NASA TECHNICAL MEMORANDUM

NASA TM X-52889

NASA TM X-52889

HIGH-TEMPERATURE POLYIMIDE HYDRAULIC ACTUATOR ROD SEALS FOR ADVANCED AIRCRAFT

by William R. Loomis and Robert L. Johnson
Lewis Research Center
Cleveland, Ohio

and

John Lee
Royal Industries, Tetrafluor Division
El Segundo, California

TECHNICAL PAPER proposed for presentation at
National Aeronautic and Space Engineering and Manufacturing
Meeting sponsored by the Society of Automotive Engineers
Los Angeles, California, October 5-8, 1970

E-5863

HIGH-TEMPERATURE POLYIMIDE HYDRAULIC ACTUATOR ROD SEALS FOR ADVANCED AIRCRAFT

by

William R. Loomis, John Lee,* and Robert L. Johnson

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

ABSTRACT

This paper summarizes the results and findings of a program to design, develop, and evaluate actuator rod seals for use in advanced aircraft high-temperature hydraulic systems. The rod seals are intended to function efficiently and reliably for 3,000 hours in the temperature range of -40° to 500° F. Preliminary studies of various material and design combinations showed that a polyimide low-pressure second stage V-seal in a two-stage configuration had the greatest potential in long-term duty cycle testing in a simulated actuator test system. Modifications of this seal, that provided for improved fatigue life and more efficient loading, met the test objectives of 20×10^6 short-stroke cycles of operation at 500° F. Severity of this testing was equivalent to 3,000 hours of duty cycle operation. The validity of design techniques used to achieve performance goals was shown.

*Royal Industries, Tetrafluor Division

INTRODUCTION

Sustained supersonic flight has become a reality within the past few years, and the trend has been toward the development of even higher speed aircraft. As operating conditions become more severe with succeeding families of aircraft, design margins of many components will decrease substantially. Not the least to be affected by these considerations are hydraulic system components, particularly the dynamic flight and engine control actuator seals.

Temperature-life requirements for aircraft hydraulic systems are illustrated in figure 1. Present commercial subsonic jet aircraft hydraulic systems seals are operating satisfactorily in excess of a thousand hours at temperatures in the range of 160 to 180° F (1)* while Mach 2 military fighters are limited to less than 1000 hours at 275° F due to deficiencies of presently developed seals. Previous laboratory work had established that elastomeric rod seals are thermally restricted to several hundred hours of service at 400°F(2), and that the best non-elastomeric seals were limited to less than 500 hours at 600° F due to deficiencies in seal design and/or seal materials (3).

One approach to meeting the rigorous operating environment anticipated for future aircraft is the use of two-stage seals for fluid containment in hydraulic actuators. In this type seal, shown in figure 2, the first stage is subjected to full hydraulic system pressure of 3000 to 4000 psi, and leakage past this seal is returned back to the reservoir. The second stage is subjected to a return pressure of only about 100

*Numbers in parentheses designate references at end of paper.

to 200 psi. The general objective of this report is to summarize the results of a program to develop zero leakage second-stage seals for 500° F operation. The long-range goal of this program is to produce rod seals intended to function efficiently and reliably for 3000 hours in the temperature range of -40 to 500° F.

The BACKGROUND section of this report gives an account of some prior work in the development of actuator seals (2) that led to the inception of this reported work. The discussion includes: (A) a description of high temperature seal materials and their selection for evaluation and (B) a synopsis of results from testing with various seal types.

This reported work was directed specifically towards the use of polyimide as the material of construction for the second-stage seals. The objectives were as follows: (A) Design and develop new and improved polyimide V-seal concepts from the 45° V-seal designed and evaluated in work under NASA contract NAS3-7264 (2). This redesign was based on an analysis of geometric configuration, physical properties, and known performance and failure modes, (B) Develop other seal designs which most effectively use the good mechanical properties of the polyimide material, (C) Perform high frequency short-stroke cycling tests with the three most promising one-inch seal configurations developed in this work and with the one-inch 45° V-seal developed previously (2).

The test facility consists of a double ended test actuator and is operated with a chlorinated phenyl methyl silicone fluid at a temperature of 500° F ±20° F, a fluid pressure of 100 to 150 psig, and at an actuator cycling rate of 300 cpm ±25 cpm with a piston rod total stroke length of 0.20 inch ±0.02 inch. Goal of the testing is to run for 20×10^6 mechanical cycles or until seal failure as evidenced by fluid leakage rates in excess of 3 cc per hour.

Part of the studies reported herein were made by Fairchild Hiller Corporation, Republic Aviation Division, under NASA contract NAS3-11170 (4).

BACKGROUND

The polyimide plastic was selected as an actuator rod seal material based on an evaluation of numerous materials comprising the general categories of plastics, soft metals, and hard metals. These materials were evaluated for compatibility with various high temperature fluids at temperatures to 600° F (2). Sliding wear tests were also conducted on the candidate materials. High temperature mechanical properties of the materials were obtained to provide a further basis for evaluating the candidate materials. The results obtained from the foregoing evaluations led to the selection of polyimide material. Studies of friction and wear characteristics of polyimides (5) verified the potentials of the polyimide material.

Chemically, polyimides are organic condensation polymers formed from the reaction between aromatic dianhydrides and aromatic diamines. The polyimides have an operating range for many applications from -400° F to as high as 600° F with short-term capability up to 900° F. Retention of original properties such as stiffness and resistance to deformation at high temperature is excellent. At 500° F they are 30-60 times stiffer than polytetrafluoroethylene (PTFE) materials and have more than ten times the tensile properties of PTFE. These outstanding characteristics make polyimide a leading candidate in applications such as seals, bearings, valve seats, pump vanes and in numerous electrical applications. High resistance to radiation and low out-gassing tendency also permit wide applications in space vehicles. Table I presents a summary of properties of polyimide materials.

Early developmental work (2 and 3) on the polyimides produced seal configurations that performed exceedingly well as compared to seals developed from other nonelastomeric and metallic materials. An extensive analytical and experimental study was made (2) to find the most promising seal designs-material combinations for second-stage seals. Those that were selected for endurance studies are shown in Table II. These seals were endurance studied at temperatures to 500° F in a double-ended test actuator assembly (fig. 2) together with a polyimide split contracting ring first-stage seal.

Figure 3 depicts the flight and cyclic profiles and the thermal environment under which the seals were tested. This is a hypothetical duty cycle for a Mach 3 aircraft actuator wherein short-stroke mechanical cycling, such as occur during cruise, comprise the major portion of the profile. Typical results from these endurance studies are summarized in Table III.

Of the seals evaluated under these conditions, the polyimide second-stage V-seal demonstrated the best potential for meeting the projected requirements. Although the seals ultimately failed, the type of failure was attributed to high wall stresses which may be readily reduced by simple design changes.

SEAL DESIGN ANALYSIS

Based on test results obtained in reference 3, failure of the one-inch diameter polyimide V-seal after 1300 hours of operation was caused primarily by fatigue as a consequence of the seal's shape and loading condition. A time-dependent factor may have also been significant: namely, that slow relaxation of the material at temperature could have caused changes in geometry and loading conditions that were of sufficient magnitude to contribute to failure. Failure of the V-seal usually occurred at the inboard or pressure side element (an example is shown in fig. 4), with progressively less damage to the middle and outboard elements. Location of these elements is given in the V-seal sketch in Table II. The inboard elements received the full effects of fluid pressure, distributing some of the load to the cavity walls and the balance to the other two elements. These factors point again to geometry and loading as the determinants of failure, as the most heavy loaded member consistently sustained the worst damage. The seals usually cracked circumferentially; some radial cracks were observed. The circumferential failures were close to the point of support by the inboard load ring, indicating either a point of inflection in bending or a shear plane. The radial cracks could have been tensile failures due to shrinkage resulting from thermal aging. The polyimide material is rather notch sensitive, and consequently, imperfections in the material may have caused some of the failures. In either case, loading and geometry were considered to be fundamental causes of failure.

The foregoing premises were further substantiated on the basis of results obtained in analyses of the seal's geometric shape, operating stresses and thermal effects on the polyimide material. Of the parameters studied, operating stresses and thermal stresses were found to be the most significant in effects on seal performance. The study showed that the main cause of failure was due to the seals being stressed more highly than present guidelines would suggest. The analysis also showed that thermal stresses represent approximately 30 percent of the total stress.

From a design standpoint, reduction of thermal stress is difficult because of relatively high coefficient of thermal expansion of the polyimide. Additionally, the stress resulting from the working pressures is also a fixed parameter which leaves mechanical loading stress as the major design parameter that could be altered. Sealing contact stresses need be no higher than to establish intimate contact at sealing interface. Mechanical stresses should be minimized.

Based on these analyses and investigations, two modified versions of the original V-seal design were evolved. Figure 5b shows a reconfigured V-seal with 30° leg angles. For comparative purposes the original 45° V-seal design configuration is shown in figure 5a. The cross-sectional thickness of the 30° V-seal was approximately 0.032 inch. Changing the angles of the sealing legs from 45° to 30° resulted in longer seal legs, which permitted greater leg deflections for a given load. Thus maximum deflection was achieved with minimum spring loading of the seal. As the design study indicated that loading of the O.D. and I.D. surfaces differed considerably, a dual load path loading system was devised, which permits asymmetrical loading of the seal. Referring again to figure 5b, initial application of the axial load by the outboard loading springs causes the inner load ring to make contact with the inner seal leg. As the inner load ring is spring loaded, it moves axially inward while maintaining a predetermined load on the seal, thus permitting the outer loading surface to make contact with the outer seal leg. The use of this dual loading arrangement resulted in a more uniform and controllable seal load. Another modification of the original V-seal configuration is shown in figure 5c. This design further improved the original V-seal designs by incorporating linearly tapered sealing legs to minimize the bending stresses at the transition surfaces of the seal. In effect the tapered leg configuration relocated the maximum bending stress away from the notch sensitive area of the seal. This relocation of stress minimized cracking. In addition, the tapered leg configuration gave seal deflections (fig. 6) equivalent to those obtained with the 30° V-seal, but at approximately 35 percent lower seal circumferential loading. This resulted in lower contact stresses at the seal contact surface between the polyimide element and the actuator rod.

Additional seal designs were evolved, which offered improvements over the original 45° V-seal. In these designs, attempts were made to establish a good balance in operating stresses, wear compensation, and friction. Details are reported in reference 4.

Bench tests were conducted on the candidate seals to validate the basic assumptions used in the design phase. It was desired to improve the loading characteristics of the seal so that maximum seal deflections, for the purpose of wear and misalingment compensation, could be obtained while subjecting the seal to the lowest stress level possible. Seal deflection, leakage and friction were the criteria used to evaluate the new designs. The original 45° V-seal design was included in the testing to obtain baseline data for evaluating the modified designs. Results of these tests are summarized in Table IV. Seal deflections as a function of seal loading for the two best configurations as compared to the original V-seal design are shown in figure 6. Figure 7 shows the effect of seal design on friction and sealing stress for the 45°, 30° and tapered leg V-seals.

Based on these results, the following seal configurations were selected for the high temperature cycling tests: (A) 30° V-seal with dual loading device (fig. 5b), (B) Lip seal (Table II) with slotted metal hoop spring, and (C) Tapered leg V-seal with dual loading device (fig. 5c). The above configurations were evaluated in conjunction with the original 45° V seal design (fig. 5a) used in reference (2).

SEAL TEST APPARATUS AND PROCEDURE

The high temperature cycling test apparatus used in this work is basically the same as the one used in studies under NASA contract NAS3-7264 and described in more detail in references (2) and (4). The rig consists of a hydraulic power supply package, an actuator drive, and the seal test actuators.

The power supply consists of an electric motor-driven variable-delivery pump, which is capable of supplying a flow of 10 gpm at pressures to 4000 psi. This hydraulic unit powers the servo controlled actuator which drives the seal test actuators. The stroke length and cycling speed of the driving actuator are controlled by a cam and variable speed electric motor. The stroke length is regulated by positioning the servo valve drive link on the cam. The drive link also serves as the feedback device to close the servo loop. Pressure taps are installed in the driving actuator piston chambers to monitor cylinder pressure. By monitoring the pressure in the driving actuator cylinder, an indication of seal friction can be obtained throughout the testing. As the pressure in the driving actuator is a function of the load being driven, a steady-state pressure value can be established during testing. Thereafter, any increase in seal friction or driving load would result in an increase in pressure over the steady-state value, thus warning the operator of an impending malfunction.

The test actuators are attached to a common crank arm. Each test actuator contains two different seal configurations. Pressurized fluid is supplied to the test actuators from an accumulator under a nitrogen charge. Pressure lines to the test actuators are routed separately; shut-off valves are installed on each line to permit shut-down of the failed actuator. A floating piston is incorporated in the accumulator to provide a barrier between the oil and nitrogen. The accumulator also serves as a fluid make-up system to compensate for leakages.

Filling of the system is accomplished with a hand pump. Leakage drain lines are provided on each end of the test actuator to monitor seal leakage. System fluid drain lines are also installed on each actuator to facilitate draining. Thermocouples for monitoring fluid and seal temperatures are also provided.

Testing of the candidate seals for the three most promising one-inch seal configurations along with the previously developed 45° V-seal, the selection and description of which were given in the previous section, was conducted concurrently in two separate test actuators. These double ended actuators were used in prior studies (2) and described in the BACKGROUND section.

Procedure for conducting high frequency short-stroke cycling tests included continuous operation of the test seals at a fluid temperature of 500° F ±20°F with shut-downs over weekends. The test actuators were mounted under an oven hood which insured maintenance of temperature of the test seals at the same temperature as the test fluid. The cycling rate was 300 cpm ±25 cpm, and the piston rod total stroke length was held at 0.20 inch ±0.02 inch. The high frequency short-stroke cycling test was selected because previous work (2) had shown that this type operation was the most critical part of an endurance duty cycle. The greatest wear had occurred during rapid short-stroke operation. The test fluid was chlorinated phenyl methyl silicone, and the test was run to failure of the seals or completion of 20-million short-stroke cycles. This is equivalent to operating for about 3000 hours of simulated flight duty cycle operation. Seal failure for these tests was defined as fluid leakage from the test seals in excess of one drop per minute or approximately 3 cc per hour. This is a leakage rate comparable to that experienced with O-ring type actuator seals in present day commercial jet aircraft in normal operation.

EXPERIMENTAL TEST RESULTS

Results of the high temperature cycling test are summarized in Table V. Of the four seals evaluated, the 30° V-seal and tapered leg V-seal, which are improved versions of the original 45° V-seal design, successfully completed the 20 million short-stroke cycle test. Both seals were subjected to a total of 1172 hours of operation of which 80 percent of the time was at 500° F. As shown in figure 8, leakage accumulated at the end of the test was 27.5 cc and 25.5 cc for the 30° V-seal and tapered leg V-seal, respectively. The original 45° V-seal design developed excessive leakage after 11.3 million cycles. Figure 9 depicts the condition of the seals after the high temperature cycling test. The 45° V-seal showed incipient cracks near the inside radius of the seal. Erosion of material from the dynamic sealing portion of the seal is also evidenced. Both of these failure modes were exhibited by the 45° V-seal in prior testing (2), wherein failures occurred at approximately the same number of cycles in a similar manner. Excessive loading is believed to have caused both conditions. The 30° V-seal was in excellent condition except for a small circumferential crack on the outside surface of the outboard seal. As this seal was exposed to an air atmosphere, it was suspected that the crack was due to high temperature air aging effects. The tapered leg V-seal was in good condition with no evidence of cracking. This fact points to the benefits derived from the use of tapered sealing legs.

SUMMARY OF RESULTS

Studies were made to further the development of high-temperature hydraulic actuator rod seals for advanced aircraft. The effort was directed specifically towards the use of polyimide as the seal material in the second stage of a two-stage configuration. Improvements were made on earlier V-seal designs and other designs were evolved which most effectively used the mechanical properties of the polyimide. Long-term cycling tests at 500° F ±20° F on the most promising second-stage seal configurations were conducted to evaluate design improvements. Testing of the candidate seals was performed concurrently in two separate test actuators using a chlorinated phenyl methyl silicone fluid. The actuators were operated continuously, except for weekends, at the test temperature until failure (fluid leakage exceeded 1 drop per minute rate) or until completion of 20 million short-stroke cycles. The cycling rate was 300 cpm ±25 cpm, the piston rod total stroke length was 0.20 inch ±0.02 inch, and fluid pressure was 100 to 150 psig. The experimental data and analysis revealed the following:

1. The capability of polyimide rod seals to meet the specified goal of 20×10^6 short-stroke cycles at temperatures to 500° F with a leakage rate of less than one drop per minute, was successfully demonstrated by two seals: a tapered leg V-seal and a 30° V-seal both with dual loaded load springs.

2. The use of a variable-thickness cross-section in a seal design, such as with the tapered leg V-seal, provided a minimum stress level

which was found to be a practical approach for minimizing bending stresses at the critical notch sensitive areas of the seal.

3. The modified 30° V-seal showed improved flexibility with the use of longer seal legs.

4. Asymmetrical loading provided by a dual load path loading device. with acting load rings and springs on both axial ends of the sealing element assembly, resulted in a more uniform and controllable seal load.

5. The primary causes of failure of the 45° V-seal were excessive seal loading and uneven distribution of the load. This resulted in circumferential cracking at stress concentrations that exceeded the strength of the polyimide.

REFERENCES

1. R.E. Williams, "A New Look at Supersonic Aircraft Hydraulic Requirements," Paper 691 C, Society of Automotive Engineers--American Society of Naval Engineers, National Aero-Nautical Meeting, Washington, D.C., April 8-11, 1963.

2. J. Lee, "High-Temperature Hydraulic System Actuator Seals for Use in Advanced Supersonic Aircraft," Summary Report FHR 2702-4, Fairchild Hiller, Republic Aviation Division (NASA CR-72354), Sept. 15, 1967.

3. J. Lee, "High-Temperature and Fluid-Resistant Seal and Sealant Materials for the Supersonic Transport," Republic Aviation Corp., Air Force Materials Laboratory Report ML-TDR-64-266, 1964.

4. J. Lee, "Development of High Temperature Polyimide Rod Seals," Final Report FHR 3612-1, Fairchild Hiller, Republic Aviation Division (NASA CR-72563), Aug. 21, 1969.

5. D.H. Buckley, "Friction and Wear Characteristics of Polyimide and Filled Polyimide Compositions in Vacuum (10^{-10} mm Hg)," NASA TN D-3261, 1966.

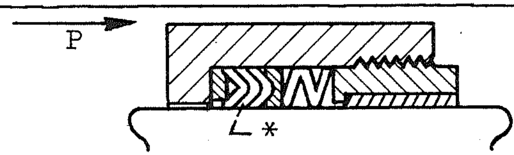
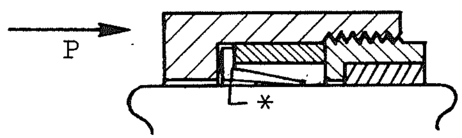
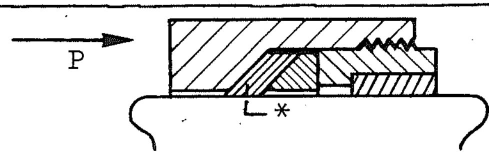
E-5863

TABLE I - PROPERTIES OF POLYIMIDE MATERIALS
(at room temperature unless otherwise noted)

Properties	Meldin PI	Meldin PI-30X	Meldin PI-15Y	XPI-182	SP-1	SP-2	Polymer 360*
Ultimate Tensile Strength, psi	11,600 6,000(500°F)	3,320 1,370(500°F)	7,200 3,340(500°F)	11,000 6,000(482°F) 5,000(600°F)	10,500 6,000(482°F) 2,500(600°F)	7,000 3,500(482°F) 2,500(600°F)	13,000 4,100(500°F) 1,500(550°F)
Elongation, percent	2.9 9.0(500°F)	2.0 4.6(500°F)	1.7 4.2(500°F)	5-8	6-7 6-7(482°F)	4-5 6-7(482°F)	13(yield) 7(yield,500°F)
Flexure Strength, psi	11,800 6,400(500°F)	5,420 2,620(500°F)	10,770 6,010(500°F)	18,000 6,600(475°F)	14,000 7,000(600°F)	13,000 6,200(600°F)	17,200 8,900(500°F)
Flexure Modulus, psi	610,000 248,000(500°F)	370,000 166,000(500°F)	860,000 480,000(500°F)	480,000 330,000(475°F)	460,000 230,000(600°F)	610,000 330,000(600°F)	395,000 252,000(500°F)
Compressive Strength, psi	61,900 31,000(500°F)	13,000 7,000(500°F)	31,600 16,300(500°F)	22,300(yield)	>24,000 >12,000(482°F)	18,000 11,000(482°F)	17,900(yield) 7,500(500°F)
Compressive Modulus, psi	530,000 300,000(500°F)	280,000 111,000(500°F)	680,000 260,000(500°F)				191,000 138,000(500°F)
Coefficient Thermal Exp.,in/in°Fx10^{-5}	**2.4(73-400°F) ***1.7(73-400°F)	3.2(73-400°F) 2.2(73-400°F)	1.8(73-400°F)	3.18(-22°F-435°F)	2.6-3.0(73-392°F) 3.3-3.9(392-752°F)	2.1-3.0(73-392°F) 2.4-4.8(392-752°F)	2.6(75-509°F)
Coefficient Friction (air)	0.5	0.2-0.25	0.3-0.35	0.15	0.15-0.26	0.15-0.21	
Thermal Conductivity (Btu/hr/ft^2/°F/in)				0.087	2.6-3.3	3.8-4.2	1.32
Impact Strength (Izod),ft.-lb/in.	0.5	0.4	0.3	0.6-0.8	0.9 1.1(482°F)	0.2 0.5(482°F)	2-4

*Thermoplastic polymer
**Molded direction
***Cross direction

TABLE II - RECOMMENDED ROD SEAL DESIGN AND MATERIALS
(From ref. 2)

SEAL TYPE	DESIGN CONFIGURATION	RECOMMENDED MATERIALS	ALTERNATE MATERIALS
V-SEAL		Unfilled polyimide (SP-1)	Nickel Foametal with CaF_2 + BaF_2
LIP-SEAL		Vascojet-1000 or Cobalt-molybdenum alloy(75%Co+25%Mo)	
REED-SEAL		Vascojet-1000 and silver alloy (72% Ag+28%Cu) combination	Cobalt-molybdenum alloy and silver alloy (72%Ag +28%Cu) combination, Unfilled polyimide (SP-1)

*Sealing elements. With the V-seal configuration, the inboard element is on the pressure side.

Table III. Typical Results-Hydraulic Actuator Seals
(From ref. 2)

Seals	Time* (hrs)		Mechanical Cycles, millions		Thermal** Cycles
	Total	at 500° F	Total	at 500° F	
Polyimide V-seal	1358	631	10.0	8.9	315
Cobalt-Moly Lip-Seal	171	77	1.4	1.0	38
H-11 Tool Steel-Silver Reed Seal	433	186	2.6	2.2	89

*Tests terminated at maximum leakage rate of 3 cc/hr.
**Each thermal cycle 180 minutes.

Table IV. Summary of Wear Compensation and Seal Friction of Candidate Polyimide Seal Configurations (From ref. 4)

Seal Configuration	Method of Loading	Diametral Wear Compensation	Seal I.D. Radial Deflection at Design Load	Sealing Stress	Friction
		inch	inch at lb/in.	psi	pounds
45° V-Seal	*	<0.006**	0.0012 at 10.6	350	95
45° V-Seal (modified)	***	0.006 (no leakage)	0.0027 at 10.6	350	90
30° V-Seal	*	<0.006**	0.0025 at 7.0	216	110
30° V-Seal (modified)	***	0.006 (no leakage)	0.0027 at 7.0	216	90
Lip Seal	hoop spring	0.006 (no leakage)	0.0027 at 3.0	130	29
Wide Angle V-Seal	*	0.013 (no leakage)	0.007 at 16	265	64
Tapered Leg V-Seal	***	0.006 (no leakage)	0.0027 at 4.5	150	72

*Standard load ring; Belleville springs
**Leaked at wear shown
***Modified load ring; Belleville springs

Table V. Summary of High Temperature Cycling Test With Polyimide Seals (From ref. 4)

Seal Configuration	Total Test Time (hrs)	Time at 500° F (hrs)	Total Cycles, millions	Cycles at 500° F, millions	Accumulated Leakage (cc)
45° V-Seal	730.5	586	13.2*	10.5	180 cc/hr rate**
30° V-Seal	1172	937	21.4	17.9	27.5
Spring Loaded Lip Seal	220	178	3.4	3.2	21 cc/hr rate**
Tapered Leg V-Seal	1172	937	21.4	17.9	25.5
Wide-Angle V-Seal (replaced lip seal)	1044	824	18.8	15.8	103.3
Wide-Angle V-Seal (replaced 45° V-Seal)	534***	416	9.8	7.5	79***

*Seal failure occurred at 11.3 million cycles, but seal was kept under test to obtain additional data.
**Test discontinued.
***Test stopped without failure at conclusion of program.

E-5863

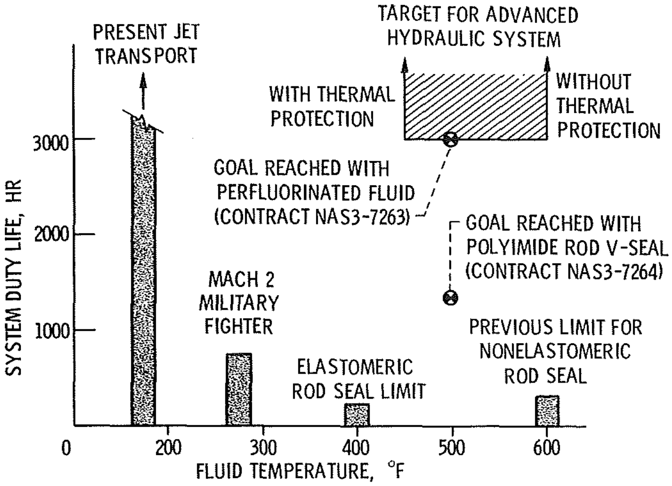


Figure 1. - Temperature-life requirement for aircraft hydraulic systems.

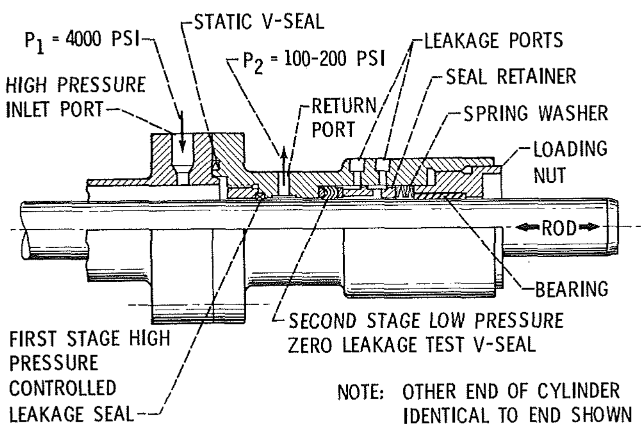


Figure 2. - One-inch rod seal test actuator.

E-5863

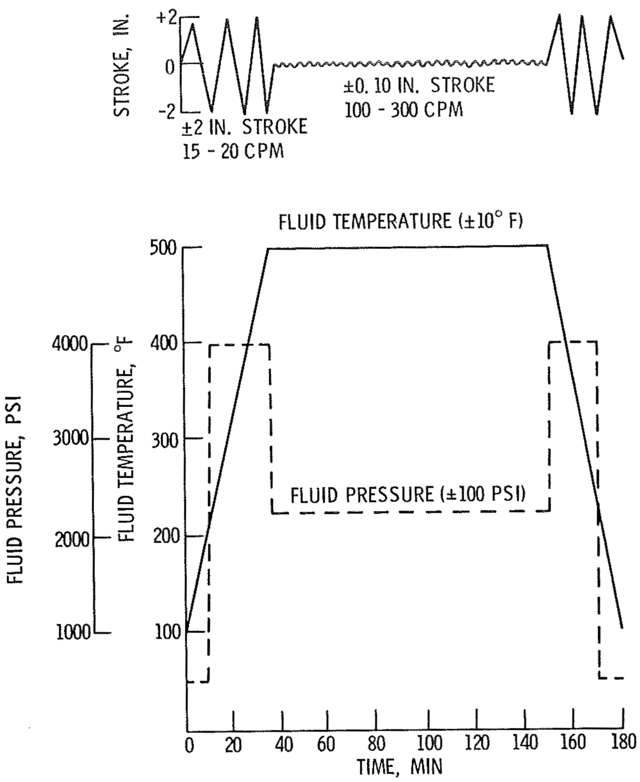
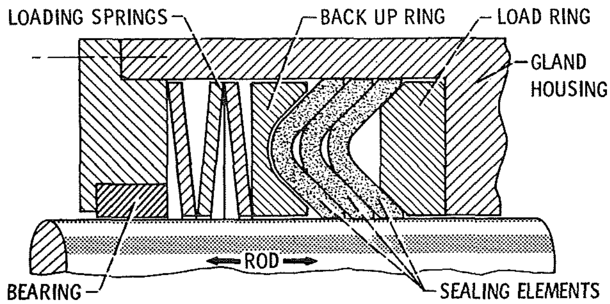


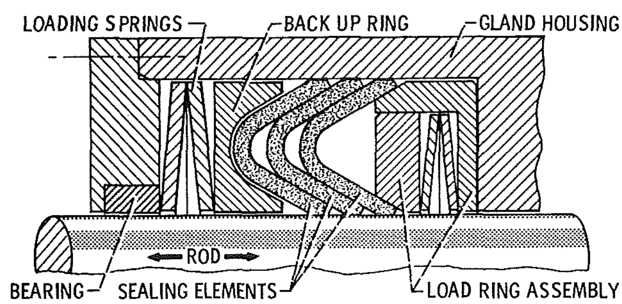
Figure 3. - Endurance test duty cycle.

Figure 4. - Inboard element from one-inch polyimide 45° V-seal after 1358 hr duty cycle test at 500° F showing circumferential and radial cracks.

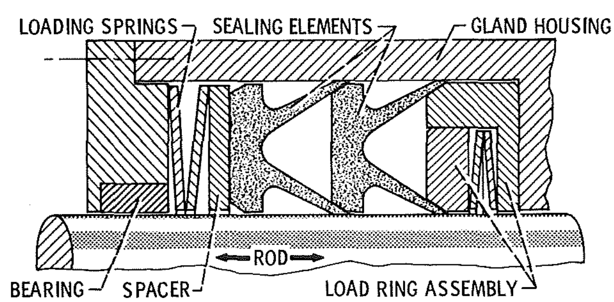
E-5863



(A) 45° V-SEAL, ORIGINAL DESIGN.



(B) 30° V-SEAL WITH SPLIT LOAD RING.



(C) TAPERED LEG V-SEAL WITH SPLIT LOAD RING.

Figure 5. - Rod seal designs with polyimide sealing elements.

CD-10852-15

E-5863

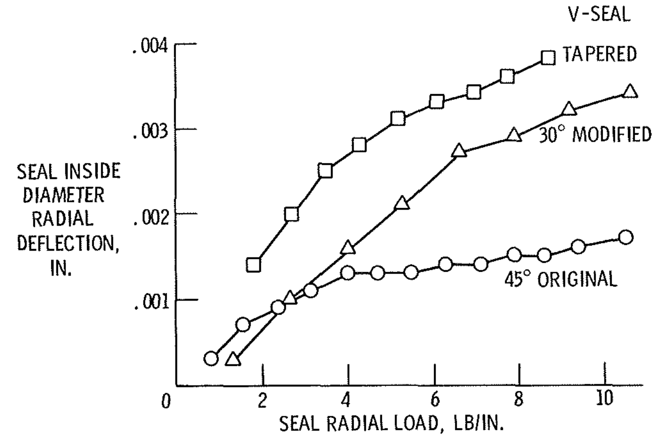


Figure 6. - Load deflection test results - inboard seal inside diameter radial deflection against radial load for three candidate seal configurations.

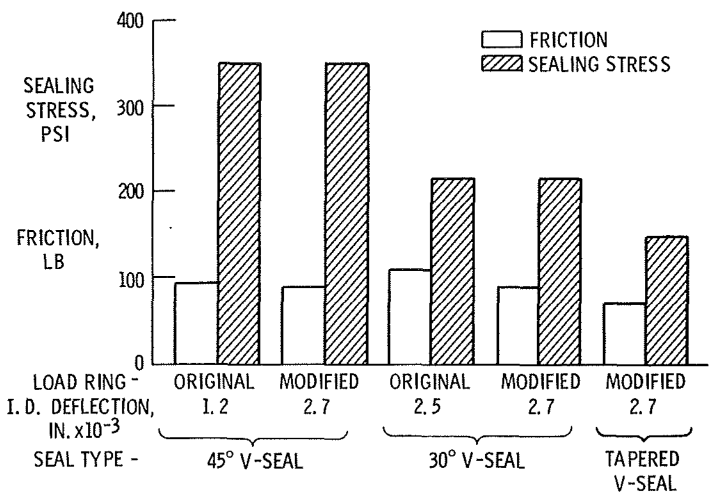


Figure 7. - Effect of seal designs on friction and sealing stress.

E-5863

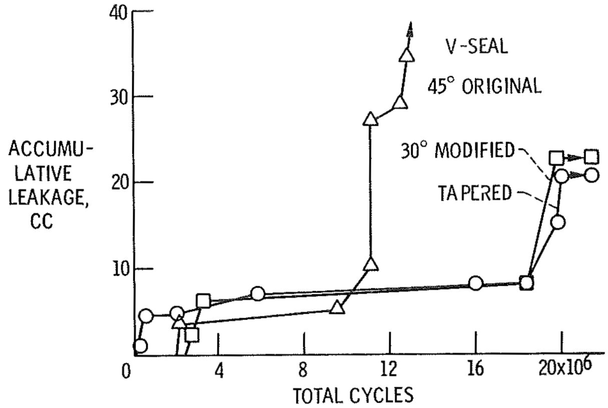


Figure 8. - Cumulative seal leakage high temperature cycling test at 500° F.

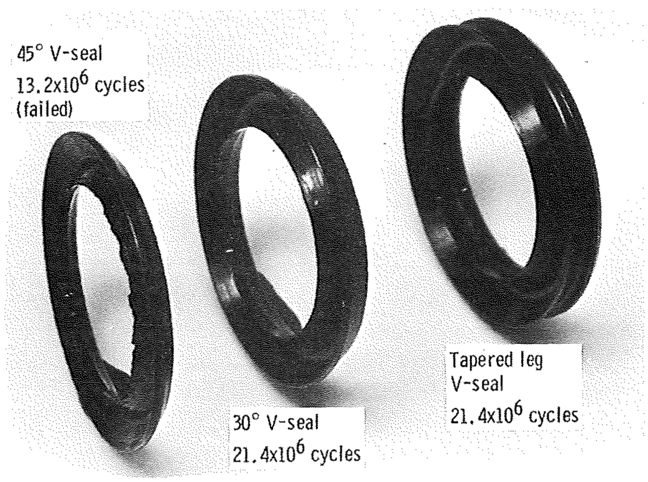


Figure 9. - Inboard elements from one-inch polyimide 45° 30°, and tapered leg V-seals after 500° F short stroke cycling tests.