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ENVIRONMENTAL AND CUSTOMER-DRIVEN SEAL REQUIREMENTS

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SUMMARY

Public awareness of environmental hazards, well-publicized effects of hazardous leakages (Three Mile Island, *Challenger*), and a general concern for planet Earth have precipitated emission limits that drive the design requirements for seals applications. Types of seals, barrier fluids, and the necessity of thin lubricating films and stable turbomachine operation to minimize leakage and material losses generated by rubbing contact are discussed.

ENVIRONMENTAL CONSIDERATIONS

Ludwig and Greiner (refs. 1 and 2) pointed out that in technical societies the fluids which must be sealed range from the familiar fluids, such as water and oil, to unfamiliar fluids, such as oxygen, hydrogen, and toxic chemicals. The seals developed for these applications have many diverse forms, from low-cost automotive water pump seals to very sophisticated seals for liquid oxygen and liquid hydrogen turbopumps, such as those used in the space shuttle main engines. It is also recognized that seals have a significant cost impact in regard to maintenance, downtime, and health hazards. Personnel exposure to even low levels of some substances can have serious health consequences, with airborne debris (fibers, metals, bleed fluids, and combustion byproducts) being one form of most interest. The insidious aspect is that the health damage does not become manifest until late in life.

In regard to chemicals that may be a health hazard, Wegman (ref. 3) pointed out that one source of worker exposure comes from leaks in valves and pumps and stated that preventing such health hazards (occupational diseases) is highly desirable because they tend to be chronic, untreatable, and fatal and may go unnoticed if not resulting in an unusual group of clinical manifestations. Industrial carcinogens cause an excess risk that does not appear to drop after exposure ends. Specifically, Spivey (ref. 4) listed numerous substances that appear to be associated with excessive lung cancer mortality, among these are polycyclic aromatic hydrocarbons, bis chloromethyl ether (BCME), and chloromethyl methyl ether (CMME).

Other health hazard sources include the insidious nature of lost, forgotten, and buried toxic chemical and hazardous wastes from strategic manufacturing facilities; storage depots for fuels, chemicals, and bombs; nuclear wastes stored on site; and "abandoned" nuclear and refinery facilities. Many sites were established during World War II when other considerations took precedence. Some areas are so toxic that current technology offers no solution, and the unsettling potential for mishaps and contamination of the soil, the water table, and the atmosphere is significant.

These hazards and increasing world concern about the presence and use of noxious, toxic, and hazardous compounds on planet Earth has prompted legislation at nearly every level of government. The Occupational Safety and Health Administration (OSHA) and the Environmental Protection Agency (EPA) have developed exposure limits for hundreds of substances, with additional substances added daily (e.g., ref. 5). Regulators have gone from a position of little or no concern to one of severely restricting all hazardous emissions.

In order to assist planners and regulatory agencies, simulation programs are being employed to determine cleanup procedures and to evaluate the impact of hazardous materials on the planet and its inhabitants. For example, SIMSITE deals with the cleanup of toxic, radioactive, biological, or foul waste sites; SIM-EARTH allows one to simulate the global impact of managing the Earth's resources; SIMREFINERY simulates the production and marketing of, for example, a refinery product from the crude oil state; and SIMPOWER simulates the production and distribution of power over a large power grid such as on the west coast. (Private communication, Tom Cochran of Yosemite Inc.)

For manufacturers and users of valves, pumps, compressors, and other processing devices the focus has been on volatile organic compound emissions (e.g., the California South Coast Air Quality Management District (SCAQMD) limits fugitive emissions to 1000 parts per million (ppm)).

New sealing requirements are set out in American Petroleum Institute API-610 and American National Standards Institute ANSI-B73 standards dealing with new sealing chamber design requirements.

It is especially important to realize that wear debris contributes to emissions (e.g., asbestos in brake linings) and that seal dynamics plays a major role in the control of rubbing and wear debris generation. Not only are the tribological properties of seal materials essential to the performance of a low-emissions seal, but the wear debris must be benign.

Sealing by low-emissions mechanical face seals centers on thin lubricating films and barrier fluids. Three types of seal technology to control emissions are (refs. 1, 2, and 6) single-seal systems and both tandem and double dual-seal systems.

Single-Seal Systems

A properly designed and operating single mechanical seal (fig. 1) can limit emissions to less than 500 ppm, with emissions to the atmosphere limited further by the vapor recovery and disposal technique.

Dual-Seal Systems

A tandem mechanical seal (fig. 2) is made up of two seal assemblies and a barrier fluid that isolates the process fluid from the atmosphere (i.e., a zero-process-fluid emissions seal when attention is paid to vapor pressures and miscibility). The inboard assembly seals the process fluid and the outboard assembly seals the barrier fluid. Emissions to the atmosphere are limited by the recovery and disposal techniques. Examples of common barrier fluids are given in table I and are discussed later.

The double mechanical seal (fig. 3) has two assemblies operating in a barrier fluid that is circulated at a higher pressure than the process fluid and may be internally or externally pressurized. Again zero emissions can be met with proper filtering and disposal.

Emission limits for these seal systems are set in table II (adapted from ref. 6).

MANUFACTURE

The manufacture of seals requires the use of hazardous materials and machining procedures. For example, the rub runner for the brush seal system requires a hardened smooth-running surface. Such a

surface can be built up by plasma spraying, electroplating, ion implanting, CVD/PVD (chemical/physical vapor deposition), sol-gel methods, and filtered arc and laser methods. It is costly and time consuming for manufacturing facilities using these techniques to satisfy the requirements as established by local and Federal environmental laws covering airborne emissions; external radiation levels; noise; water-based effluents; solid liquid and bulk waste disposal procedures; and the handling and storage of toxic, radioactive, and other hazardous materials. Consequently, alternative methods are sought; for example, iron coating solutions generate low amounts of toxic byproducts in a relative sense.

REGULATIONS

For regulations applicable to the control of volatile organic compound emissions from process pumps and compressors, see title 40, part 60, of the Code of Federal Regulations (abbreviated 40 CFR 60). Method 21 (in appendix A of 40 CFR 60) specifies measurement equipment and procedures for these emissions. In California the Bay Area Air Quality Management District has issued regulation 8, rule 25, covering pumps and compressors in refineries and chemical plants, and SCAQMD has issued rules 466 and 1173 with similar coverage (ref. 6).

The definitions of leaks in reference 6 are of some interest:

- (1) Leak definition: Instrument reading of 10 000 ppm or greater or visible drip, spray, or mist
- (2) Inspection schedule:
 - Visual, each calendar week
 - Instrument, monthly
- (3) Repair schedule: First attempt within five calendar days; repair not later than 15 calendar days after leak is detected.

Perhaps the torte system will be invoked to resolve environmental situations (i.e., a party sues another, giving the person the right to prove his complaints rather than setting standards in terms of parts per billion). For example, suits may be brought over who controls aerospace vehicle fuel dumps in regulated areas and the intentional or emergency disposal of hazardous waste sprayed in unregulated areas from an aerospace vehicle.

BARRIER FLUIDS

Isolation of hazardous fluids (e.g., hydrogen and oxygen, acids, and radioactive gases) is often achieved by introducing into tandem, dual, or multiple seals or other seals a barrier fluid that is "drained" for treatment or disposal. Emission restraints and restrictions on the use of volatile hazardous air pollutants can be eased by using barrier fluids.

Air and water are common barrier fluids. Although the choice of a barrier fluid is application specific, parameters to be considered are (ref. 7)

- (1) Compatibility of barrier and process fluids
- (2) Cost and availability
- (3) Lubrication, corrosiveness, and degradation with time (under load)
- (4) Environmental compatibility and ease of recycling

- (5) Steady-state rise and fluctuations in seal face temperature
- (6) Post-test arithmetic average Ra of the absolute value of the unfiltered roughness profile

Inert gases (e.g., noble gases, nitrogen, and carbon dioxide) are effective barrier and purge gases. For example, helium barrier gas effectively isolates hot, hydrogen-rich steam from oxygen in space shuttle main engine applications (fig. 4, refs. 8 and 9). However, it is costly in terms of mission payload, and more efficient designs are being pursued.

Common barrier fluids and the results from testing with a 42.7-mm-diameter cartridge type of bellows seal operating at 3600 rpm are shown in table I. The seal inboard face was silicon carbide (SiC) versus SiC, and the outboard face was carbon versus SiC. The process fluid was 10 wt hydraulic oil. For these tests water showed low face temperature rise, low fluctuations, and low post-test Ra but may not be the barrier fluid of choice because of incompatibility (refs. 8 and 9).

The memory and reality of the Three Mile Island nuclear mishap are clear, and the stringent sealing requirements established by the Nuclear Regulatory Commission dictate a special class of compliant foils and compliant face seals. Face seals have very thin films and special materials to minimize thermo-mechanical distortion. They must operate with a large stability margin. Nuclear seal packages are usually staged seals or multiple seals to prevent the working fluid leaking to the environment. All leakage is collected, processed, and disposed of or returned to the system. For example, for a multiple-seal system operating at 3600 rpm and 2500 psi the first face seal configuration operates with a mating ring flatness of 3.5×10^{-4} in., or three light bands, and leaks about 3 gal/min of brackish water. The second face contacting seal operates near 30 psi. The third contacting seal dam, face seal, or emergency seal operates near 5 psi and is a single-dam bellows type with scraper rings to remove contaminant buildup before the working fluid is returned to the system.

In another application the U.S. Army decreased a tank's specific fuel consumption (sfc) by slowing the compressor at idle but failed to recognize that the compressor air buffered the oil sump labyrinth seal. Occasional blowby occurred and smoke entered the cabin. Because it would have cost millions to reprogram the sfc controller, a decrease in oil pressure was sought as the solution. The point is that both the overall system and the environmental effects must be considered when changes are made either in the field or on the drawing board.

Similar problems are reported in small aircraft turbomachines during startup and shutdown where oil leakage (smoke) may cause an oil sump redesign; this problem is further discussed in the next section.

Automotive engines, and other terrestrial-based engines, are more focused on EPA requirements. For example, valve stem sealing requirements for 98 standards show the need for redesign.

AEROSPACE-RELATED SEALING

Perhaps the aerospace industry is unique in that rather than having an agency dictate the leakage standards, it is the customer who drives requirements (e.g., for the cabin air system in commercial aircraft, where customers pay significant sums of money to be afforded creature comforts and are unwilling to put up with the smell of kerosene in the cabin). Because the cabin air is bled from the compressor, it becomes essential that this air be made as free of contaminants as possible, including the effects of recycled cabin air.

Further, the sealing required to maintain spacecraft environments (e.g., Apollo and shuttle) entails complete life support systems that are sealed to the hostile environment of space. Here the astronauts put up with orders of magnitude more difficult environments than the commercial aircraft customer, but there are limits (Grissom cabin fire). The *Challenger* is probably one of the most publicized seal failure incidents in history and led to many design and philosophical changes.

In early aircraft engines a significant amount of smoke would be discharged upon startup and sometimes during operations owing to unspent fuel mixtures and oil being dumped into the exhaust. Smoke, which implied fire, was of concern to the passengers, who demanded changes, and most of today's engines are nearly smoke free. A low-smoke, low-emissions engine requires interface seals to prevent hazardous materials from reaching the atmosphere. Thus, the need is for low-leakage interface seals, such as a face seal or a leaf seal or some form of contacting seal. The cabin and local environmental problems are more acute at startup and shutdown, as during normal operations the engine is at altitude, where dilution air abounds. However, the upper atmosphere is probably the worst place to put polluted materials. They can reduce the effective sunlight, alter the atmosphere, and deposit thin contaminant layers all over the face of the Earth.

Aircraft and stationary gas turbines generating power for utilities must deal with dilution air leakages including oxides of nitrogen (NO_x). New static brush and rope seals are being tested or considered to minimize the leakage between the compressor and the combustors. It is important to recognize that not only are these leakages objectionable to the "customer," but they also imply losses that decrease the performance of the turbomachine. For example, the high-speed civil transport (HTSC) goal, 5 g NO_x /kg fuel burned, requires combustor sealing. It is also recognized that a 1-percent decrease in turbomachine efficiency results in a 6-percent increase in gross HSCT takeoff weight.

Surface wear can generate debris that can enter the combustion system and form oxides as it passes through the engine tailpipe. Further, upon the impact of a hard landing the rotors can be displaced and rub into the seals. These materials can be released into the combustion stream or into bleed air (hopefully not into the cabin air). The toxicology of these products is not well known and further studies are required.

Some seal configurations are held open during the startup and shutdown transients to decrease rubbing contact, and it is important to bypass cabin air during these periods and flush the system (e.g., the smell of jet fuel due to faulty sealing and buffering) prior to bleeding cabin air.

Further, the toxicology of environmental air coupled with engine bleed air is poorly defined. Although most airports are at some distance from civic centers (e.g., the new Tokyo airport), the building trend is to surround the airport with civic activities. Certainly, the environmental problems at the Hong Kong airport are unique to the world because the volume handled is large and the airport is situated within a heavily populated area. In a sense it is like New York's Laganardia airport, where large amounts of debris darken the shoreline, the result of improper consumption of fuel and oil where leaking seals can commit excessive amounts to engine airflow.

Current sealing concerns center on EPA non-point-source discharge permits. For example, at New York's Kennedy airport, runway runoff effluent, such as oil and fuel spills, deicing agents, and engine exhaust products, are to be collected and treated chemically and biologically prior to release as a result of a 1980's suit. The cost is borne by the customer through airport use taxes. The regulation covers anything "leaked" onto the runway or apron. One may recall that early flights of the Blackbird involved large fuel spills over the hangar floor, apron, and runway. The key here is how much effluent reaches a regulating point where it can be measured. Furthermore, as any tracker knows, when there are no tracks, only man could have been there.

Potential sources of aerospace regulation (manned and unmanned vehicles) include

- (1) EPA, which is currently involved in ground effluent control and has a program with the National Oceanic and Atmospheric Administration (NOAA) at Boulder, Colorado, to model atmospheric diffusion
- (2) OSHA, which may move to regulate cabin air requirements
- (3) RCRA, which covers the operations of every working industry
- (4) The Clean Air Act, which may be extended to regulate the exhaust products

One should remember that Queen Elizabeth's decree that all the unsightly soot be removed from the smokestacks led to the creation of sulfur dioxide and hence acid rain in England, implying that regulation may not be the answer.

GROOVED COMPLIANT FACE SEALS

The very low leakage requirements dictated by environmental considerations and the quest for high performance at increased efficiency dictate thin lubricating films, barrier fluids, and well-controlled dynamics. Over 10 years ago Larry Ludwig (refs. 1 and 2) invested his life in mechanical seals (fluid film and contacting face and shaft seals), and the industry followed the NASA work closely. Larry predicted that mechanical seals would be the seals of the future in aircraft engines, but original equipment manufacturers (OEM's) were satisfied with labyrinth seals for many gas path and shaft applications.

Since that time, microtechnology, smart configurations, smart controls, and EPA and customer drives for zero net leakage have forced researchers and OEM's back toward mechanical seals. The standard configurations (cylindrical, labyrinth, and tip) continue to be used, with brush seals as an intermediate step between low-leakage and zero-net-leakage seals. New developments in labyrinth seals, brush seals, and hydrostatic and hydrodynamic effects in seals and bearings will continue to expand our current technology and make one type more effective than another—in a leapfrog fashion. Each seal/bearing design must be investigated as to its life, leakage, stability, load transmission, simplicity, cost of mission failure (human and robot, both terrestrial and aerospace), maintainability, cost, effectiveness, etc., and then a selection can be made. Maybe the simple, effective labyrinth seal used in the Hottle engine or some modified form is "best"!

WHAT'S COMING

In the future more microetched seals and bearings with specially tailored grooving to transmit loads and active control of surfaces and dynamics will replace many "low cost" seals and bearings but never entirely. The high-end cost will be magnetic bearings, which will require no seals and no bearing contact—essentially providing very long life and very low dissipation. The hybrid magnetic-foil bearing promises stability and load capacity at low rpm (magnetic capability) and at high rpm (hydrodynamic capability). Turbomachines and rotating machinery in general will have new envelope designs, be more compact and more efficient, tend toward zero net leakage, and operate at higher speeds.

Further on, magnetic "envelopes" and rotating tubular compressors and turbines could evolve and rotate at very high speeds (perhaps over 1 million rpm, depending on diameter). The exterior envelope will compress the rotating members to mitigate the excessive hoop stresses.

Seals must mature to the point that orifice metering of cooling fluid rather than unreliable seal leakages would be used to supply cooling requirements. However, simple cost-effective solutions (e.g., the labyrinth seal) will not be made obsolete by expanding high technology.

Actively controlled seals are coming. Those using piezoelectric drivers, shaped-memory alloys, or hydrostatic orifices are evolving but are not yet in engines (refs. 10 to 12 and private communication from M. Braun of University of Akron).

Seal acoustics is being considered in the seals code program along with secondary and power stream flow integration. Turbomachine noise is generated not only by the blade/stator interfaces but at the sealing surfaces as well. Shroud and interstage seals whistle, especially when the interface travels above Mach 1. A rotating shock field has to develop into an axial flow field with attendant dissipation of vortex formations (unattended these formations would dissipate, but they interact with structure and other flows to form unwanted sound). Noise abatement is important to the customer in at least two ways: (1) objectionable sound is reduced and (2) 1-dB sound reduction increases gross takeoff weight for the HTSC by 1.5 percent.

Costing models will be used in terms of design, manufacturing, operations, and life. Costing models will enable the designer to select various contracting options and couple them with operations protocol and manufacturing technology to determine how local or global design changes improve the life and decrease the cost of the seal.

Currently, our NASA seals code development by Mechanical Technologies Incorporated and CFD Research Corporation is on target but needs more consideration of compliant seals, seal acoustics, integrating secondary flow paths with the power stream, the concept of surface microgrooving, and active control to provide load transmission and stability with a minimum of "lubricant" requirements. In combination with the NASA programs Texas A&M has developed seal stability coefficients for a variety of shaft seals, and they need to be extended to the compliant configurations.

CONCLUDING REMARKS

Concern for the uniqueness of planet Earth and the health and welfare of its inhabitants has precipitated a set of rules (laws) regulating the emissions of machines, in particular turbomachines. The original equipment manufacturers, the workers, the users, and the general public are aware that hazardous materials leak from seals and that materials generated during rubbing can be deleterious to their "health and wealth." In the aerospace industry, customer satisfaction, efficiency, and performance rather than regulation have been the drivers to mitigate seal leakages.

Integration of secondary flow paths with the power stream and development of thin-film, stable-operating compliant seals with and without barrier fluids are required to meet the goals. One such class of seal is the compliant foils and compliant face seals. The hybrid magnetic-foil bearing provides stability from lift-off (start/stop transients) throughout the engine operating envelope. Minimizing leakage, loss of rub materials, and cost and optimizing performance, efficiency, noise reduction, and life between overhauls continue to drive aerospace seal requirements and, along with regulations, to drive terrestrial seal requirements.

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TABLE I.—PROPERTIES OF COMMON BARRIER FLUIDS FOR DUAL SEALS

[Adapted from references 6 and 7.]

Barrier fluid	Practical temperature limits				Comments
	Lower		Upper		
	°F	°C	°F	°C	
Water	40	4	180	82	Use corrosion-resistant material; protect from freezing. Consult seal manufacturer for proper mixture with water to avoid excessive viscosity.
Propylene glycol	-76	-60	368	187	
n-Propyl alcohol	-147	-99	157	69	Contains additives.
Automatic transmission fluid	55	13	200	93	
Kerosene	0	-18	300	149	Contains additives.
No. 2 diesel fuel	10	-12	300	149	
Inert gases ^a	Dewpoints		----	----	Can displace oxygen in habitats; low oxygen sensors may be required.
Benign gases ^b	Dewpoints		----	----	Low oxygen sensors may be required.
Air (dry)	Dewpoint		----	----	Is combustion compatible with other oxidative-sensitive environments.
(ambient)	Dewpoint		----	----	
Hydrogen	Dewpoint		----	----	Must consider sensitivity to oxidizers along with flame propagation limits.

^aNoble gases (e.g., helium), nitrogen, and gas mixtures (e.g., a combination of helium and nitrogen).

^bFor example, carbon dioxide.

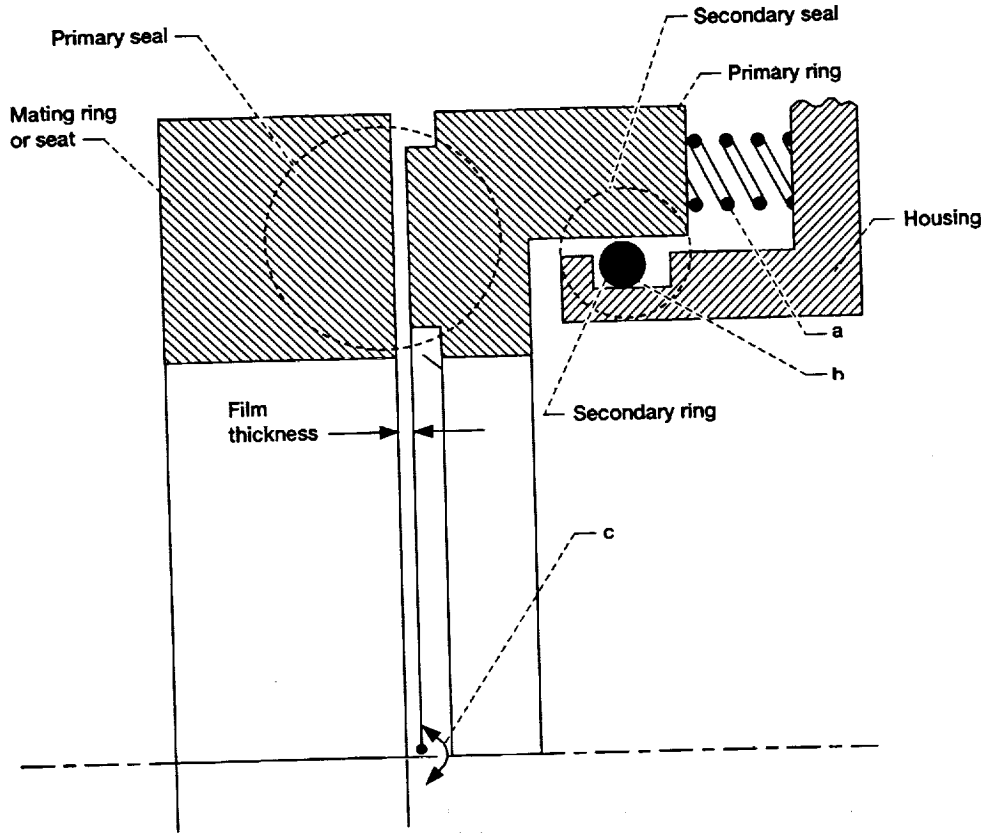
TABLE II.—EMISSION LIMITS AND APPLICATIONS GUIDE

[Size, to 152 mm (6 in.) diameter; pressure, to 40 bar (600 psi); speed, to 28 m/s (5600 ft/min) surface. Adapted from reference 6.]

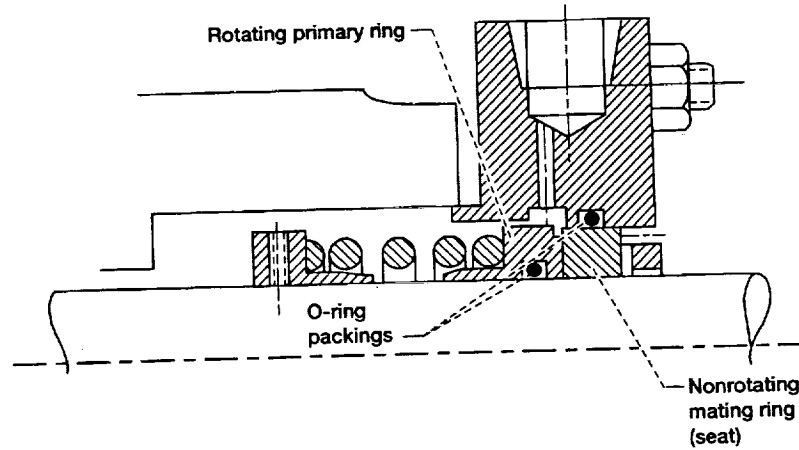
Emission limits 1 cm from source, ppm	Specific gravity	Technology
1000 to 10 000	>0.4	Single, double, or tandem seals are acceptable. Single seals may be acceptable depending on actual operating conditions, seal size, pressure, and temperature. Tandem or double seals may be required to meet emission regulations.
500 to 1000	>0.4	
0 to 500	>0.4	Tandem or double seals are acceptable.
0 to 500	<0.4	Double seals are required.

Primary ring properties

- a Axial flexibility (spring loaded)
- b Secondary-ring sealing diameters
- c Angular flexibility (nose will tend to align itself to angular misalignment of seat face)



(b) With nonrotating primary ring.



(a) With rotating primary ring.

Figure 1.—Single mechanical face seal.

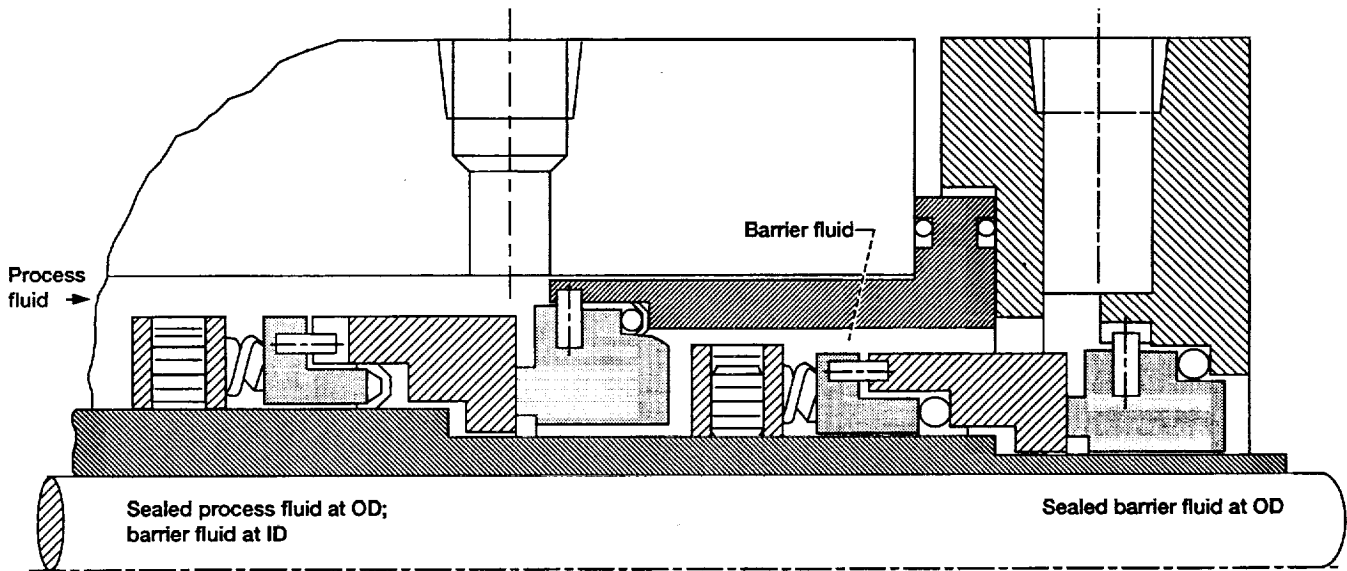


Figure 2.—Tandem seal (rotating-primary-ring type).

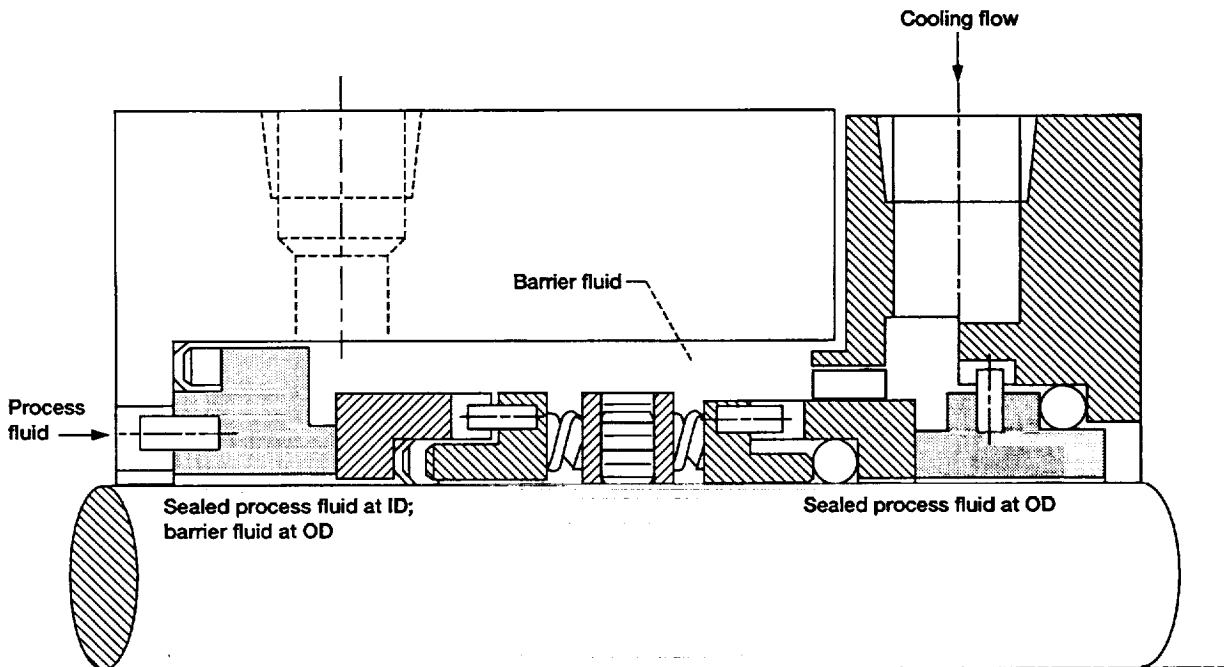
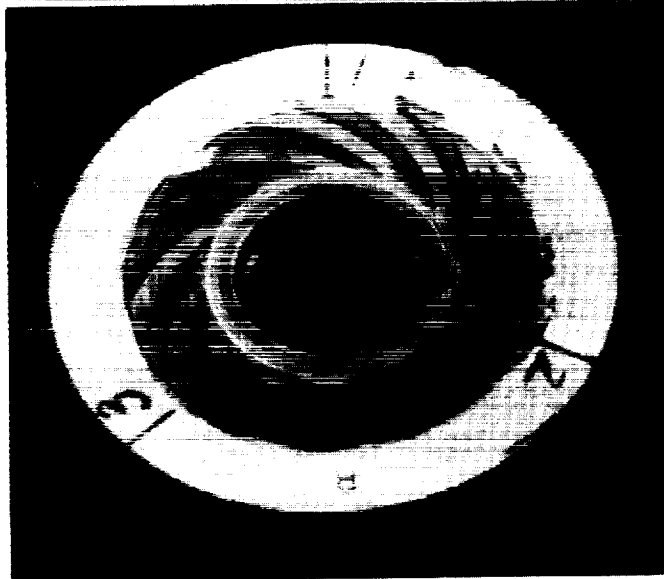
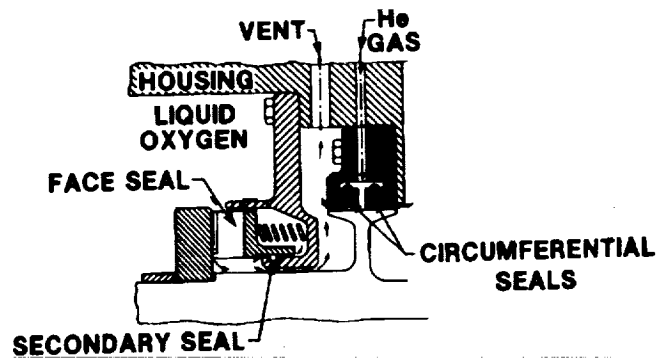


Figure 3.—Double seal (rotating-primary-ring type).



Face-type, spiral-groove, primary liquid oxygen seal.



Circumferential-type, Raleigh-lift-pad, helium purge seal.

Figure 4.—Liquid oxygen turbopump seal with buffer gas.