOWABLE PARTICULATES PER SQUARE FOOT
(PER SQUARE METER) OF CRITICAL SURFACE

Particle size range (μm)*	Maximum quantity	Per Sq. meter
0 - 10	No silting permitted	None
11 - 25	85	915
26 - 50	8	86
51 - 100	4	43
>100	0	0
Fiber length (μm)		
100 - 175	1	11
>175	0	0

In addition, a total hydrocarbon content (THC) assessment should be performed in lieu of the normally specified nonvolatile residue (NVR) assessment. Determination of THC permits a qualitative as well as a quantitative measure of the effectiveness of the cleaning process. Since the THC limit of 3 $\mu g/ft^2$ (32 $\mu g/m^2$) of cleaned surface area (based on a 100-ml sample of flushing fluid) is far more stringent than the normal NVR specification of 1 mg/ft^2 (11 mg/m^2), users of this THC process can be better assured that their hardware is essentially free of nonparticulate contaminants.*

Experience has shown that approximately one-half of all parts cleaned will fail to meet either the particulate or the THC specification on the initial sampling; consequently, recleaning is required until all parts pass both specifications.

After a part has been cleaned to these specifications, it should be bagged by itself in FEP Teflon film. The Teflon used for bagging oxygen system parts should be as clean as the item being packaged. Teflon has been chosen for the initial packaging of oxygen system parts over such alternative materials as polyethylene and nylon because its surface is relatively nonshedding, it is more easily cleaned, and it is more oxygen compatible. Some drawbacks of Teflon are its high cost, its tendency to develop an electrostatic charge which attracts particles, and its permeability to water. To reduce particulate contamination, the part is sealed in the Teflon bag while in the final cleaning area (laminar flow clean room) using a special heat sealer. The Teflon bag is then covered with a polyethylene outer bag which is heat sealed. This outer bag protects the Teflon and the part from abrasion, statically attracted particles, and moisture. A label should be affixed to each bagged part to document the cleanliness level achieved.

* μm is micrometer. μg is microgram. mg is milligram.

After system and component disassembly and cleaning, reassembly of components and systems must be stringently controlled to assure that the achieved cleanliness levels are not compromised. All components requiring reassembly (such as valves, regulators, and filters) should be reassembled in a filtered-air environment such as a Class 100 clean room or flow bench. Personnel should be properly attired in clean room garments and gloves. All tools that contact component internal must be cleaned to the specified levels. Only approved lubricants such as batch-certified Krytox 240 AC or Braycote 3L-38RP should be used, and then sparingly. Bear in mind that lubricants, although identified as oxygen compatible, can react with oxygen when system design temperature, pressure, or pressure rise rate limits are exceeded. Also, a lubricant can migrate into an area that should not be lubricated, thereby causing functional anomalies (such as regulator control mechanisms that fail to respond properly because of contamination by excess lubricant).

Reassembly of systems should be accomplished in a manner which minimizes contamination of the system. Some techniques commonly employed include buildup of the system as subassemblies using the same techniques as for components (filtered-air environment, etc.). When the size or location of a system precludes this practice, a low pressure purge of the system by a clean inert gas during reassembly or a portable clean tent can be used to reduce contamination.

After the system has been reassembled, a pressure integrity and leak test should be performed, using an appropriately filtered inert gas that has been analyzed for contaminants. Then the system should be purged with a high pressure, high volume clean inert gas in an attempt to mobilize and remove any particles generated during reassembly. After this purge or "blowdown," the system may be vented, then pressurized with oxygen. It is a good practice to perform the first oxygen pressurization of a system by remote control since ignition of assembly-generated contaminants can occur.

System cleanliness verification and reverification procedures should be performed whenever significant disassembly and reassembly has occurred or contamination is suspected. Also, if the oxygen system contains components with a history of in-service failure, appropriate traps (e.g., filters) or other easily analyzed components should be removed, inspected, and replaced periodically.

Oxygen systems can be sampled for gasborne particulates by attaching a filter to each outlet of the test system and then flowing a clean inert gas or oxygen through the filter as fast as is possible without exceeding the maximum allowable working pressure for either the filter or the system. A better measure of the system's ability to deliver oxygen of a desired cleanliness can be taken if the sample flow rate exceeds the system end-use flow rate. The quantity and size as well as the type of particulate can be determined by performing a chemical/metallurgical analysis of the trapped particles.

Gasborne particulate analysis is commonly used on a gas sampling volume of 35 standard cubic feet (1 cubic meter). Using a standard volume

permits direct comparison with other gasborne particulate samples; however, this method of system sampling is not directly correlative to the sampling of internal component or system surfaces.

Oxygen systems can be sampled for surface-borne particulates and hydrocarbons, halocarbons, and other nonvolatile residue by removing system lines or components that lend themselves to contaminant entrapment, either by position or design (e.g., a system low point or a filtering device) and subjecting the lines or components to sampling and analysis. Specific solvents may be used to separate selected materials; e.g., carbon tetrachloride may be used to dissolve halocarbon oil without also mobilizing Krytox or Braycote lubricants. After a line or component has been flushed or visually inspected, it should be recleaned before it is reinstalled in the oxygen system.

In summary, while cleanliness will not make a poorly designed fabricated system safe, contamination can cause the best systems and components to be hazardous.

9. SUMMARY

Much analytical and experimental work has been done in recent years to broaden the understanding of the ignition-triggering mechanisms and physical combustion processes of metallic and nonmetallic materials in pure oxygen environments. However, because of the immense complexity of this many-faceted problem, little headway has been made in developing analytical models for the design of such systems. On the other hand, major progress in advancing the ability of oxygen systems to cope with the demands for higher performance, pressures, temperatures, etc., has been made through the application of empirical testing of materials in configurations representing their intended uses and through the use of design techniques which protect or shield the more susceptible nonmetallics from direct impingement or interface with the oxygen. This handbook, therefore is an attempt to document the practical "state-of-the-art" which has been developed by a significant element of the Aerospace community in recent years for the design of high pressure oxygen systems.

This handbook presents a unique and useful synopsis of a great bulk of data on the ignitability of both metallics and nonmetallics in oxygen at various pressure conditions. The synthesis of this data is indeed a tremendous time saver since it allows the designer to deduce at a glance the better performing materials for oxygen usage. Furthermore, the handbook also presents many examples of proven component design features along with illustrations of undesirable features which should be avoided. Additionally, the handbook treats the important aspects of component and systems testing and cleaning and handling, information derived from many thousands of manhours of effort directed toward the improvement and perfection of manned space vehicles. By careful attention and utilization of the recommended detailed component and systems design features prescribed herein, along with the adherence to the limited but adequate list of recommended materials, the designer should be in a good posture to avoid the many pitfalls and problem areas that have been experienced by others in the past. When requirements dictate the use of materials not contained on the recommended list, the designer should proceed with caution and verify design adequacy by appropriate component and systems configuration and overstress tests.

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