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Self-Lubricated Seals Development for High-Pressure, Oil-Free Compressors

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ABSTRACT

Continued progress in the development of self-lubricated piston and rod seals for oil-free, high-pressure air compressors is described. Seal material characteristics based on filled polytetrafluoroethylene (PTFE) as well as new, potentially improved seal materials are discussed. Piston speeds up to 450 feet per minute have been investigated. Wear results from several long-term tests at 4500 and 5000 pounds per square inch are shown. A useful piston seal life exceeding 2000 hours has been demonstrated.

ADMINISTRATIVE INFORMATION

This assignment is a part of the work approval in reference (a). In reference (b), the technical program for elimination of the air-oil explosion hazard associated with the high-pressure air compressor and associated piping systems was established. This study was authorized under Sub-project S-F013 08 05, Task 4090.

REFERENCES

(a) BUSHIPS ltr 3900, ser 340-343 of 9 Aug 1961
(b) NAVENGRXSTA ltr NP/9450(950) of 27 Jul 1961
(c) NAVENGRXSTA Rept, "Semiannual Progress Report, Fundamental Scientific Program," S-R011 01 01, Apr 1963, pp. 26-27
(d) NAVENGRXSTA Rept, "Semiannual Progress Report, Fundamental Scientific Program," S-R011 01 01, Aug 1963, pp. 20-23
(e) MEL Rept 95 681A of 30 Aug 1963
(f) MEL Rept 68/64 of 13 Aug 1964

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SELF-LUBRICATED SEALS DEVELOPMENT FOR HIGH-PRESSURE, OIL-FREE COMPRESSORS

1.0 INTRODUCTION

The objective of this program is to develop a sealing system for high-pressure air compressor pistons and piston rods that will not require fluid lubricants. This will eliminate the present air-oil explosion hazards in high-pressure air systems, increase compressor reliability, and minimize system maintenance requirements.

1.1 Background. Hazards of fire or explosion exist in high-pressure air systems when combustible compressor lubricants are present. Filters and solid absorbents reduce the downstream combustion potential by removing much of the carried-over lubricant. These oil extraction devices require diligent servicing to maintain their effectiveness and, under shipboard conditions, it is difficult to determine whether they are functioning correctly. Moreover, the compressor interstage coolers and interconnecting piping plus all other air piping ahead of these oil-removal devices are potential explosion regions.

1.2 Approach. In this development, the approach has been to eliminate fluid lubricants from the air compression cylinders and to establish machinery design criteria for the reliable production of oil-free, high-pressure air. This approach is, therefore, aimed specifically at the development of seal designs using self-lubricating solids capable of providing both sealing and lubrication functions in the high temperature and pressure environments of high-pressure compressors.

1.3 Previous Work. References (c), (d), and (e) described developmental experiences with plastic piston-ring-type seals and materials for such piston-seal designs. Reference (f) subsequently described a somewhat different piston seal device which appeared to offer advantages not then attainable with conventional piston rings. The new piston seal, conceived by MEL, consists essentially of a hollow cylinder or sleeve which is deformed at one end to bear against the stationary compressor cylinder. The entire sleeve, made of a deformable, self-lubricating material, is available for wear and no leakage path develops until substantially the entire sleeve is consumed. Reference (f) also described the materials, operating characteristics, environmental conditions, and results of a successful 1500-hr* test of the sleeve-type piston seal at a discharge pressure of 4500 psi.

1.4 Scope. The present report describes an extension and broadening of the sleeve approach to piston seals for nonlubricated, high-pressure air compressors. Studies of sleeve-type piston rod seals are in progress, and initial results will be discussed.

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*Abbreviations used in this text are from the GPO Style Manual, 1959, unless otherwise noted.

2.0 DESCRIPTION OF PISTON ASSEMBLIES

Two piston configurations, similar in function but differing in detail, have been developed. As shown in Figures 1 and 2, both pistons have a two-element seal. One element is a cylindrical sleeve that is stretched outwardly at one end to form a seal between the cylinder bore and the follower. The second element is the follower which, by virtue of its curvature, is instrumental in the stretching action of the sleeve. The two piston configurations differ in the method by which each is aligned or guided in the cylinder bore. The piston shown in Figure 1 is guided by loosely fitted polytetrafluoroethylene (PTFE) rider rings; alignment with this arrangement is not very exact. In the design of Figure 2, the alignment is more precisely controlled by a carbon-graphite guide fitted tightly to the piston shaft and relatively tight in the cylinder bore. A PTFE piston ring, similar to that shown in Figure 1, was originally used to end load the sleeve to force it into a stretched position. This was later found to be unnecessary, and the piston ring was removed. Followers made of polyimide or carbon-graphite materials have been used. Sleeves have been made also of PTFE containing various types and quantities of filler materials. Evaluation of an advanced design sleeves made of a metal - PTFE composite material is in progress.

3.0 METHOD OF INVESTIGATION

The various piston configurations and materials were evaluated by operation in the booster-type compressors as described below.

3.1 Equipment. Two compressor complexes similar to that described in reference (f) were used in the investigation. Each complex consisted of a booster-type, two-cylinder compressor, a flowmeter, a moisture indicator, pressure vessels, and appropriate gages and piping to form a closed piping circuit. Clean dehydrated air was supplied to the piping circuit from a regulated pressure source to replace air leakage. Each compressor was fitted with two vertical cylinders separated from the lubricated crosshead guides by both oil seals and a sufficient distance to prevent lubricating oil from entering the nonlubricated cylinder area. In the arrangement used, the piston seals under test were subjected to the full differential between cylinder working pressure and atmospheric pressure on each stroke. The two cylinders operated in parallel with a common suction and a common discharge. Each compressor cylinder had a bore of 3/4 in. and a stroke of 4-1/2 in. Both test compressors were powered by variable speed drives.

3.2 Test Conditions. The operating conditions of 400 rpm (300 fpm piston speed) and discharge pressure of 4500 psi which prevailed during the 1500-hr test of reference (f), were initially continued during the investigations reported herein, with the exception that water was maintained in a pressure vessel at the compressor suction to produce a nominally saturated air intake. Later, when the second test compressor was installed, a 5000 psi discharge pressure and 600 rpm (450 fpm piston speed) were used. Subsequently, the older test machine has been upgraded to 5000 psi and 475 rpm (356 fpm piston speed). Discharge air temperature has been generally maintained at 300 to 310 F.

4.0 EXPERIMENTAL DEVELOPMENT

Current studies are aimed at the refinement of piston and seal designs. Sleeve materials are relatively critical and are therefore being studied under operating conditions of increasing severity.

4.1 Sleeve Materials. Besides having good self-lubricating properties in the 300 to 500 F temperature range, potential sleeve seal materials must be capable of considerable elongation. Only the fluorocarbon family of materials has been found to have these qualities in the required degree. Of this group, the filled PTFE materials offer the best elongation and wear resistance at high operating temperatures. The choice of filler material to be blended with the PTFE resin usually depends on the particular use with no single combination suitable for all purposes. Almost any material that can withstand the approximately 700 F PTFE sintering temperature can be added to the basic resin and almost any reasonable material will improve the wear resistance of the unfilled resin. Glass fibers, bronze powders, molydisulfide, asbestos, carbon, and many other materials are commonly added to PTFE resin to achieve some particular combination of properties. Most of the readily available filled-PTFE materials have been investigated as potential sleeve materials.

4.1.1 While many instances of successful, long-term sleeve seal operation have been observed during this investigation, there have been occasional characteristic sleeve breakage failures. Figure 3 shows three typical failures where a break or hole has developed in the sealing surfaces. The fracture always initiates on the inside surface and then propagated through to the outside of the sleeve. The general appearance of the failures is similar regardless of whether the PTFE filler is in the form of a particle or a fiber, although the size of the break is generally smaller when the filler is a small diameter fiber. A fibrous filler will, in general, allow a greater ultimate elongation percentage than will an equal volume of a particulate-type filler. This fact may explain some of the differing results obtained with the two general types of fillers. However, varying results have been obtained from seals made from the same rod stock and from supposedly identical PTEE stock obtained from different suppliers or even from a single supplier. The production of molded PTFE is somewhat related to powder metallurgy in that both processes involve a high-pressure compacting and a high-temperature sintering operation. The physical properties of the sintered PTFE can vary greatly as a result of the processing techniques of the entire molding and curing cycle.

4.1.2 The addition of filler materials to the PTFE introduces further complications to an already complicated process. The determination of quality in the finished product is not simple. Material density measurements above a minimum value are usually accepted as a quality measure. However, for sleeve seal materials the molded stock should have a low crystalline structure which would yield a low acceptable density. A highly crystalline material containing numerous or large voids may also have a low bulk density. Thus, density alone cannot define the other physical properties of filled PTFE materials. A further complicating factor is the microproperties of a material. The reported characteristics of a filled PTFE resin are based on the macroproperties or properties obtained with large bulk material. In the sleeve seal application, however, the sections become relatively thin and the sealing contacts are small. Thus, the microproperties are critical in that a single large void, flaw, or nonhomogeneity in the sealing contact surface may initiate an eventual failure.

4.1.3 Because of the yield characteristics of the materials involved, the analytical interrrelating of such factors as total strain, cyclic strain, follower shape, sleeve material, and operating conditions is very difficult. The approach has been to use available materials while studying the factors which affect the utility of this type seal. The knowledge gained is then used to guide the selection of new materials and designs.

4.1.4 Glass fibers, while greatly improving the wearing properties of the PTFE resins are very hard and abrasive. It has been speculated that wear of metal cylinder liners rubbed by the glass-filled PTFE might be high. The desirable elongation characteristic obtained with fiber-filled PTFE, therefore, prompted a search for fibers which might offer advantages over glass. Recently fibers have been made by carbonizing and graphitizing rayon fibers. Fiber strengths as high as 60,000 psi were reported. These fibers, in various proportions, were blended with PTFE. Subsequent testing, in all cases, indicated higher sleeve wear and failure rates than had been experienced with the glass fibers. PTFE fibers have also become available recently. Because of their highly oriented molecular structure, they possess tensile strengths greatly exceeding that of molded PTFE resins. Stock containing these PTFE fibers in PTFE resin was made and investigated. Wear rates were unexpectedly high. A possible explanation is that, at the 700 F plus sintering temperature of PTFE resins, the PTFE fibers lose their highly oriented molecular structure and revert to a randomly oriented structure similar to that of the matrix resins. These fibers do, however, offer great potential for many other self-lubricating applications.

4.2 Cylinder Materials. Surfaces rubbed by a seal must be considered as well as the seal itself. The proper selection of cylinder or piston rod materials is based, primarily, on wear, although physical strength must be also considered. Ideally, a film of PTFE is transferred from the seals to the rubbed metal surfaces. The transferred PTFE film then acts as a layer of solid lubricant between the two surfaces. The characteristics of the metal surfaces should be conducive to the formation of this lubricating film. Most published opinion on the subject considers that steel hardened to Rockwell C55 or harder with a 4- to 8- microinch surfaces finish has nearly optimum characteristics for low wear with PTFE seals. PTFE against cast iron is also considered as a satisfactory wearing combination, whereas dense chromium plating is generally considered a poor choice for use with PTFE. However, compatibility studies conducted by this Laboratory have consistently indicated that most of the commonly available filled-PTFE materials are compatible with dense chromium plate. In reality, bench-type tests often fall short of completely simulating an end-use application. Corrosion, for example, seldom enters into short-term bench wear tests, but must be considered in end-use compressors. Chromium plate offers a simple and adequate protection against corrosion and, as compressor tests have indicated, provides a compatible cylinder liner surface for use with glass-filled PTFE. MEL experience indicates that less wear of seals or liner surface occurs with dense chromium than occurs with cylinders made of either Type 440-C chromium stainless steel hardened to Rockwell C 55-57 or nodular iron with an induction-hardened bore. After nearly 10,000-hr of test operation, one chromium-plated cylinder bore has been worn less than 0.001 inch.

4.3 Piston Designs. The dry air results reported in reference (f), as well as the initial operation with saturated air, were obtained with piston designs similar to that shown in Figure 1. With this design, guidance of the piston in the cylinder was by the loose-fitting rider rings and therefore was relatively imprecise. Some sleeves wore unevenly, apparently due to an eccentric position of the follower or to piston misalignment. The latter condition was indicated by severe rider ring wear. In setting up the second test compressor, therefore, a self-aligning joint was used to connect the piston rod to the crosshead and a new piston design was used. The new piston, shown in Figure 2, connects the follower to the piston with little or no lateral freedom and incorporates an upper guide which is fitted closely to the cylinder bore and tightly to the piston shaft. The upper guide aligns the piston in the cylinder and also serves as a pressure pulse buffer for the sleeve.

4.3.1 In order to minimize the cold clearance between the piston and cylinder, both the upper guide and the follower were made of materials having low coefficients of expansion. Carbon-graphite materials impregnated with metals were selected.

4.3.2 For the initial operation of the new-design pistons, a copper-lead-impregnated, carbon-graphite upper guide and follower were installed in one cylinder of the compressor and silver-impregnated carbon-graphite units in the other. Failure of the copper-lead-impregnated carbon-graphite parts occurred after 17 hr of operation at 5000 psi discharge pressure and 600 rpm. The failure involved an intense fire in the cylinder that led to melting damage to the piston and piston rod. The casualty was apparently associated with the breakage of the piston shaft at the threaded section. This presumably led to hard bearing of the guide on the cylinder wall, resulting in overheating and ignition of the carbon-graphite material in the presence of high-pressure air.

4.3.3 According to the supplier of this material, the Pure Carbon Company, Incorporated, a temperature in excess of 2000 F would be required to initiate combustion of the type observed. No other instance of this type of failure in compressor service is known. The Pure Carbon Company, Incorporated, noted that the heat-generating characteristics of silver-impregnated material were considerably lower than that of the copper-lead-impregnated material. Thus, there should be less risk of a similar casualty with the silver-treated material. Since the casualty, piston shafts of increased strength have been operated several thousand hours with the silver-impregnated carbon guides. No evidence of overheating or burning has been observed.

4.4 Rod Seals. Most compressors, expansion engines, and pumps require stationary seals where a piston rod moves into a pressure zone. These rod seals may be similar to contracting, piston rings, or they may be of a unique design. Nonlubricated piston rod seals for high-pressure applications have, in general, offered even more of a development problem than have piston seals. Heat dissipation is cited as the main difficulty and rightly so since the nonlubricated (NL) seals usually have very low thermal conductivities and there are no lubricating fluids to carry away heat. Current practice is toward pressure-balanced seal designs in water-cooled packing cases.

It seemed logical that if a sleeve seal design would work as an expanding piston seal, it might also function in a contracting manner as a rod seal. An investigation in this area is currently under way. One configuration studied is shown in Figure 4. Thus far, the operating characteristics of this arrangement appear to be: good sealing, much less sensitivity to material rupture than the piston seal application, and higher wear rates than with piston seals. Insufficient data are yet available to form a basis for material or design recommendations for these seals.

4.5 Follower Contours. Arcs of circles have thus far been used for the follower contour in the area of its contact with the sleeve seal. The exit angle, defined as θ in Figure 5, is selected and the radius based on the particular follower, sleeve, and cylinder dimensions computed. The selection of a follower exit angle is based presently on a compromise between experience factors related to seal breakage, wear rate, and sealing effectiveness. Figure 5 diagrammatically illustrates the effect of follower exit angle on sealing characteristics. Figures 5a and 5b compare a follower with a small exit angle to one having a larger exit angle. As the exit angle decreases, the contact area between the follower and the under side of the sleeve, w, and also the contact between the outside of the sleeve and the cylinder wall, ℓ, both increase. Conversely, however, as the exit angle decreases, there is an increase in the axial and radial forces which produce sleeve wear. As the follower contact width, w, in Figure 5, is decreased, two detrimental effects may result: First, the axial force differential across the sleeve may decrease sufficiently to cause unseating on the downstroke, and, second, the sealing dam may become insufficient to prevent a pressure rupture of the sleeve. Therefore, the follower contour must be selected with due consideration for the sleeve material properties as well as operating conditions.

5.0 RESULTS AND DISCUSSION

5.1 Effect of Moisture. The seal performance described in reference (f) was obtained while compressing air which contained practically no water vapor. This was done to eliminate corrosion and subsequent scale as a factor in seal wear. In multistage compressors, however, air almost always enters the upper stages saturated with water vapor. To simulate this condition, subsequent trials were made with saturated air. The materials used were either the same as those reported in reference (f) or were duplicated as closely as possible. The piston configurations were as shown in Figure 1. The rider rings and piston ring were made of bronze-filled PTFE and the sleeve material was 25-percent glass-filled PTFE. The follower material was changed from the polyimide material to a metal-filled carbon-graphite material to minimize thermal expansion considerations. The results initially indicated a trend toward an increase in wear rates as water was added to the system. There were, however, scattered data which reversed the trend. A dramatic failure proved conclusively that liquid water had at times been carried into the compression cylinders from the saturator. In the presence of free water, the wear of the PTFE sleeve seals increased by factors of five or more. When the water was present in the form of a vapor only, the wear rates of the 25-percent glass-filled PTFE sleeve seals decreased to the level of and even below that obtained in a dehydrated atmosphere. Figure 6 illustrates the trend toward reduced wear with water vapor present. The change in slope of the upper curve after 985 hr was attributed to the known presence of liquid water on at least one occasion.

5.2 Effect of Speed. The wear data generated thus far in this program has to a large extent been a by-product of many short term tests involving many seal materials and dimensional variations as well as several basic piston designs. This approach was necessary to allow an evaluation of many sleeve materials and to solve initial problems. Some useful data have been obtained from several life expectancy tests. These data, although somewhat incomplete, indicate several trends. Some apparently conflicting data have also shown up. Figure 7 shows wear rate changes with increased rubbing speed for 25-percent glass-filled PTFE against both chromium plating and 440-C stainless steel. The wear against the 440-C follows an easily explained pattern with high wear during break-in, lower wear rate after break-in and an increase in wear with an increase in speed. The wear curve against the chromium plating follows the same trend except for an undetermined period of accelerated wear immediately prior to the increase in rubbing speed. However, the superior wearing characteristics of the chromium-plated surface over the 440-C is evident from these data.

5.3 Seal Life Expectancy. Thus far, long-term runs of 1500 and 1250 hr each at 4500 psi and 400 rpm (300 fpm piston speed), 1000 hr at 5000 psi and 400 rpm, and 2000 hr at 5000 psi and 600 rpm (450 fpm piston speed) have been completed successfully. In none of these runs was the test discontinued because of either seal failure or wear-out, but only after reaching a preselected stopping point. From a wear-out consideration, a life expectancy of several thousand hours can be built into a sleeve seal of relatively short length. The latitudes to which the wear parameters can be varied while still maintaining good seal life are yet to be explored. Figure 8 shows a seal wear curve for a 2000-hr run at 5000 psi and 600 rpm; also, comparisons of the wear trends of 15- and 25-percent glass-filled PTFE are shown. The wear of the 25-percent glass-filled PTFE indicates lower seal wear rates, but the lower glass content allows greater seal material elongation. Cylinder wear should also be reduced because of the lesser abrasive content.

5.4 Reinforced Materials. Thus far, all discussion of sleeve materials has been based on materials consisting of a matrix of PTFE resin to which one or more filler materials have been added. The resulting combination is structurally weak, as compared to most metals, but is an excellent solid lubricant. Logically, however, the matrix material should be structurally strong with incorporated solid lubricant qualities. This approach has been pursued also.

Several basic fibrous-type, matrices have been considered, including filament wound, braided or woven constructions. Preliminary results from one of these developments have tended to substantiate the envisioned value of such a material for nonlubricated rubbing applications. The material in question was made by helically winding many layers of small diameter copper-tin wire on a mandrel followed by a heating process which produced low strength welds between adjacent wire at points of contact. The resulting structure was relatively porous and spongy. Solid lubricants (PTFE and lead powders) were then introduced into the matrix by vacuum methods. The resulting construction was compacted by rolling followed by a PTFE heat-curing process. Since PTFE resins do not liquify during the curing process, intimate association of the PTFE and the ready-made matrix is difficult to achieve. For this reason, none of the material produced by this method has yet been of the highest quality. Nevertheless, encouraging results have been obtained with some of the available material. Two metal matrix densities (approximately 60 and 30%) have been fabricated thus far. The amount and cure state of the PTFE have not been determined nor have the amount and degree of dispersion of the lead. Each of these fabrications was run as a sleeve type seal in a compressor cylinder. The wear of each was considerably higher than that of a glass-filled PTFE sleeve run under comparable conditions. In each case, it appeared that increased lubrication was needed. In an attempt to increase lubrication, a thin sleeve of glass-filled PTFE was placed concentrically inside one of the filament-wound structures whose density was 30 percent. Figure 9 shows the low wear rate observed for over 1000 hr of operation after adding the inner PTFE sleeve. Included for reference is a wear curve for 15-percent glass-filled PTFE operated under similar conditions. The extremely low wear rates shown for the composite material represent a significant improvement over the glass-filled PTFE. The slope of the wear curve unexpectedly remained relatively constant when the rubbing speed was increased by 26 percent. This unexpected phenomenon may have resulted from a change in test cylinders when the speed was increased although both bores were chromium plated.

6.0 FUTURE DEVELOPMENT PLANS

6.1 Advanced Sleeve Materials. Methods for detecting both desirable and undesirable qualities in filled PTFE materials will be studied and developed. Also blending, molding, and sintering methods will be studied with the objective of obtaining optimum filled PTFE qualities. Further development of advanced metal-plastic composite materials will be pursued.

6.2 New Guide Materials. The occurrence of the carbon fire noted in paragraph 4.3.2 may raise the question of whether a potentially combustible solid was substituted for a combustible fluid.

Subsequent satisfactory use of other carbon-graphite materials plus much satisfactory performance in other areas suggests that, when properly selected and applied, these materials can perform well in many sliding applications. The fact remains, however, that under a favorable set of conditions carbon will burn with intense heat. Thus, the development of a material that is stable, self-lubricating, and of low thermal expansion will be studied with the aim of replacing the carbonaceous materials used as piston guides.

7.0 CONCLUSIONS

7.1 The elimination of liquid lubricants from the cylinders of high-pressure air compressors is feasible. A practicable piston seal employing solid lubricant concepts and offering a service life of 2000 hr or more will result from the development investigation reported herein.

7.2 Uncompleted investigative areas in this development are: improvement of piston seal reliability through material and design development; development of practicable oil-free piston rod seals employing a similar concept; and investigation of problems associated with multistage applications of the MEL seal concept.

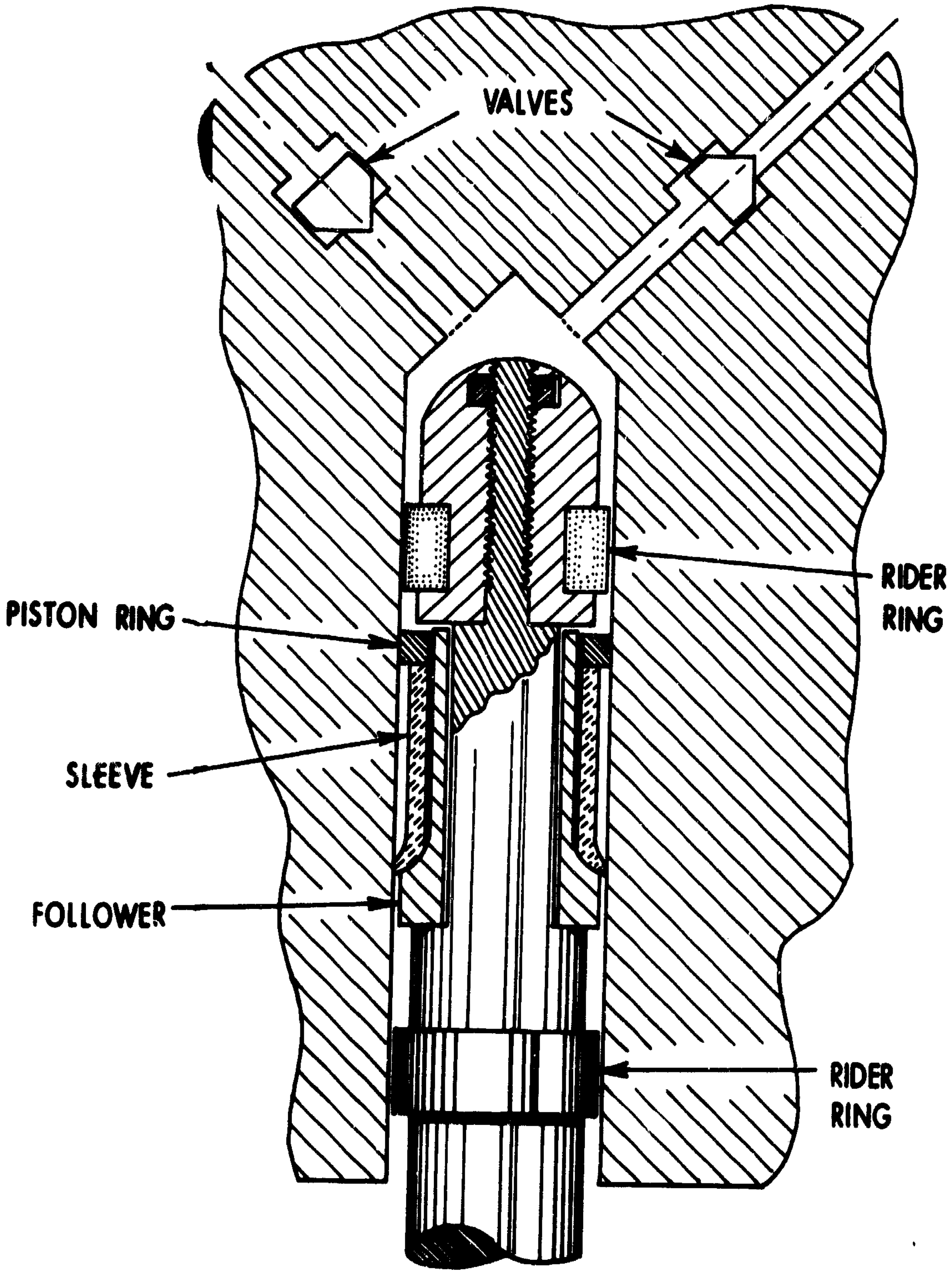

Figure 1
Sleeve-Seal Arrangement

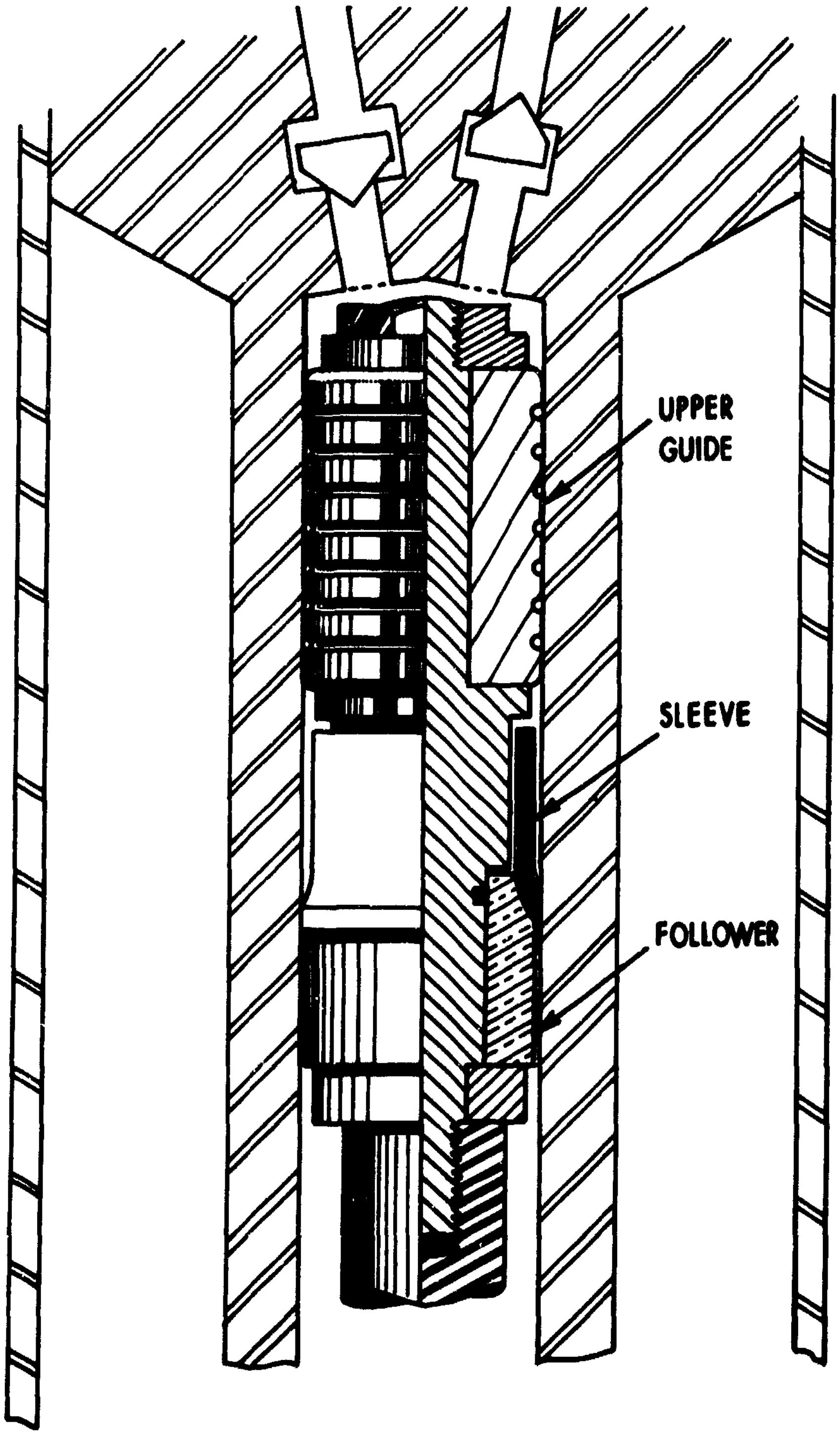

Figure 2
Sleeve Type Piston Seal

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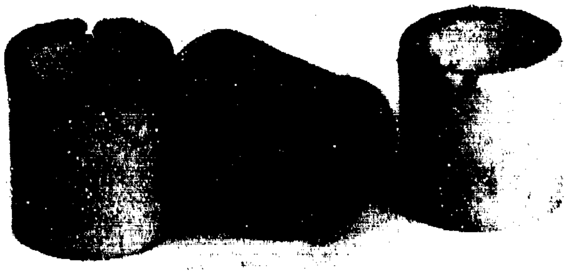

Figure 3
Ruptured Sleeve Seals

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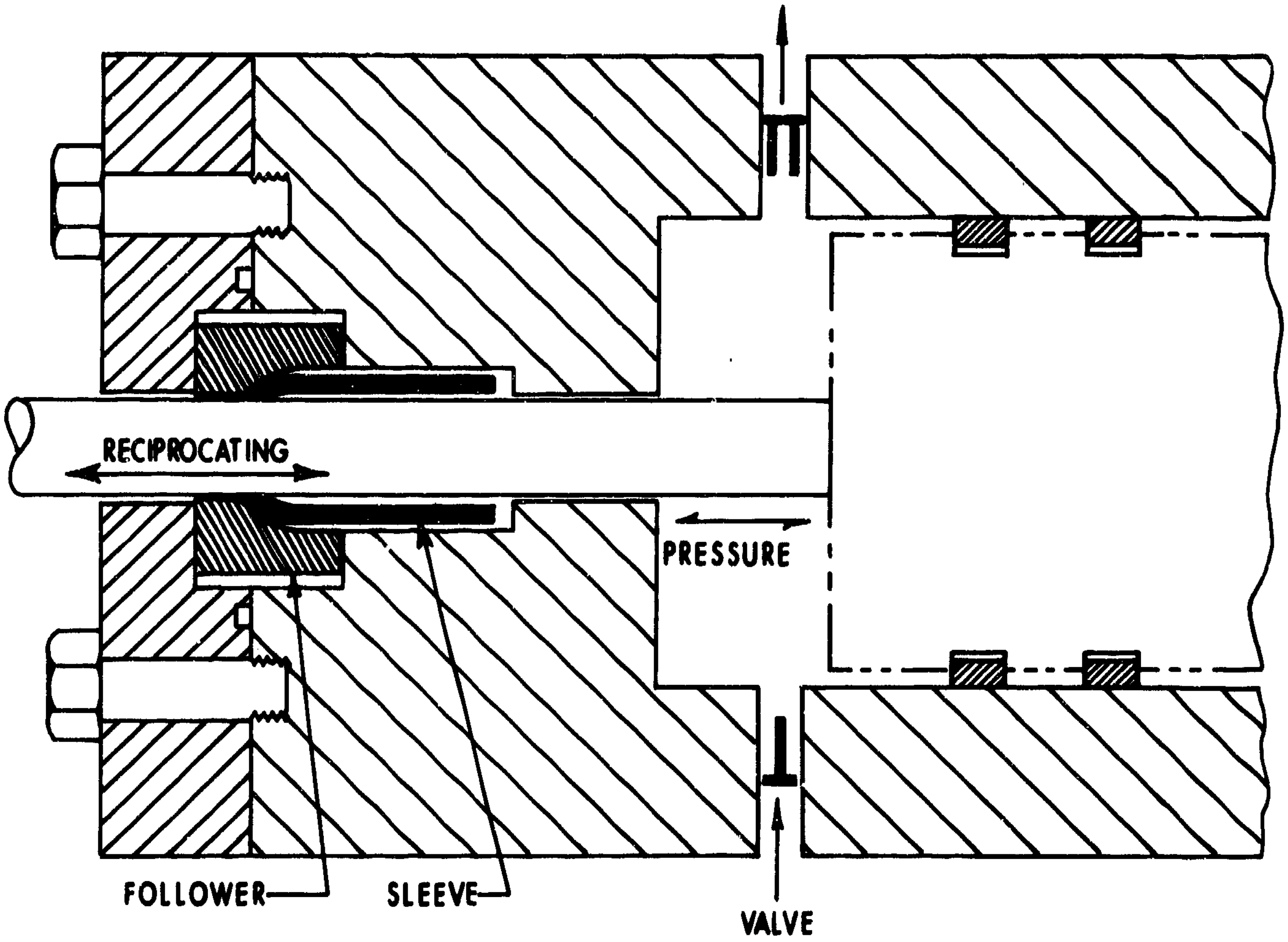

Figure 4
Sleeve Type Rod Seal

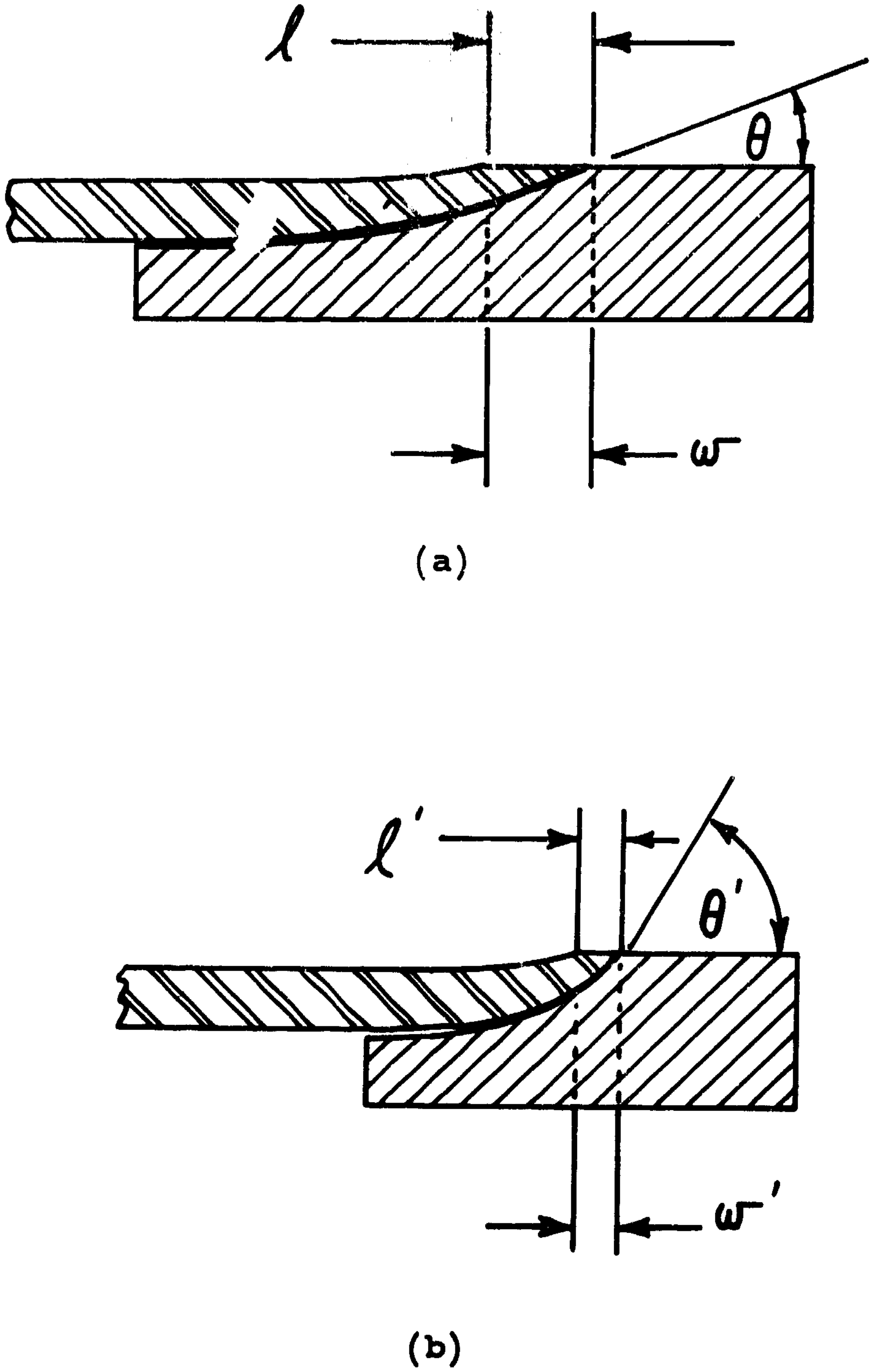

Figure 5
Sealing Widths Related to Follower Exit Angle

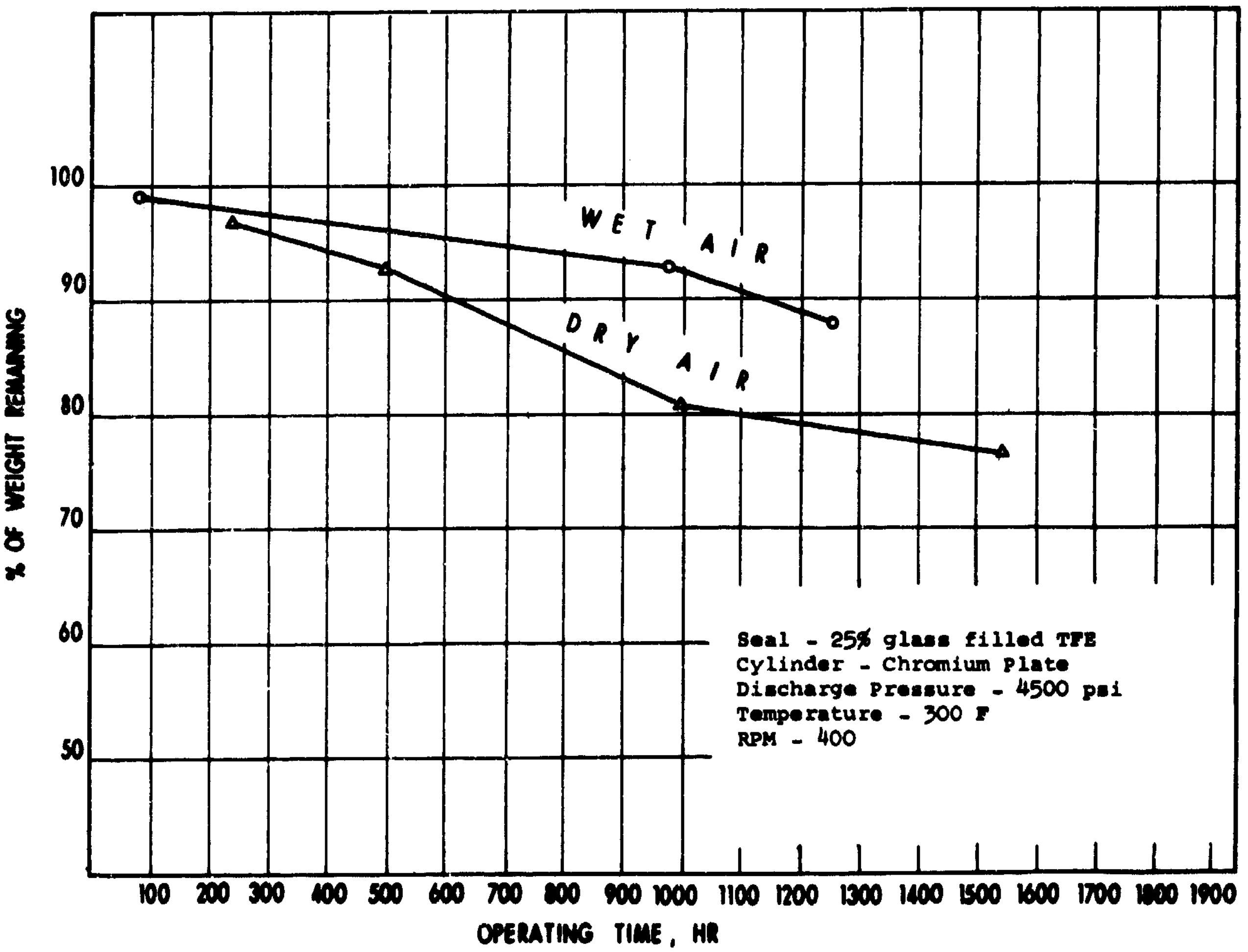

Figure 6
Seal Wear Curves

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Seal - 25% glass filled TFE   Temperature - 300 F
Discharge Pressure - 5000 psi   Wet Air

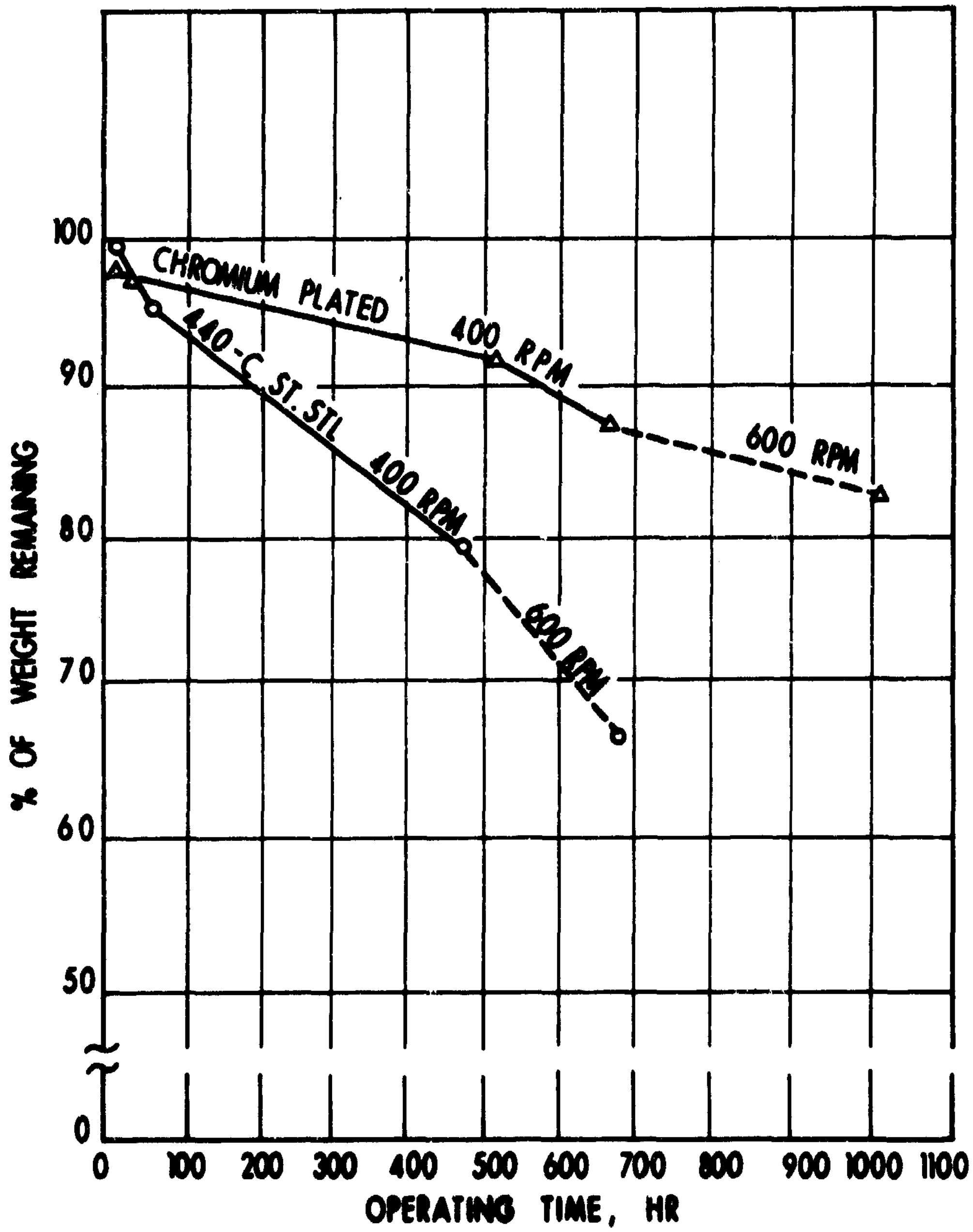

Figure 7
Seal Wear Curves

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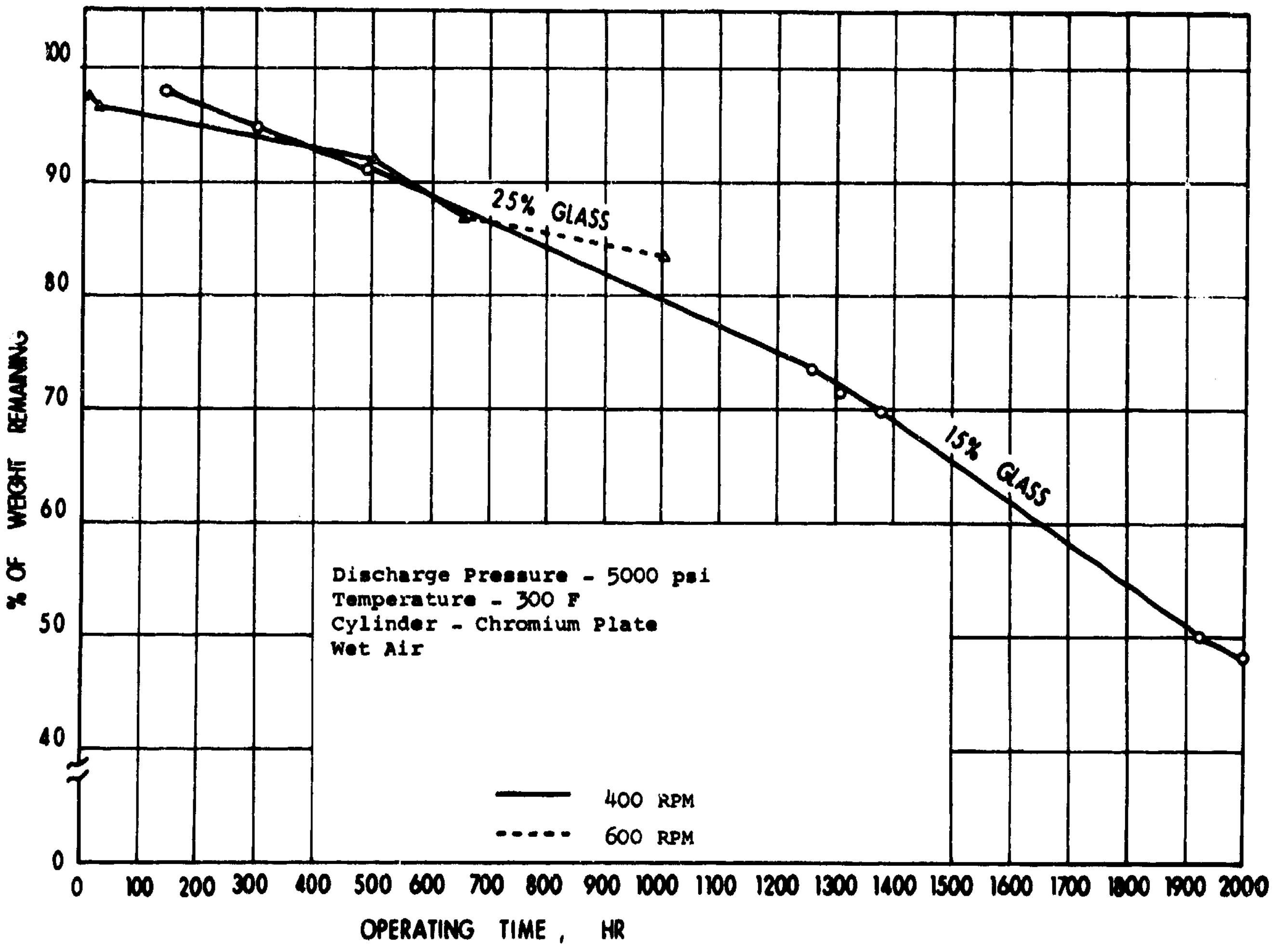

Figure 8
Seal Wear Curves

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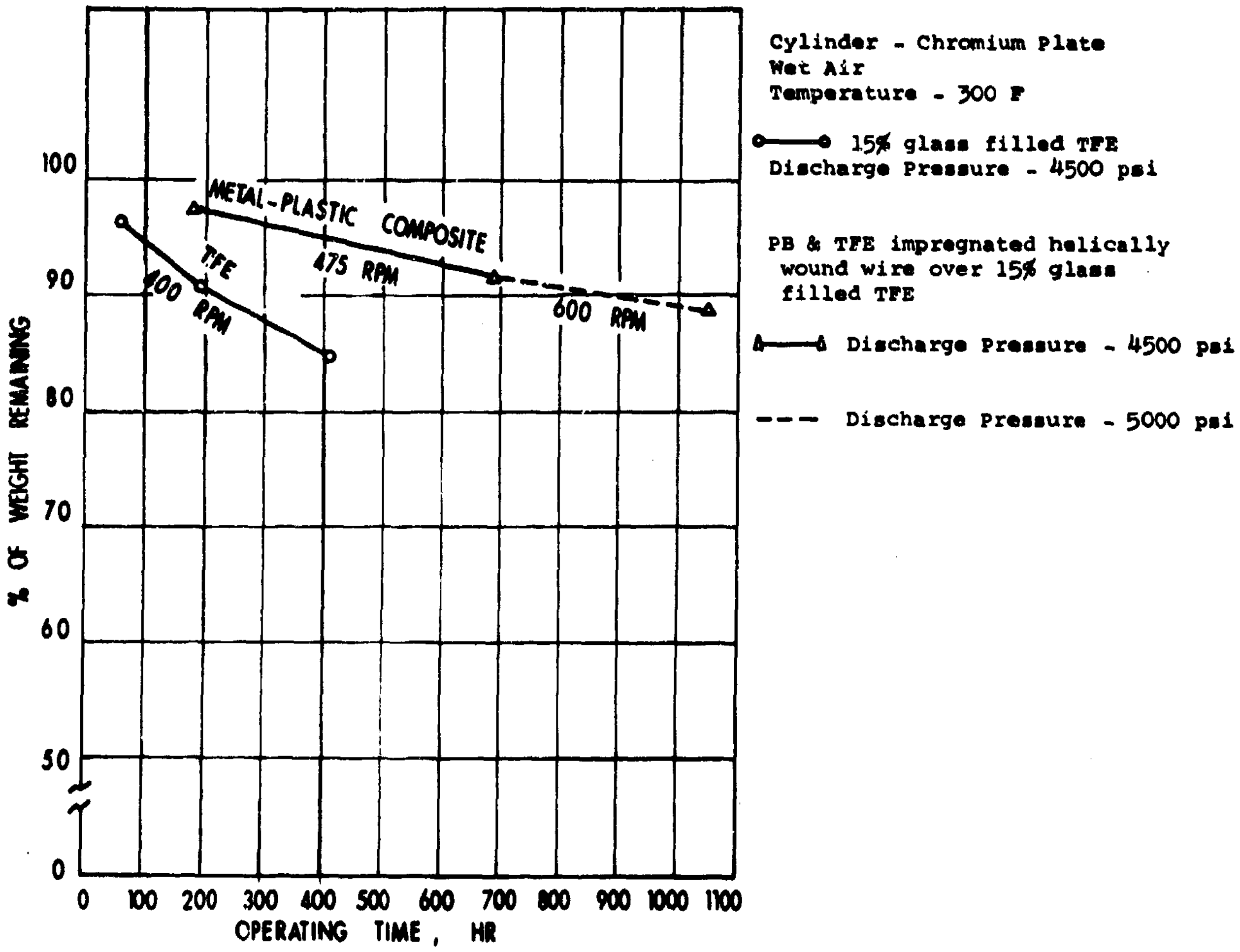

Figure 9
Seal Wear Curves

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13. ABSTRACT

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