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TESTING OF POLYIMIDE SECOND-STAGE ROD SEALS FOR SINGLE-STATE APPLICATIONS IN ADVANCED AIRCRAFT HYDRAULIC SYSTEMS

by A. W. Waterman

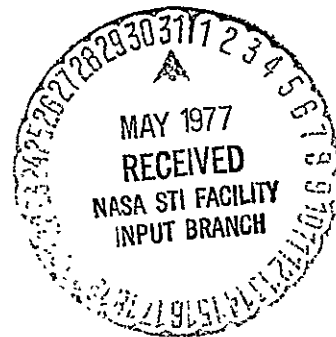
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16 Abstract <p>Machined polyimide second-stage rod seals developed during the NAS3-14317 contract were evaluated to determine their suitability for single-stage applications where full system pressure acts on the upstream side of the seal. The 6.35-cm (2.5-in.) K-section seal was tested in impulse screening tests where peak pressure was increased in 3.448-MPa (500-psi) increments each 20 000 cycles. Seal failure occurred at 37.92 MPa (5500 psi), indicating a potential for acceptability in a 27.58-MPa (4000-psi) system. Static pressurization for 600 sec at pressures in excess of 10.34 MPa (1500 psi) revealed structural inadequacy of the seal cross section to resist fracture and extrusion. Endurance testing showed the seals capable of at least 65 000 1.27-cm (0.5-in.) cycles at 450 K (350° F) without leakage. It was concluded that the second-stage seals have been proven to be exceptional in the 1.379-MPa (200-psi) applications for which they were designed, but polyimide material properties are not adequate for use in this design at pressure loading equivalent to that present in single-stage applications.</p>			
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SUMMARY

The objective of the extended program conducted under NASA contract NAS3-18529 was to continue evaluation of machined polyimide second-stage rod-seals, developed during the NAS3-14317 contract for application to advanced aircraft hydraulic systems. This objective was accomplished by evaluating the 6.35-cm (2.5-in.) K-section seal capability to satisfy single-stage seal requirements when the upstream side of the seal is exposed to full system pressure.

Completion of impulse screening tests to a maximum peak pressure of 37.92 MPa (5500 psi) was accomplished by beginning with 20 000 cycles at 13.79 MPa (2000 psi) and increasing the peak pressure by 3.448 MPa (500 psi) for every additional 20 000 cycles until seal failure. Failure of the seals was encountered twice during static pressurization; once in preparation for conducting a full duration, 200 000-cycle impulse test at 31.02 MPa (4500 psi) and again at 20.68 MPa (3000 psi). These results showed that the longer residence time at pressure caused seal cross-section fracture.

Testing was suspended after 65 000 cycles due to wear in actuator components. There had been no visible leakage from the test seals during this cyclic operation. Posttest seal inspection showed that the test seal was fractured similarly to the failure under static pressure as mentioned previously. Further testing was not conducted because the fractured seal could not be reinstalled in the actuator.

It was concluded from the results of testing that polyimide material properties are not sufficient for design of a K-section seal that will resist full system pressure as required in single-stage applications. It is recommended that no further development of either the K-section or Chevron-section polyimide seals be conducted for single-stage seal applications in airplane high-pressure hydraulic systems. Polyimide second-stage seal development efforts should be continued with the objective to standardize design dimensions for a number of seal sizes for introduction to specific low-pressure applications in industry.

INTRODUCTION

The development of advanced aircraft and space hydraulic systems requires consideration of new materials and design concepts. The higher fluid temperatures identified with these hydraulic systems preclude the use of many heretofore conventional seal design practices. The universal application of the elastomer to all hydraulic sealing applications is a thing of the past. The elastomers used in conjunction with polytetrafluoroethylene (PTFE) seal components will still have specific design applications, but critical dynamic sealing requirements will require new materials capable of long life at high fluid temperatures.

The material properties of several high-temperature plastics are acceptable for the entire range of type III hydraulic system temperatures as well as for considerably higher temperatures, making these materials prime candidates for experimental seal research for advanced aircraft and space applications. NASA initiated research that was instrumental in the development of the new machine-fabricated Chevron- and K-section second-stage seal concepts using polyimides in exploratory tests to determine sealing characteristics under various operating environments. These efforts were conducted under the NAS3-14317, NAS3-16733, and NAS3-16744 contracts (refs. 1 through 3). Experimental investigations with these seals to date have emphasized the stable strength properties of machinable polyimides and satisfactory seal performance at high temperatures over long durations during thermal cycling and during exposure to hard vacuum.

The program reported herein is a continuation of the above-mentioned seal development programs. The work conducted was to determine the highest pressure to which machined seals of the 6.35-cm (2.5-in.) diameter K-section configuration were acceptable under impulse and endurance requirements of simulated advanced aircraft single-stage rod seal applications. Successive impulse screening tests in segments of 20 000 cycles at room temperature were conducted until seal failure, with the peak pressure for each added segment set at 3.448 MPa (500 psi) above the pressure for the previous segment. Endurance testing at 450 K (350° F) in a system using Mil-H-83282 fluid was conducted to evaluate seal wear under the highest pressure loading shown satisfactory during impulse testing.

TEST SEALS

The objective of this program was to continue the evaluation of the second-stage polyimide rod-seal design developed for advanced aircraft applications under contract NAS3-14317 and reported in reference 1.

The soundness of the seal design was demonstrated during extensive endurance testing both during the NAS3-14317 contract and during the NAS3-16733 and NAS3-16744 extensions, references 2 and 3. All of the polyimide seals evaluated during these contracts were machined from SP-21 polyimide material. Fabrication by machining allowed the critical control of tolerance dimensions and surface finishes necessary to take the best advantage of the polyimide material properties. Such fabrication resulted in a seal having excellent performance characteristics.

SEAL CONFIGURATION

The test articles used were all the 6.35-cm (2.5-in.) K-section second-stage seals as designed under NASA contract NAS3-14317 and illustrated in figure 1. The test seals were machine fabricated from DuPont SP-21 polyimide material using standard engine lathe techniques.

NEW SEAL INSPECTIONS

Eight seal elements sufficient to provide four seal assemblies were available as unused parts from the NAS3-16744 contract, reference 3. These eight elements were inspected both dimensionally and visually to ascertain the accuracy of inside and outside dimensions and to determine the structural integrity of the seal elements.

The most critical dimensions were the inside and outside diameters. Accurate control of these dimensions was necessary to insure sealing at the rod surface at high temperature and sealing at the gland surface at low temperature. A nominal design dimension of 7.0810 cm (2.7878 in.) for the outside diameter provides a 0.00254-cm (0.001-in.) interference fit between the freestate seal and the nominal gland at 228 K (-50° F). The 6.3129-cm (2.4854-in.) nominal inside diameter provides a 0.00254-cm (0.001-in.) interference fit between the free-state seal and the nominal rod at 450 K (350° F). The results of the dimensional inspections are shown in table 1.

The general appearance of all of the unused seals was good. Evidence was present of fine machining marks on all elements with some nonuniformity of seal edge width or discontinuity (surface with an abrupt change in surface elevation). There were also instances of small nicks, pin holes, or scratches on some elements. Table 2 identifies the elements by the type of imperfection noted.

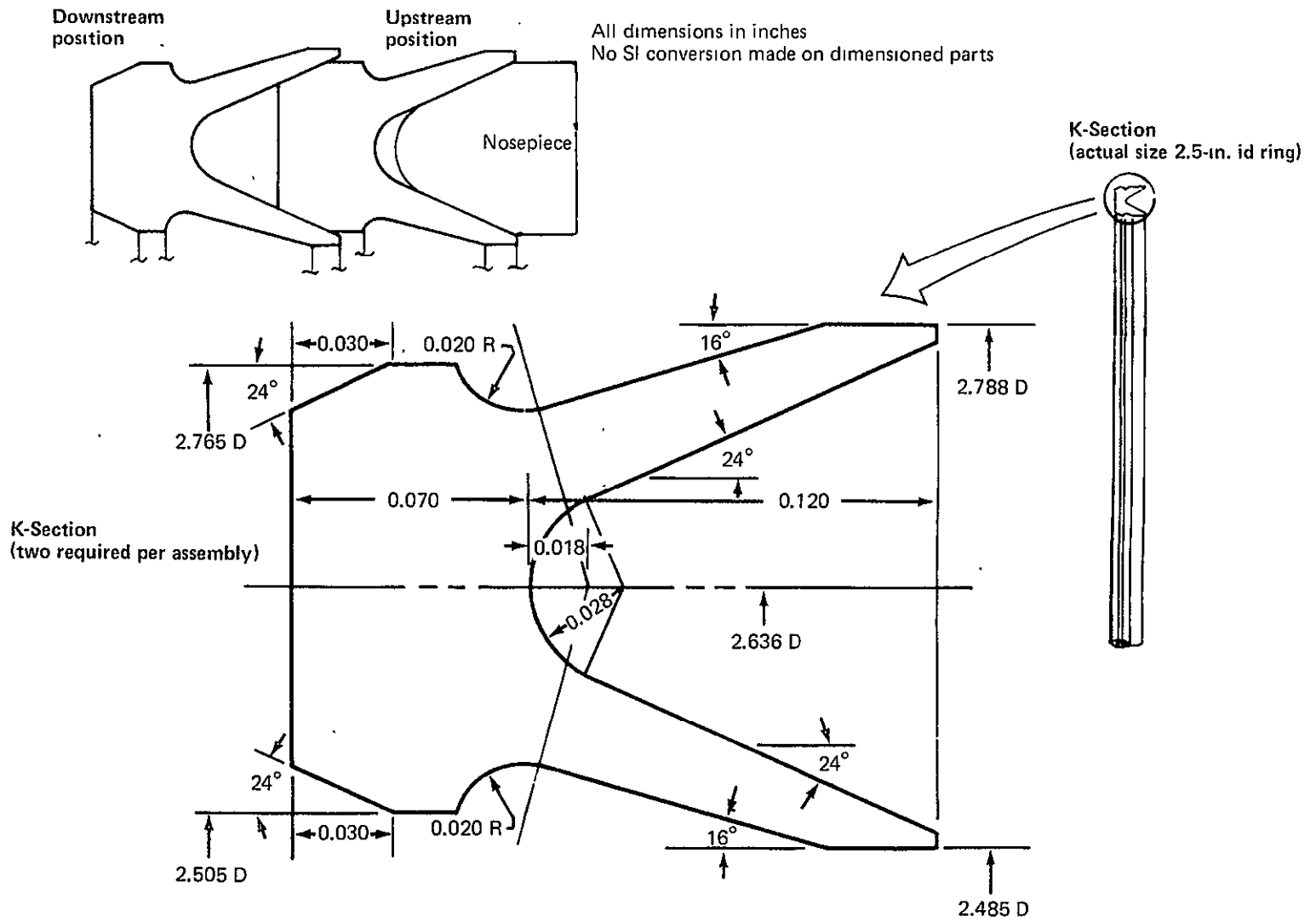


Figure 1.—Second-Stage Rod Seal Assembly, 6.35-cm (2.5-in.) K-Section

Table 1.—Unused Sealing Element Inspections

K-section ident no.	Units	Average element dimensions		Drawing deviation		Element selection for test	
		Inside diameter	Outside diameter	Inside diameter ^a	Outside diameter ^b	Test	Position
1	cm in.	6.327 (2.491)	7.088 (2.791)	+0.0142 (+0.0056)	+0.0069 (+0.0027)	Structural impulse	Downstream
2	cm in.					Not inspected; crack in seal	
3	cm in.	6.323 (2.490)	7.070 (2.784)	+0.0104 (+0.0041)	-0.0109 (-0.0043)	Screening impulse	Upstream
4	cm in.	6.330 (2.492)	7.094 (2.793)	+0.0168 (+0.0066)	+0.0132 (+0.0052)	Screening impulse	Downstream
5	cm in.	6.309 (2.484)	7.087 (2.790)	-0.0036 (-0.0014)	+0.0056 (+0.0022)	Structural impulse	Upstream
6	cm in.	6.322 (2.489)	7.071 (2.784)	+0.0091 (+0.0036)	-0.0096 (-0.0038)	Possible spare	—
7	cm in.	6.321 (2.489)	7.088 (2.791)	+0.0079 (+0.0031)	+0.0069 (+0.0027)	Endurance	Upstream
8	cm in.	6.321 (2.489)	7.087 (2.790)	+0.0079 (+0.0031)	+0.0056 (+0.0022)	Endurance	Downstream

^aDwg 64-15050 inside diameter = 6.3129 ± 0.0025 cm (2.4854 ± 0.0010 in.)

^bDwg 64-15050 outside diameter = 7.0810 ± 0.0025 cm (2.787 ± 0.0010 in.)

Table 2.—Unused Seal Element Imperfections

K-section ident no.	Cracks	Fins machine marks	Surface discontinuity	Nick	Pin hole	Scratch
1		X	X			
2	X	X	X		X	
3		X		X		
4		X	X			
5		X	X	X		
6		X		X		X
7		X	X			
8		X	X			

SEAL TESTS

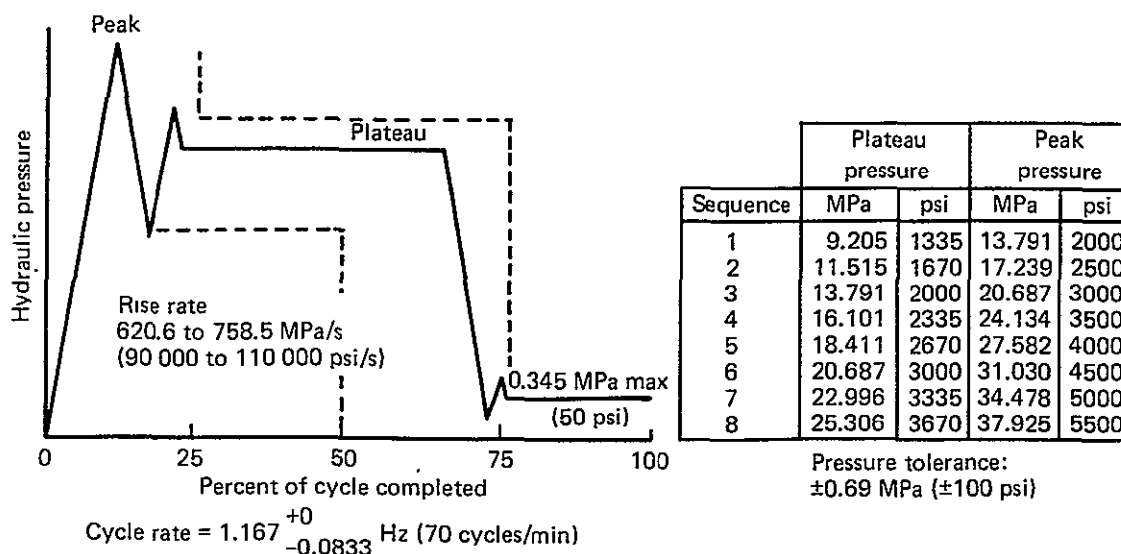
Three tests were conducted in the evaluation of the K-section seals for single-stage seal application. These tests were:

- Impulse screening test—To determine the highest pressure under which the K-section could successfully prevent leakage during 20 000 cycles of impulse and to select the pressure for the structural impulse test
- Structural impulse test—To determine the life of the seal when it was subjected to 200 000 cycles of impulse at the highest pressure successfully tested during screening
- Endurance test—To determine seal wear with K-section upstream pressure equaling the system pressure at the peak pressure tested during structural impulse

IMPULSE SCREENING TEST

TEST CONDITIONS

A single machined polyimide K-section seal using elements 3 and 4 (table 1) was evaluated by conducting a series of consecutive 20 000-cycle impulse tests at progressively increasing pressures. The testing was conducted at room temperature with the test system and procedure described in Appendix A. Peak pressure, as shown in the following table and defined as the maximum pressure attained at the completion of the initial rise of the impulse wave, was the primary requirement for the test. The plateau pressure, defined as the steady pressure following impulse wave damping, was established at two-thirds of peak pressure.



TEST RESULTS

The test seal showed minimal-to-zero leakage while being subjected to successive 20 000-cycle segments at peak pressures less than 37.925 MPa (5500 psi). After 1120 cycles of the eighth and final segment, conducted at 37.925-MPa (5500-psi) peak impulse pressure, the seal showed considerable leakage. Seal inspection showed total structural failure of both K-section elements (figs. 2, 3, and 4). Leakage data for the screening test are shown in table 3.

Table 3.—Impulse Screening Test Results

Test segment	Peak impulse, MPa	Pressure, psi	Cycles completed	Largest single leakage value
1	13.791	2000	20 000	3 500 cycles/drop
2	17.239	2500	20 000	> 5 250 cycles/drop
3	20.687	3000	20 000	3 780 cycles/drop
4	24.134	3500	20 000	15 120 cycles/drop
5	27.582	4000	20 000	No leakage
6	31.030	4500	20 000	No leakage
7	34.478	5000	20 000	No leakage
8	37.925	5500	1 120	Seal failure

IMPULSE STRUCTURAL TEST

TEST CONDITIONS

After determining the impulse pressure that caused failure of the seal to be 37.925 MPa (5500 psi), in 20 000 cycles or less, an impulse test for structural integrity was conducted under the next most severe condition successfully passed during screening tests, 31.030 MPa (4500 psi). The test was conducted on a new seal composed of elements 1 and 5 (table 1) and was to be tested to the impulse sequence shown:

Impulse cycles	Temperature	
	K	°F
40 000	311	100
115 000	408	275
40 000	450	350
5 000	478	400

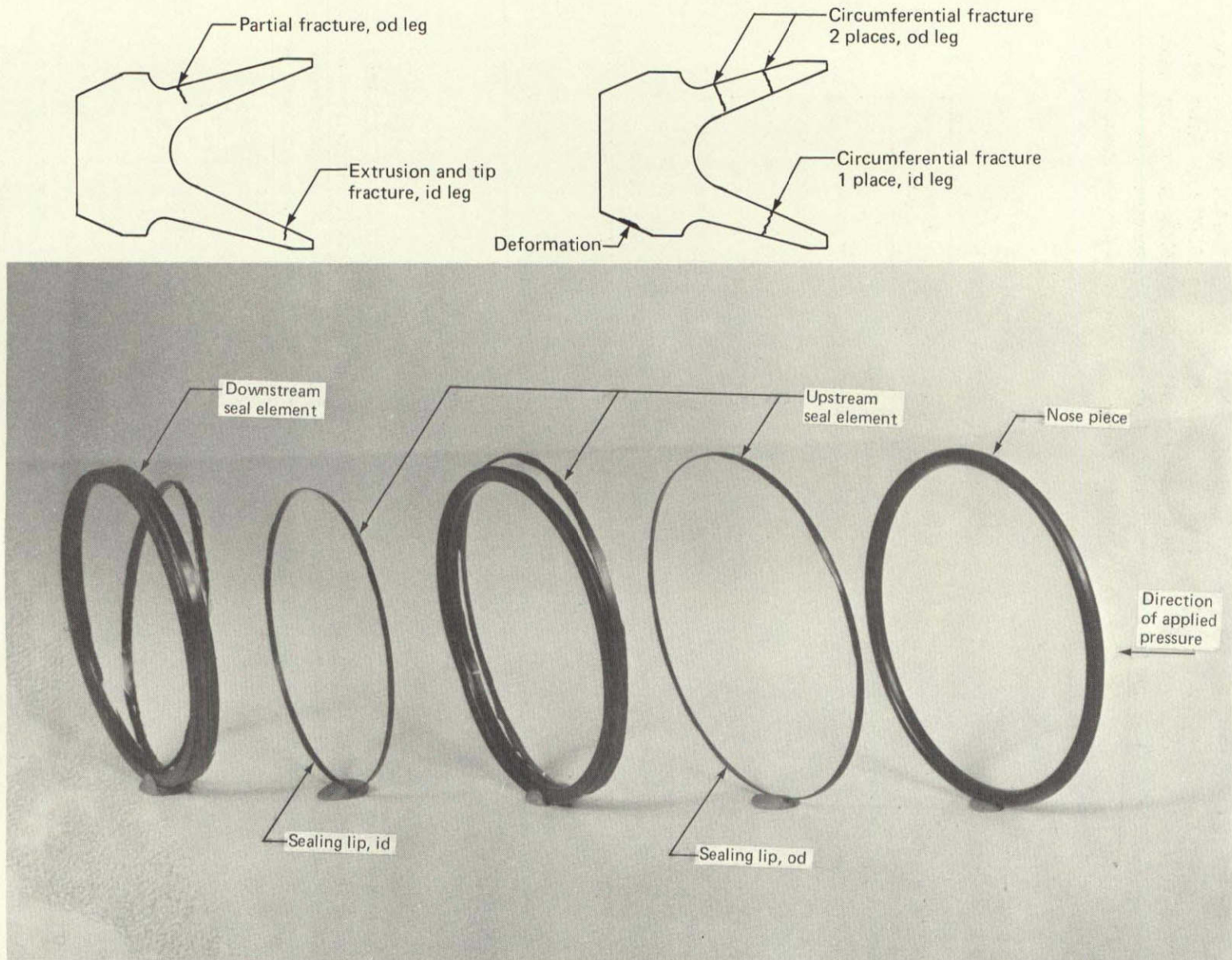


Figure 2.—Test Seal Failure—Impulse Screening at 37.925 MPa (5500 psi)

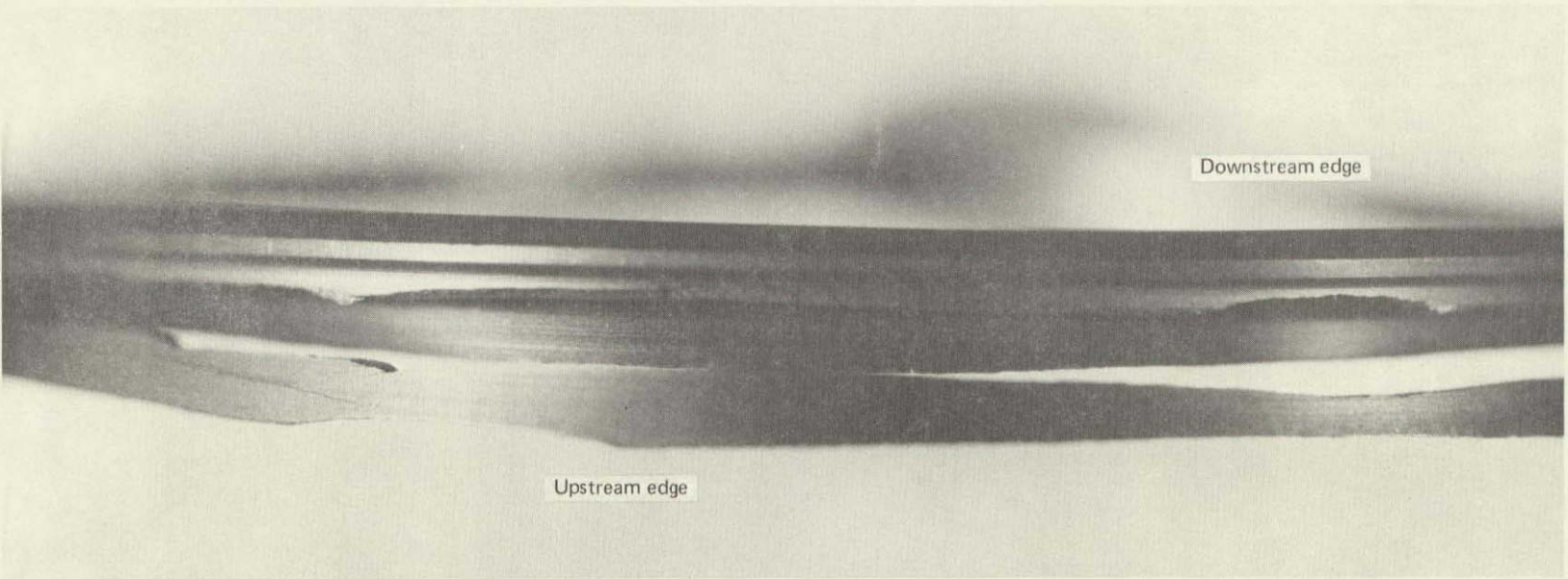


Figure 3.—Impulse Screening Test Seal, Upstream Element—Failure at 37.925 MPa (5500 psi)

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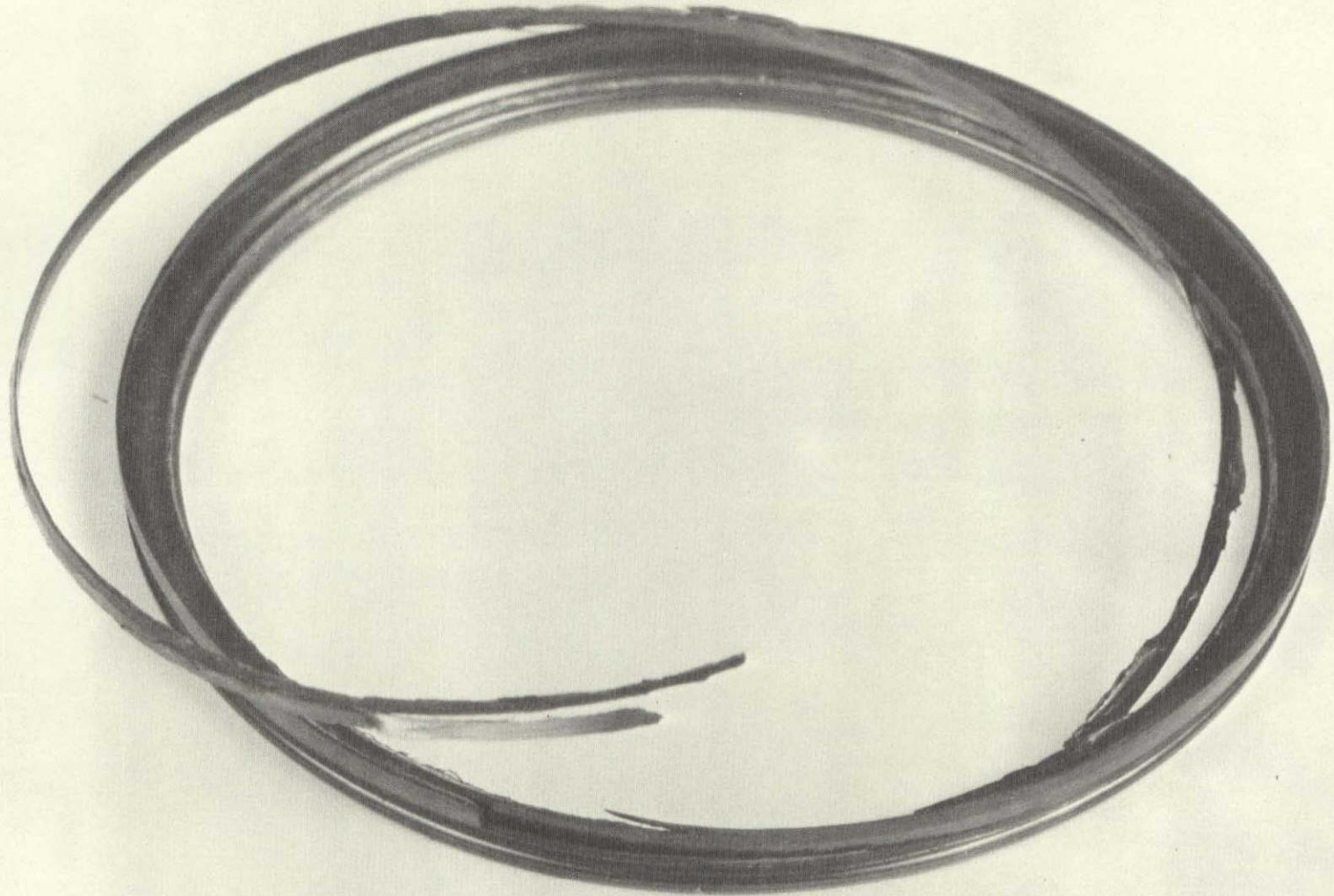
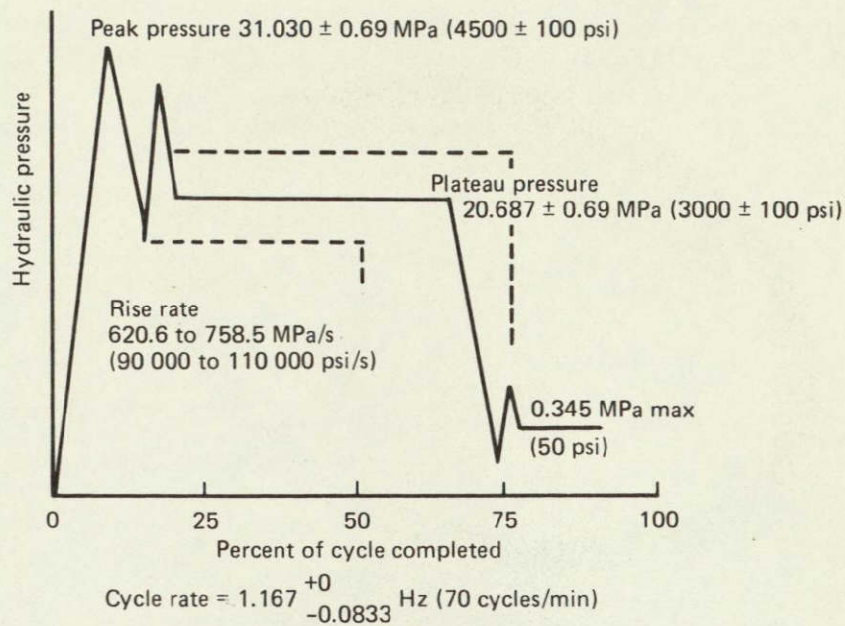


Figure 4.—Impulse Screening Test Seal, Downstream Element—Failure at 37.925 MPa (5500 psi)

Each cycle had a wave form conforming to the following requirements.



TEST RESULTS

During the static pressure checkout of the seal assembly at 17.359 MPa (2500 psi) both elements 1 and 5 fractured. The apparent reason was installation damage resulting from a tight fit of element 5, used in the upstream position. Similar static pressurizations at 20.687 MPa (3000 psi) were conducted three times during the screening test without element failure. The failures of both upstream and downstream elements (figs. 5 through 7) show major localized fractures accompanied by circumferential cracks of the inside diameter (id) sealing legs. The major fractures in both elements occurred at the same circumferential location, indicating a secondary failure in the downstream element resulting from failure of the upstream element.

An undamaged set of K-section elements, retained after completing previous testing under the NAS3-14317 contract (ref. 1), was used to conduct the structural impulse test. These seals were inspected prior to testing and indicated the following:

Element	Average element dimension				Drawing deviation			
	Inside diameter		Outside diameter		Inside diameter ^a		Outside diameter ^b	
	cm	in.	cm	in.	cm	in.	cm	in.
Upstream	6.589	2.494	7.061	2.7800	+0.2758	+0.0086	-0.0198	-0.0078
Downstream	6.591	2.495	7.061	2.7800	+0.2784	+0.0096	-0.0198	-0.0078

^aDwg. 64-15050 inside diameter = 6.3129 ± 0.0025 cm (2.4854 ± 0.0010 in.)

^bDwg. 64-15050 outside diameter = 7.0810 ± 0.0025 cm (2.7878 ± 0.0010 in.)

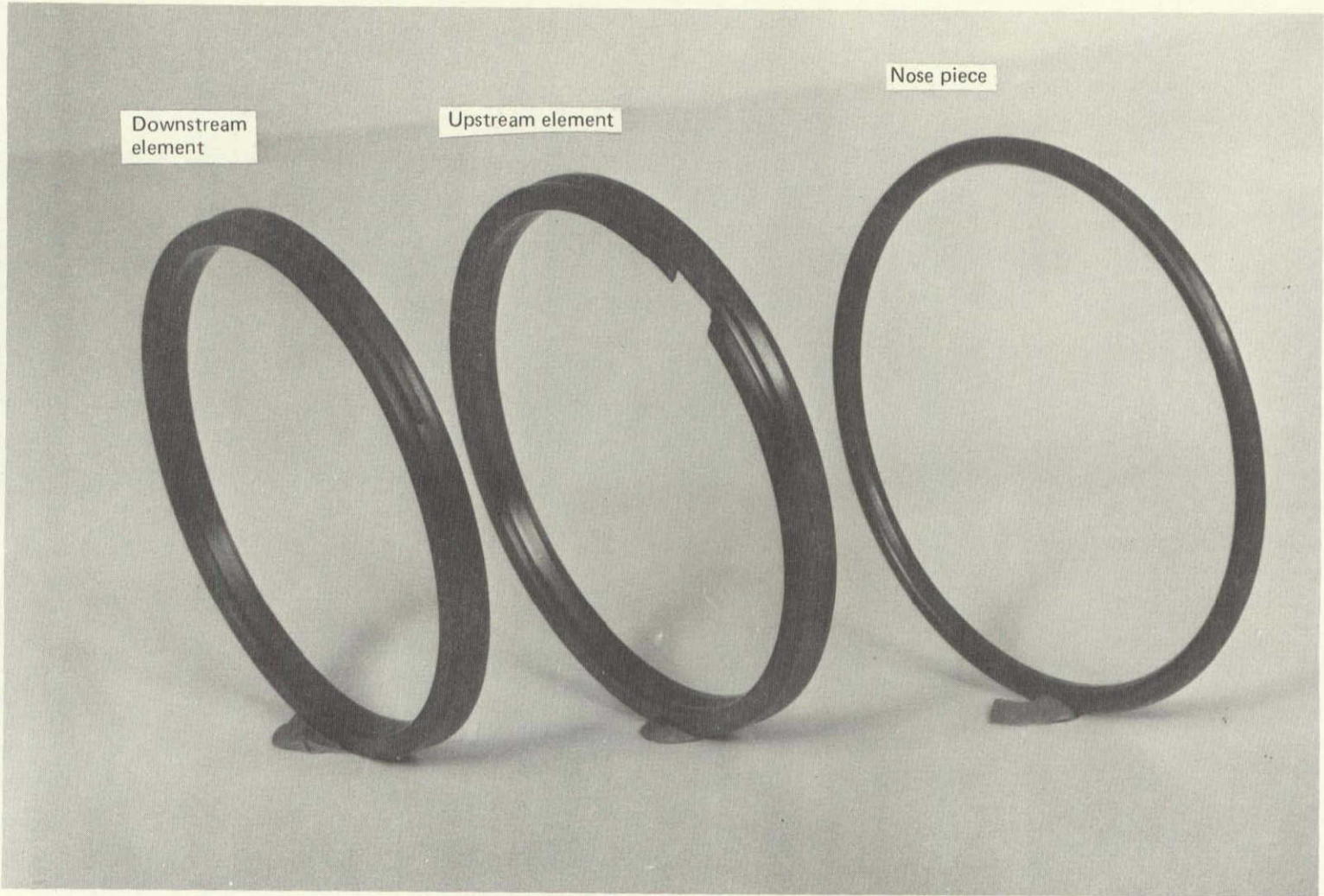


Figure 5.—Static Pressure Failure at 17.359 MPa (2500 psi)

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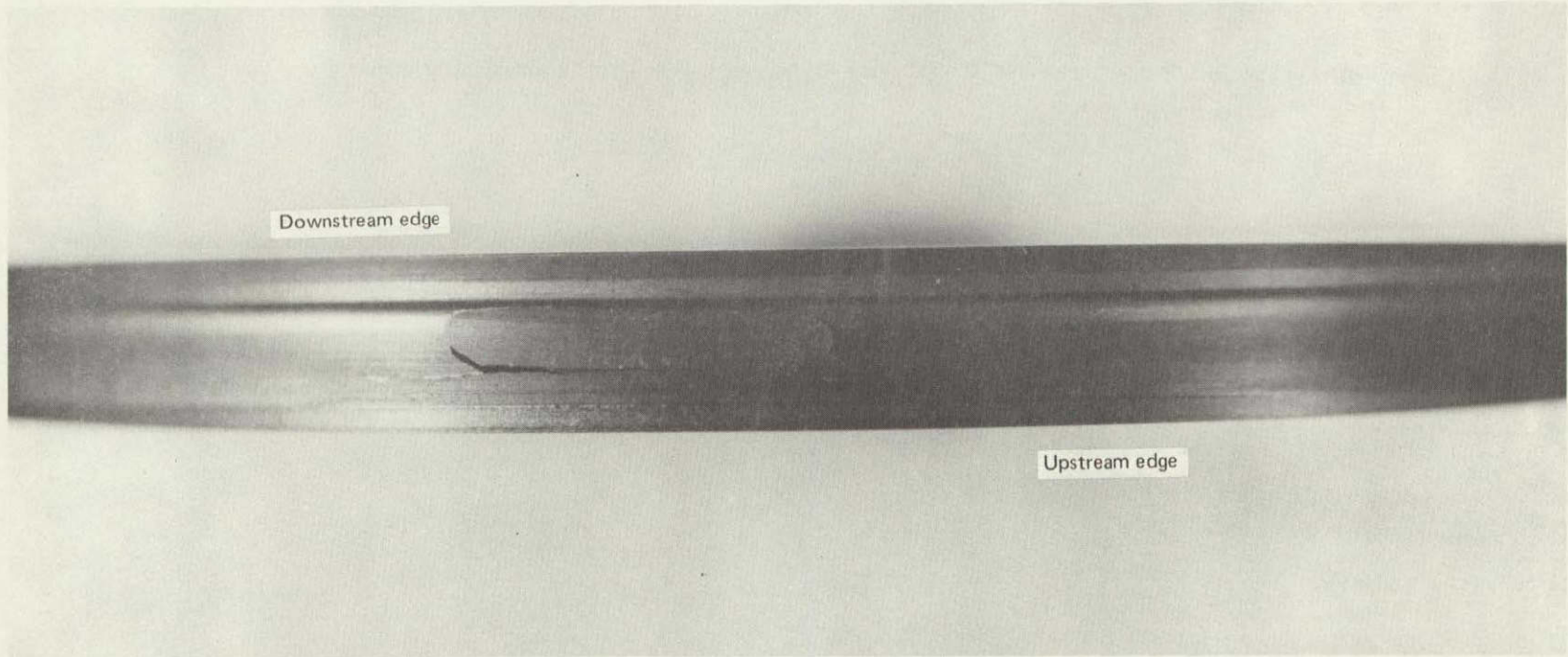


Figure 6.—Static Pressure Failure at 17.359 MPa (2500 psi)—Downstream Element, Major Fracture

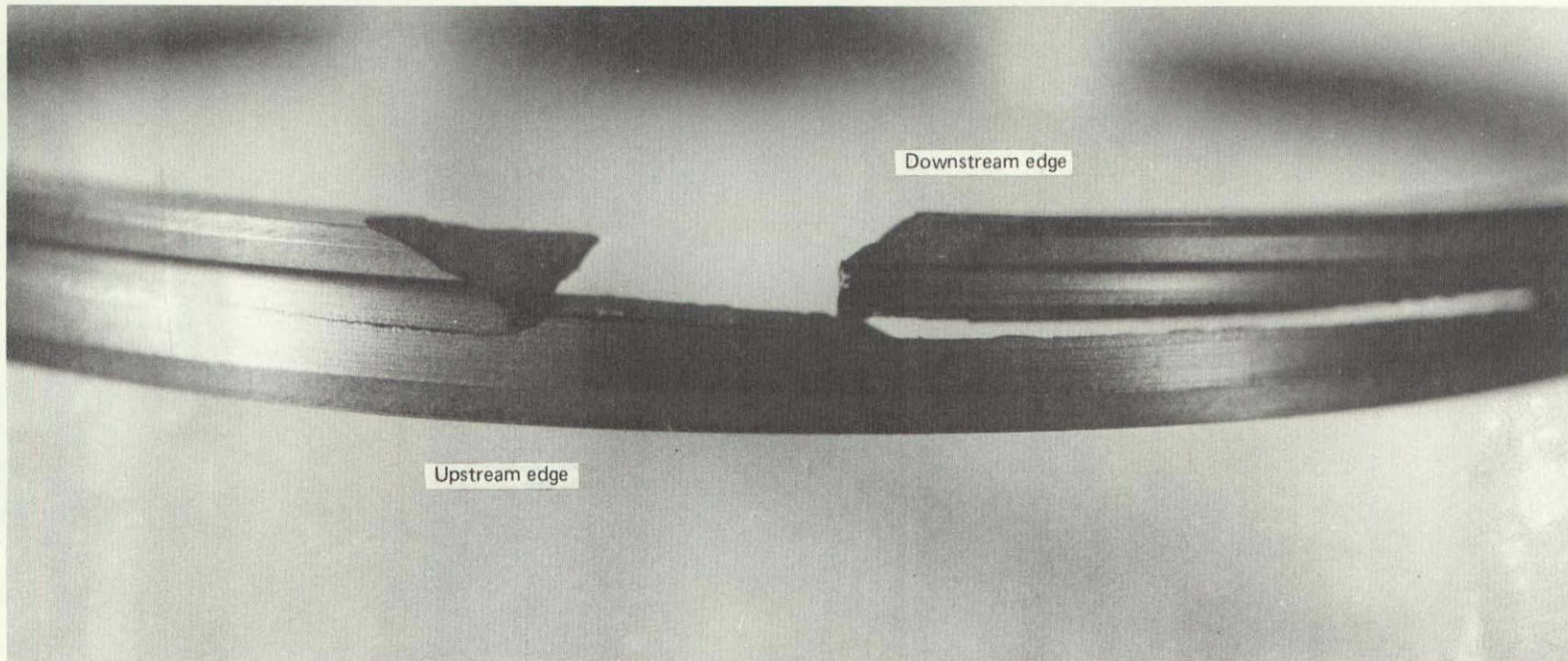


Figure 7.—Static Pressure Failure at 17.359 MPa (2500 psi)—Upstream Element, Major Fracture

These elements showed some surface scratches and a high degree of polishing on the sealing edges from wear during previous testing.

As indicated by the dimensions, the inside diameter was larger than the desired dimension and the outside diameter somewhat smaller than the desired dimension. This implied poorer sealing ability than seals that were within drawing tolerances.

The 40 000 cycles at 311 K (100° F) with 31.030-MPa (4500-psi) peak pressure were successfully completed. Temperature was elevated to 408 K (275° F). With 830 cycles completed of the scheduled 115 000, the K-sections structurally failed. There was no evidence of leakage until seal failure at 40 830 cycles. Figures 8, 9, and 10 show the major fracture points in the upstream and downstream elements respectively.

Upstream element fracture was very similar to the upstream element failure under 17.359 MPa (2500 psi) static pressurization. The cracking in the downstream element was a secondary failure resulting from the upstream element failure. The similarity of failures in impulse testing showed evidence of inadequate natural properties for a seal of the K-section geometry under a loading pressure of 31.030 MPa (4500 psi).

An impulse test at a peak pressure of 20.687 MPa (3000 psi) was conducted using a 6.35-cm (2.5-in.) K-section seal consisting of an element that had been retained after use during prior testing and element 2 of the new seal elements, table 1. The test was conducted to obtain impulse life data for an intermediate pressure between the 10.43 MPa (1500 psi) passed successfully and reported in reference 1, and 31.030 MPa (4500 psi), the above failure condition.

Pretest visual information of these seal elements showed similar characteristics to those of other used seals. Sealing lips were polished on the used element due to wear in previous tests. There were scratches on the sealing surfaces contacting the rod. The new seal element, number 2 (see tables 1 and 2), was of poorer quality than other elements but had to be used because other elements available were committed to endurance testing. The used element was placed in the upstream position and the unused element in the downstream position. Pressure at 10.43 MPa (1500 psi) for 5 minutes resulted in no leakage. There was no seal leakage during impulse testing prior to seal failure.

This seal structurally failed at 5482 cycles of the first segment of impulse testing. The possible cause for completing only the small number of cycles before failure may have been less interference fit than other seals tested in impulse screening. Photos were not taken of failed elements because the appearance was similar to the previous impulse failures at 31.030 MPa (4500 psi). The upstream element had a circumferential fracture of the outside diameter (od) leg, although the fracture did not result in separation from the seal element. The inside diameter (id) leg of the upstream element and both legs of the downstream element showed evidence of deformation suspected as being the predecessor to fracture.

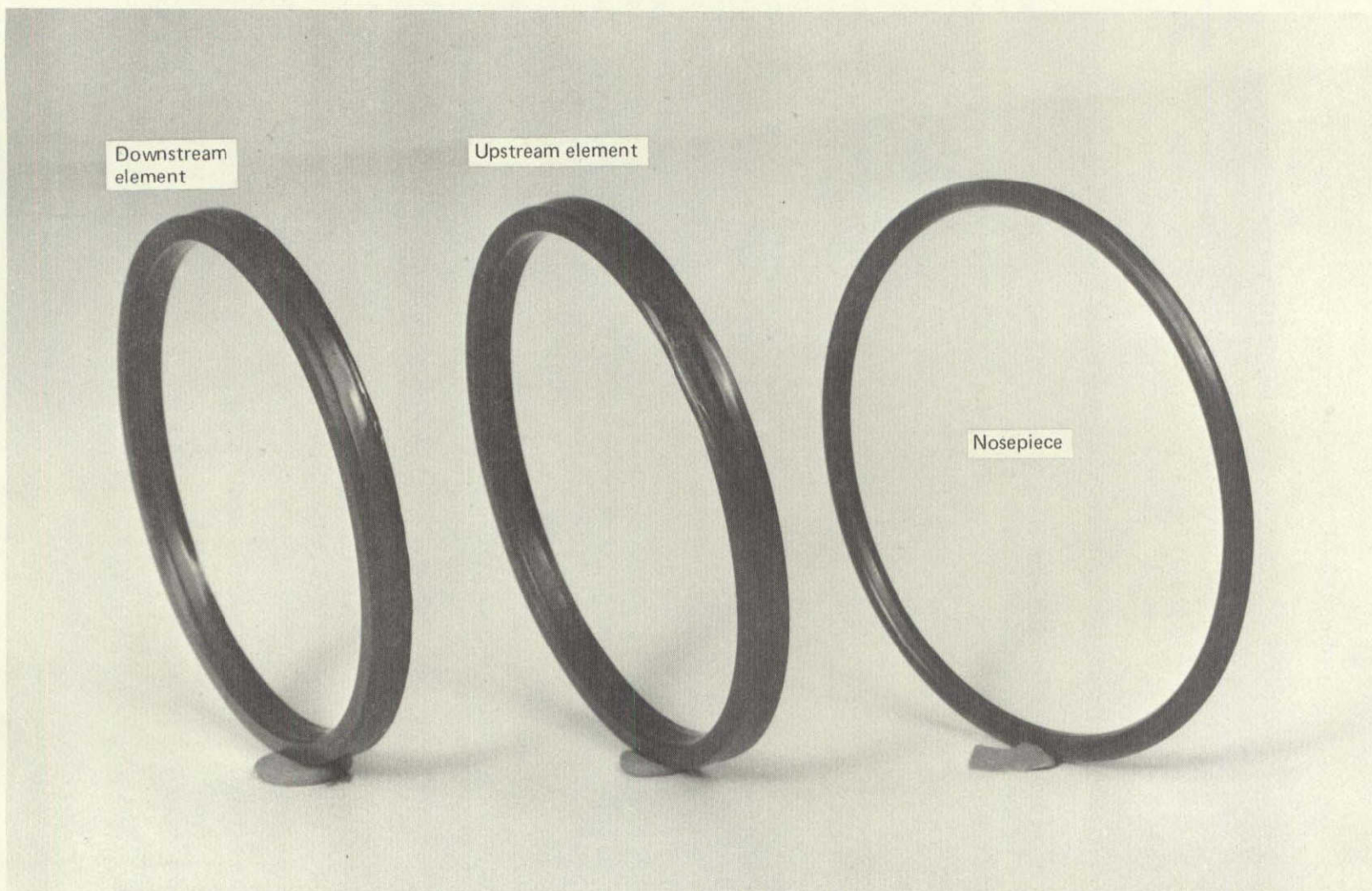


Figure 8.—Impulse Test Seal, Failure at 31.030 MPa (4500 psi)—40 000 Cycles at 311 K (100° F) + 830 Cycles at 408 K (275° F)

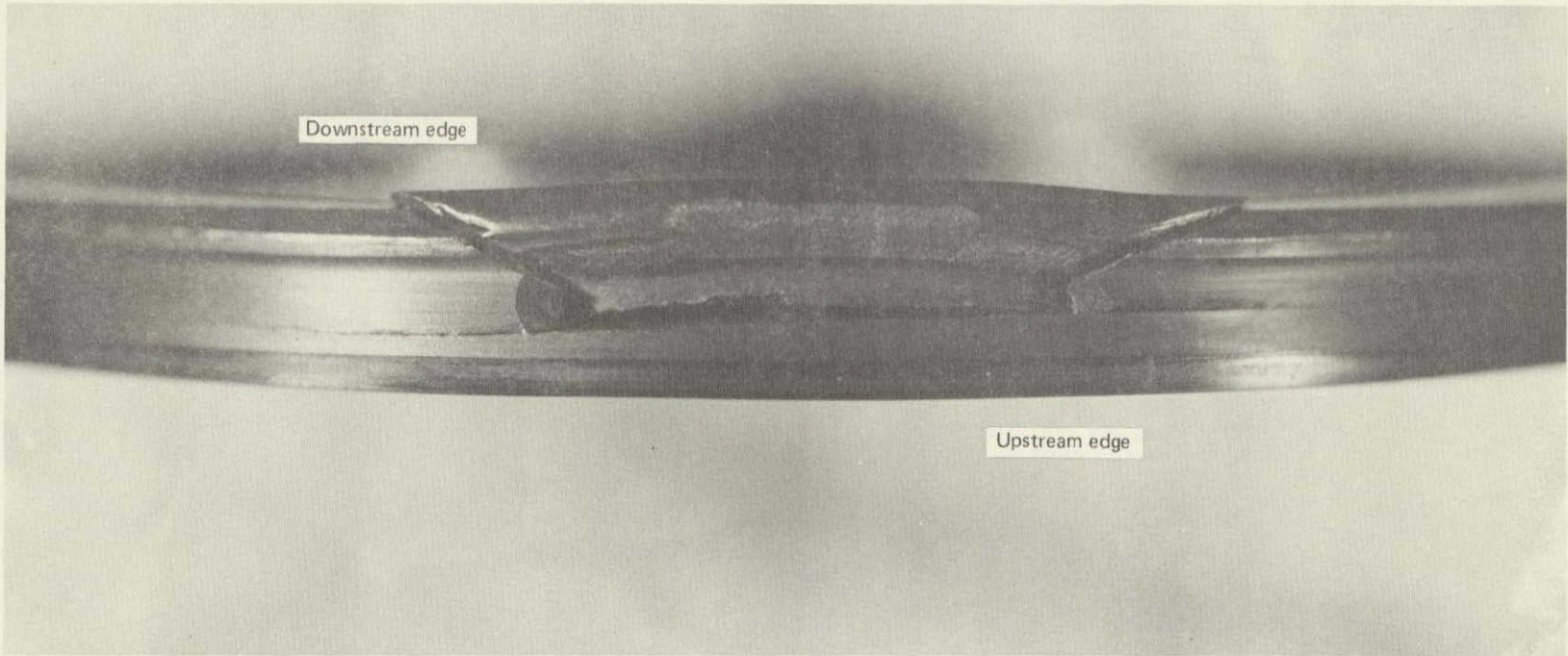


Figure 9.—Impulse Test Seal, Failure at 31.030 MPa (4500 psi)—Upstream Element, Major Fracture

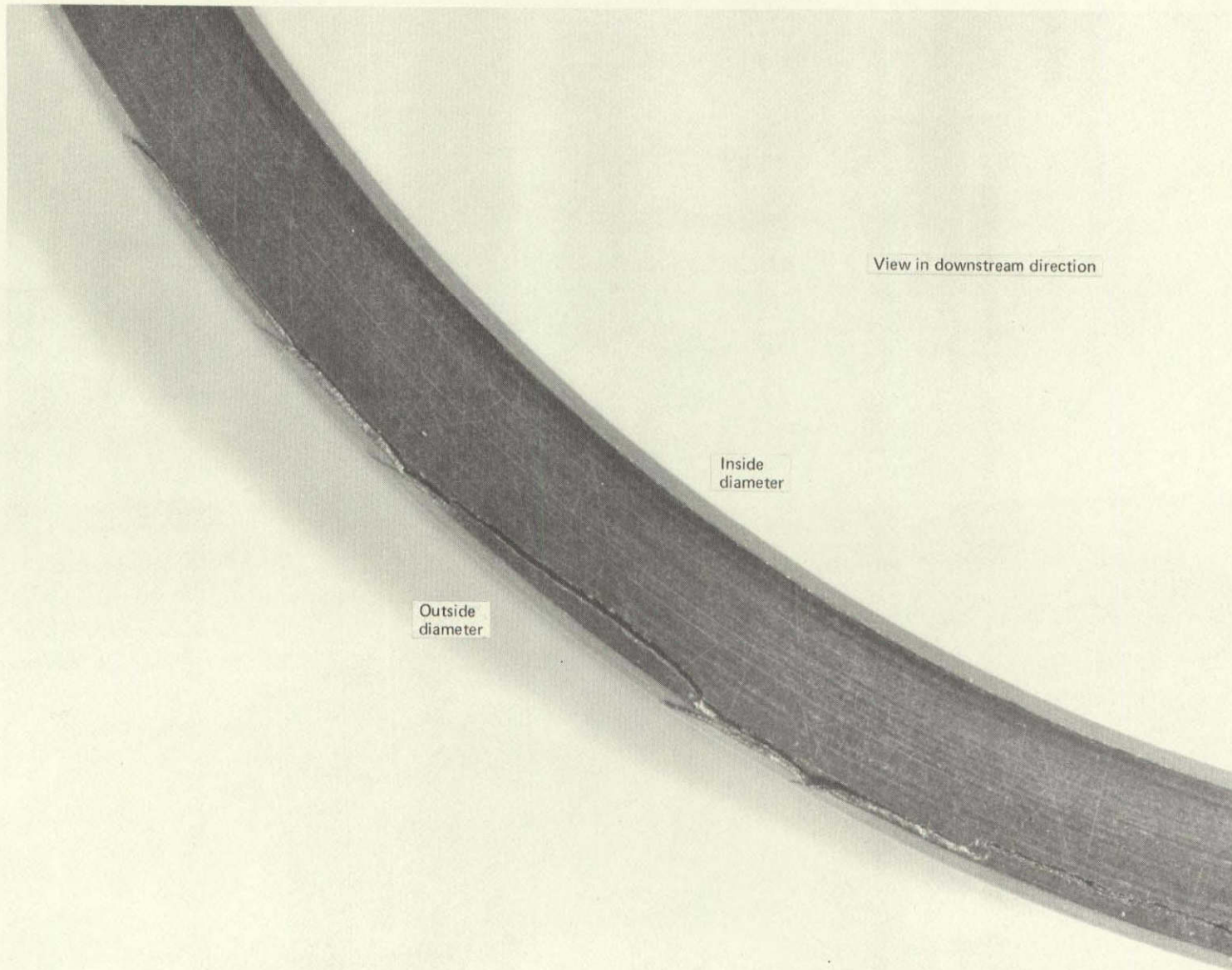


Figure 10.—Impulse Test Seal, Failure at 31.030 MPa (4500 psi)—Downstream Element, Major Fracture

ENDURANCE TEST

TEST CONDITIONS

The endurance test was conducted to provide data on the wear life of the machined K-section seal under single-stage operating conditions.

The endurance testing was conducted using the closed loop actuation system refurbished from the NAS3-14317, NAS3-16733, and NAS3-16744 testing (refs. 1 through 3) and described in Appendix B.

Only the 6.35-cm (2.5-in.) diameter rod test actuator was used. Endurance test actuator modifications required were minor. The piston rod was stripped, rechromed, and ground to the required diameter and 16-microinch rms finish. Subsequent to grinding, the rod was burnished with polyimide material to improve surface riding characteristics of the polyimide seals.

The requirements imposed during the endurance test were identical to those established for similar testing conducted on machined seals. The test duration was established at 3.85×10^6 cycles of actuation at 450 K (350° F) with the major portion (3.75×10^6 cycles) conducted under short stroke (2 percent) operation. Appendix B describes the details of the test system and operational sequence. The test spectrum conducted was to be five consecutive runs, with each run consisting of the four sequential steps stated in the following table:

Sequence number	Cycles	% load and stroke	Max cycle rate, Hz	Actuator temp for all sequences
1	7.5×10^5	2	5	450 K
2	5 000	25	0.67	(350° F)
3	10 000	50	0.50	max
4	5 000	100	0.40	

Note: 100% load = 8897 N (2000 lbf); 100% stroke = 7.62 cm (3.0 in.);
A portion of the cycles from sequences 2, 3, and 4 were randomly interspersed during performance of sequence 1.

Test temperature was 450 K (350° F) based on the MIL-H-83282 fluid used (ref. 4). Following the completion of endurance testing, the actuator was disassembled and the seal assemblies inspected.

TEST SEALS

The seal under evaluation in the endurance test actuator consisted of a second-stage K-section assembly (fig. 1) with elements 7 and 8 selected per table 1.

Because the seal was tested as a single stage, no first-stage seal was installed in the actuator.

TEST RESULTS

With the test seal installed in the endurance actuator, a 10.43-MPa (1500-psi) static pressure check was conducted with the following results:

1. Initial pressurization at 10.43 MPa (1500 psi) yielded 0.24 cc/min leakage at room temperature
2. Seal seated by pressure cycling
3. Retest at 10.43 MPa (1500 psi) yielded no leakage at room temperature

Test pressure was increased and calibration of the actuator stroke/load characteristics was begun with the accompanying seal leakage being recorded.

Pressure		Displacement		Leakage, cc/min
MPa	psi	cm	in.	
11.135	1615	1.346	0.53	1.304
18.202	2640	2.286	0.90	1.271
22.477	3260	2.972	1.17	1.899

Following the calibration the system was turned off. As pressure bled down the leakage recorded at 0.69 MPa (100 psi) was measured at 13 cc/min. Seals were removed from the actuator and the following was determined during inspections.

- Downstream element (no. 8, table 1)
 - The element had a 360° circumferential crack on the od sealing leg without full penetration of the fracture.
 - The element had a 360° circumferential crack on the id sealing leg with 260° penetration through the leg.
- Upstream element (no. 7, table 1)
 - The element had a 180° circumferential crack on the od leg penetrating through the entire cross section.
 - The element had a 310° circumferential crack on the id leg penetrating through the entire cross section.

A second attempt at conducting the endurance test was initiated with a system pressure of 10.43 MPa (1500 psi) using the last set of undamaged K-section elements available at either NASA or Boeing. The elements used in both the upstream and downstream positions showed highly polished sealing edges on both the id and od legs. There were longitudinal marks across the polished surfaces on the id leg of the upstream element from previous cycling testing.

Stroke lengths of the test actuator at 10.43 MPa (1500 psi) pressure were determined to be:

Direction	Stroke max		Stroke min	
	cm	in.	cm	
Extend	1.295	0.51	1.207	0.475
Retract	1.321	0.52	1.181	0.465

The system was operated for 65 869 cycles with 64 589 of these at 450 K (350° F). Maximum leakage was 0.0004 cc/min. At the time of completion of the above cycles, a noticeable drop in actuator stroking distance, and head/rod end pressures, indicated that some internal leakage was occurring. Inspection of both balance tube and piston seal rings of the endurance actuator (fig. 11) showed that during conditions of steady leakage the piston seal could maintain only 7.584 MPa (1100 psi) differential and the balance tube seal could maintain a differential of only 2.068 MPa (300 psi). The piston ring was intact and showed no abnormal wear. The cylinder showed longitudinal scratches that could account for the excessive leakage of the piston seal (see fig. 12).

An abnormal wear pattern was indicated on the balance tube sealing ring identified by alternating polished and dark areas across the seal. These wear areas are believed to account for the excessive leakage.

The rod showed an approximate 2.54-cm (1-in.) wear pattern where the test seal made contact. This area was blackish grey in color, indicating considerable wear of the test seal. A bluish-purple band was present upstream of the wear area, indicating localized heating in this area (see figs. 13 and 14). (A similar wear pattern was noted on the test seal module bearing surfaces where the rod made contact—see fig. 15.) Upstream of the purple band on the rod was a yellowish-brown area, which appeared to be like tarnish build-up from thermal decomposition of the fluid.

Posttest inspection of the seal elements under test (fig. 16) showed the following:

- Upstream element (fig. 17)
 - The od leg was slightly polished on the sealing surface.
 - The id leg was highly polished on the sealing surface, this extending farther back on the leg than the machined sealing flat. The id leg was cracked 160° of the circumference, but the crack did not sever the leg.
- Downstream element (figs. 18 and 19)
 - The od leg had a crack 170° of circumference that did not sever the leg. A second crack in the support block section of the K geometry was 10° in seal circumference and did penetrate through the cross section (see fig. 18).
 - The id leg was cracked approximately 180° of the circumference, and the sealing lip was chipped and worn to a very thin cross section (fig. 19).

These seals, with the fractures as described, could not be successfully reinstalled in the actuator for further testing. The presence of the structural cracks indicated that their life expectancy, if the test had not been stopped, was not very long.

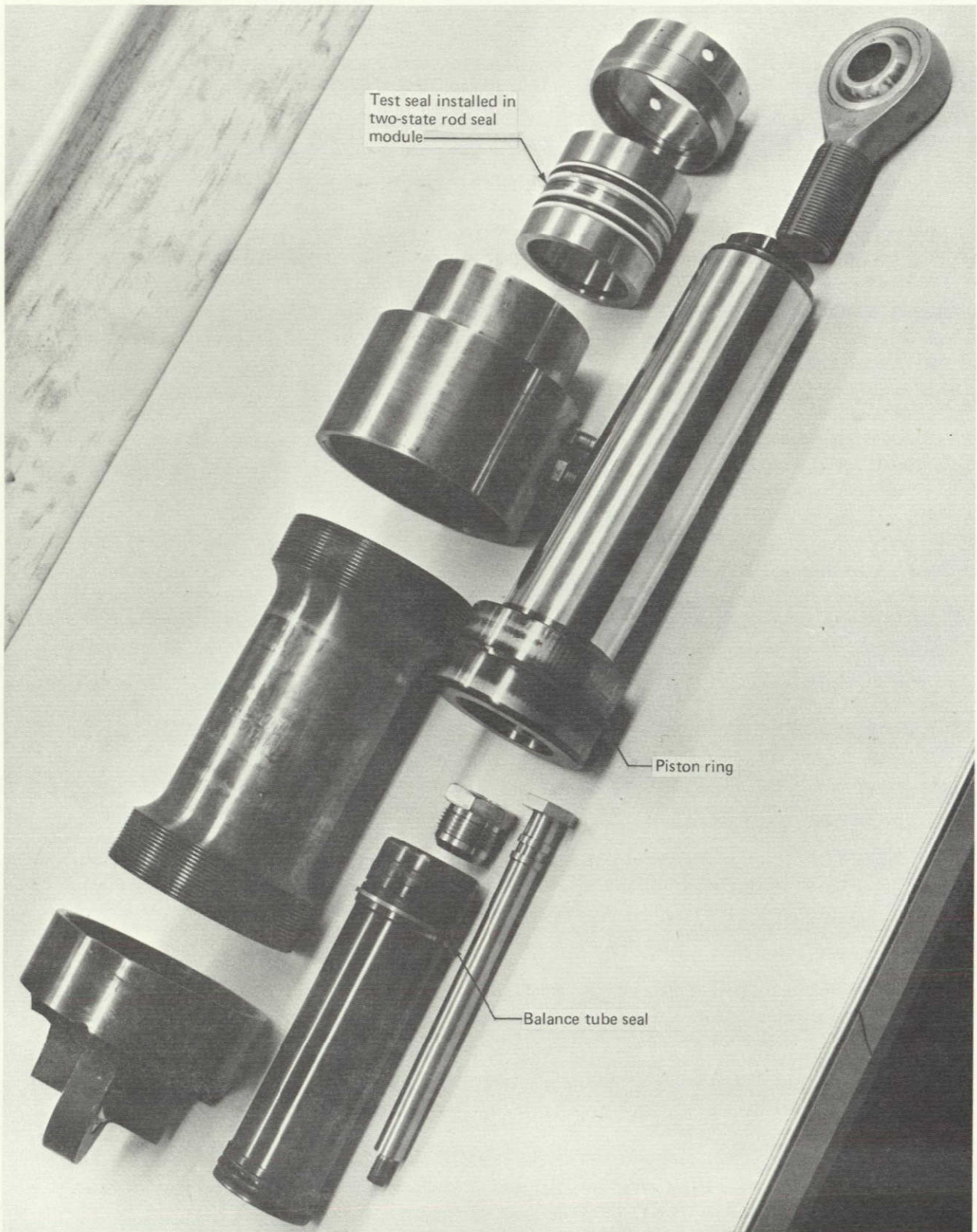
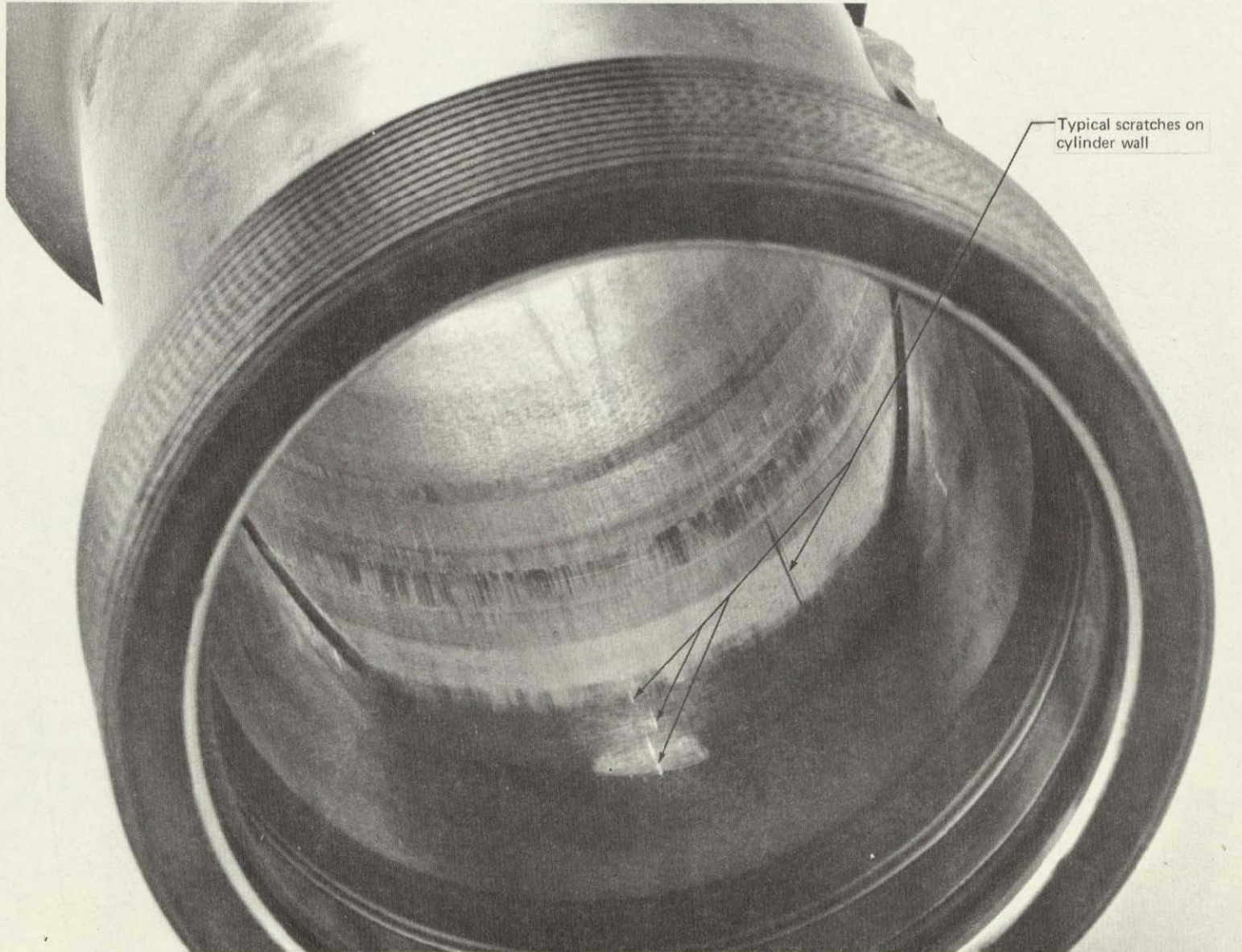


Figure 11.—6.35-cm (2.5-in.) Endurance Test Actuator



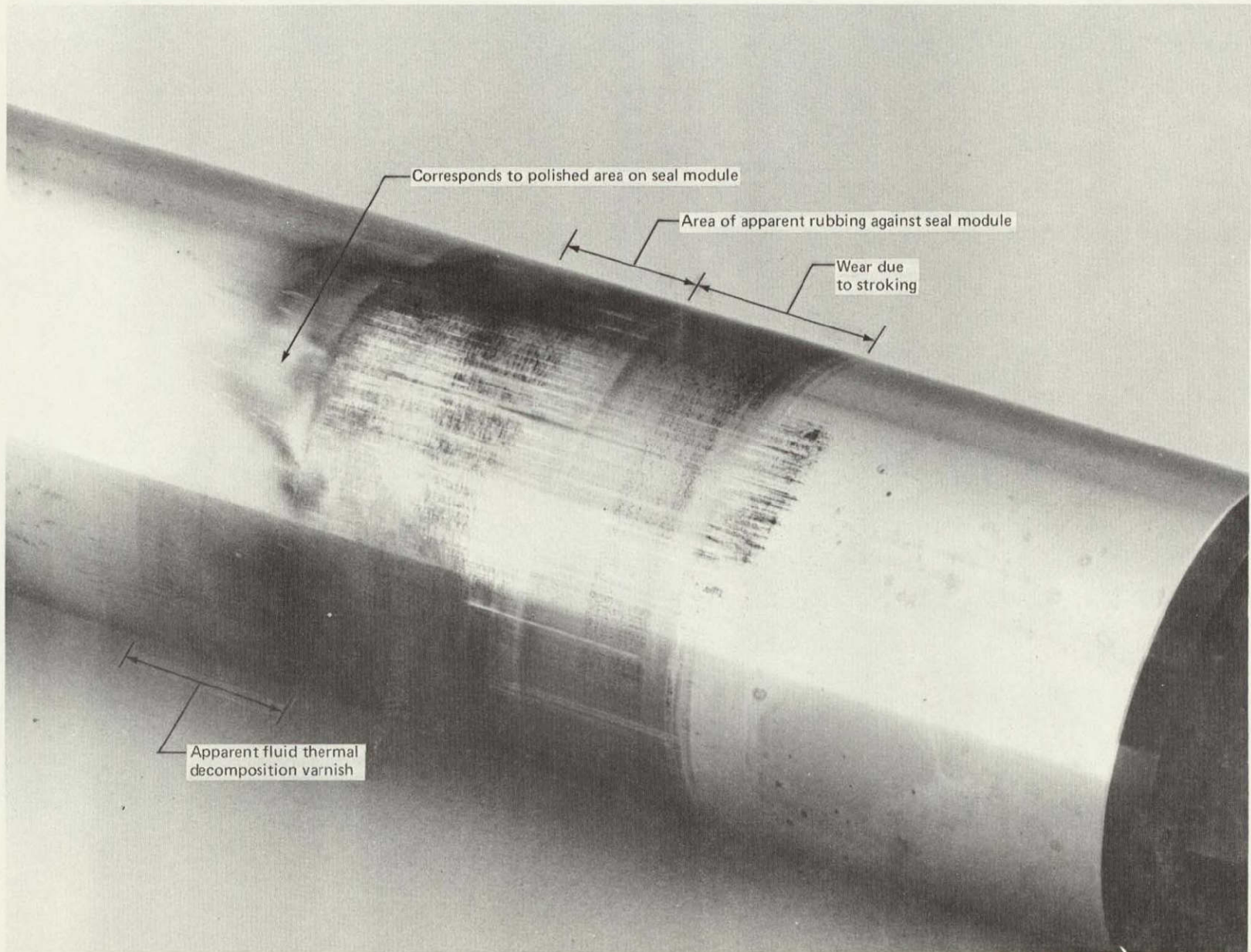
Typical scratches on cylinder wall

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Figure 12.—Endurance Actuator Cylinder After Test



Figure 13.—Actuator Rod After Endurance Test



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Figure 14.—Seal Contact Area on Rod After Endurance Test

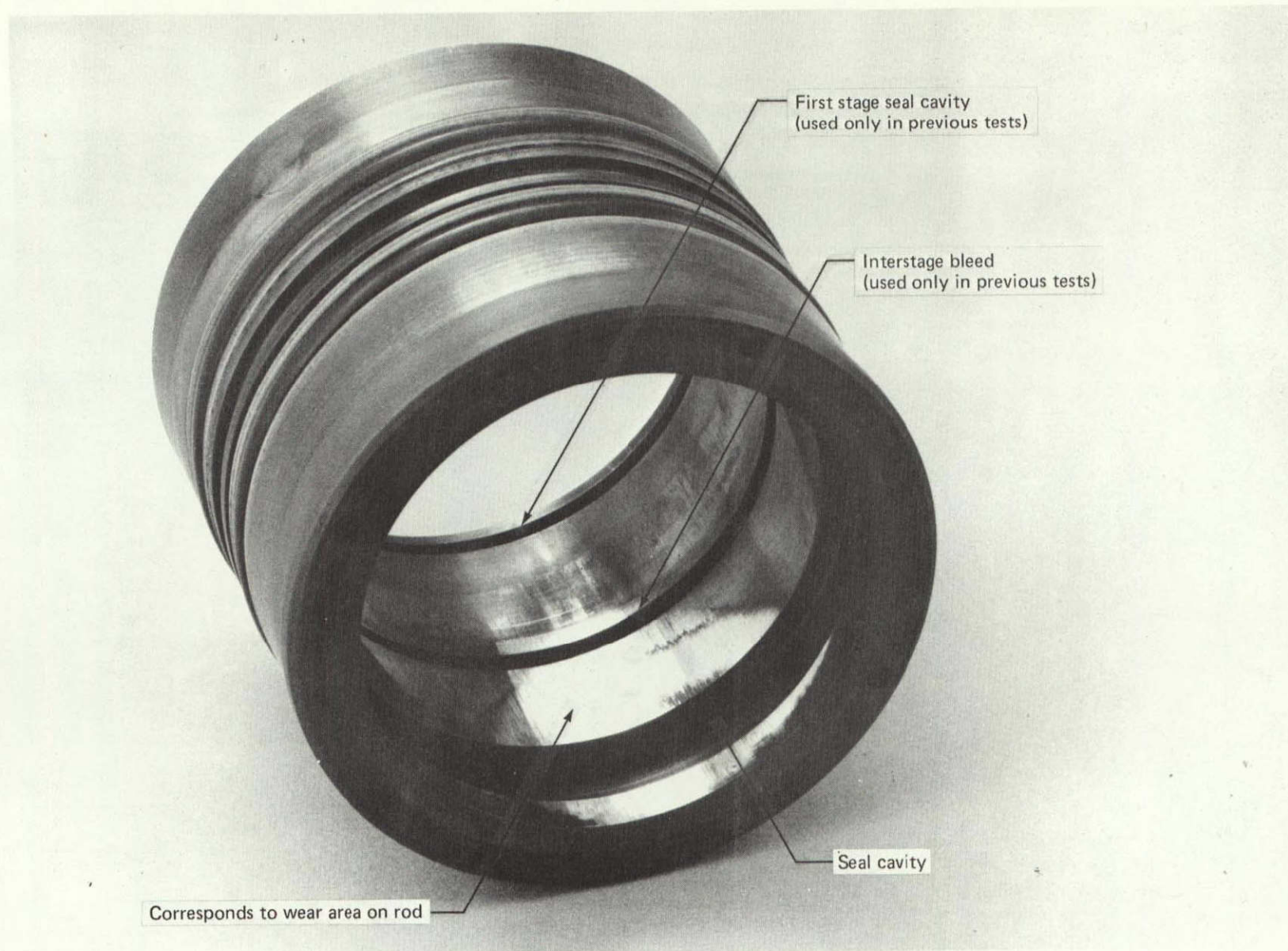


Figure 15.—Seal Module After Endurance Test

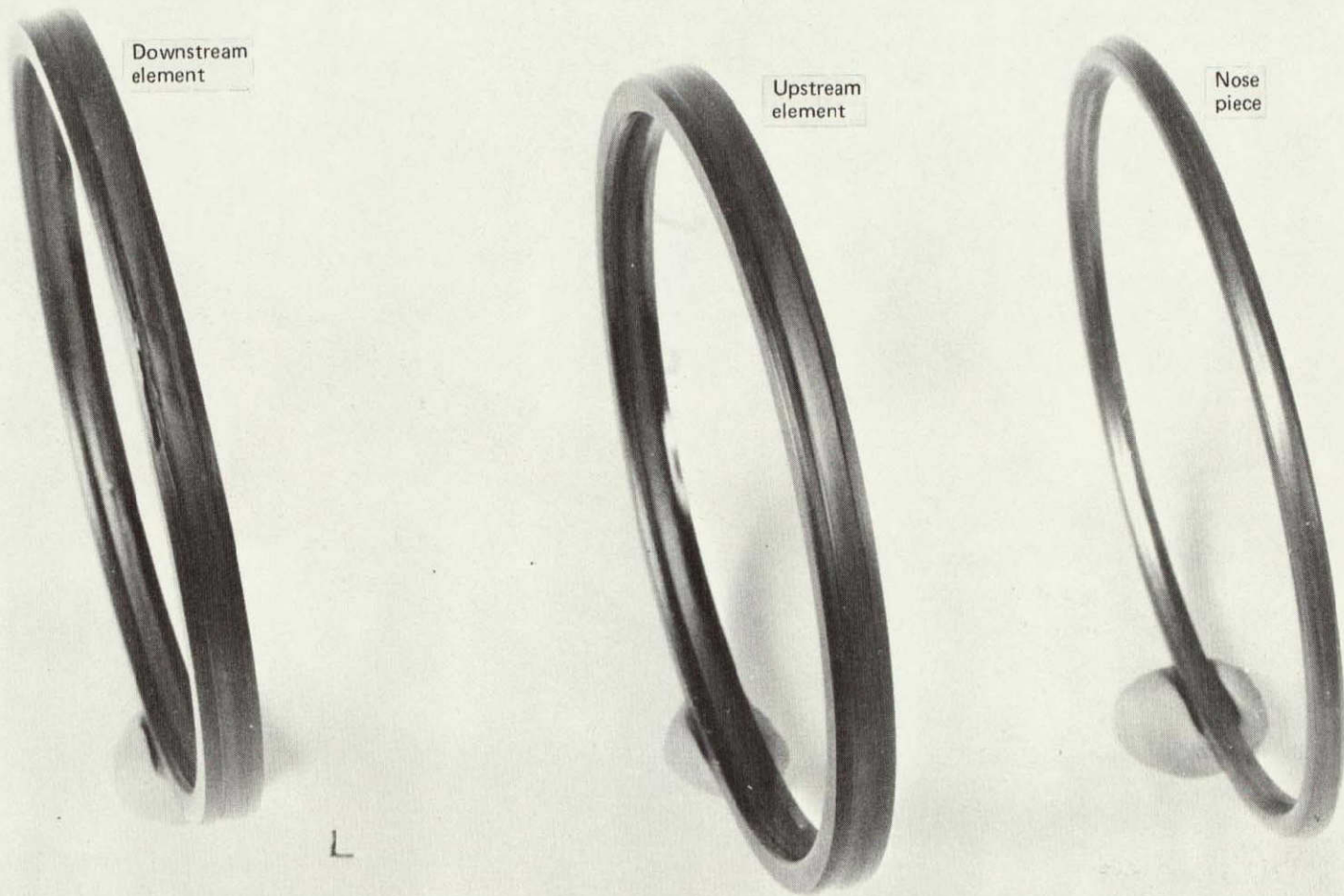


Figure 16.—Endurance Test Seals

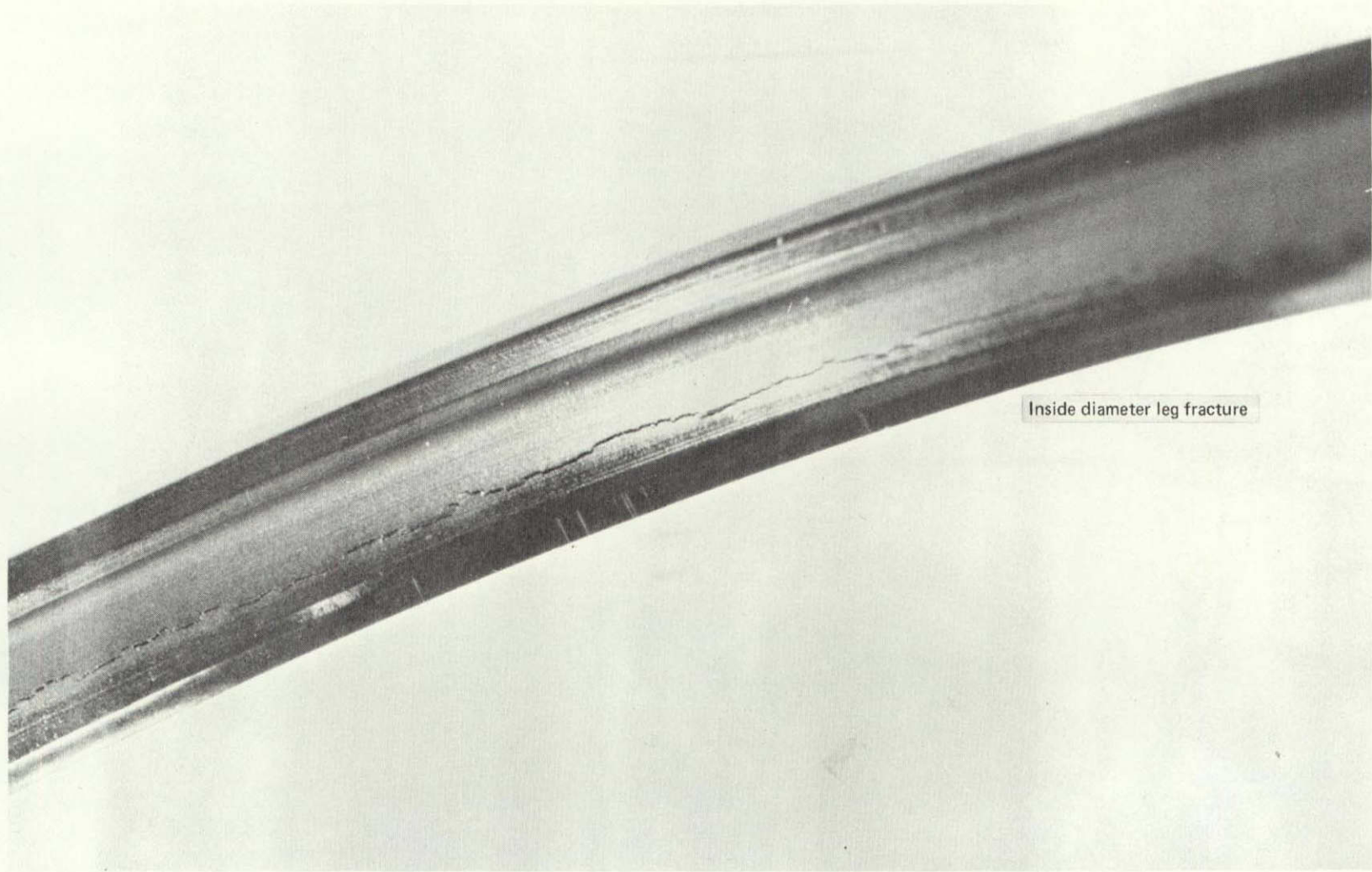


Figure 17.—Upstream Element Fracture, Endurance Test Seal

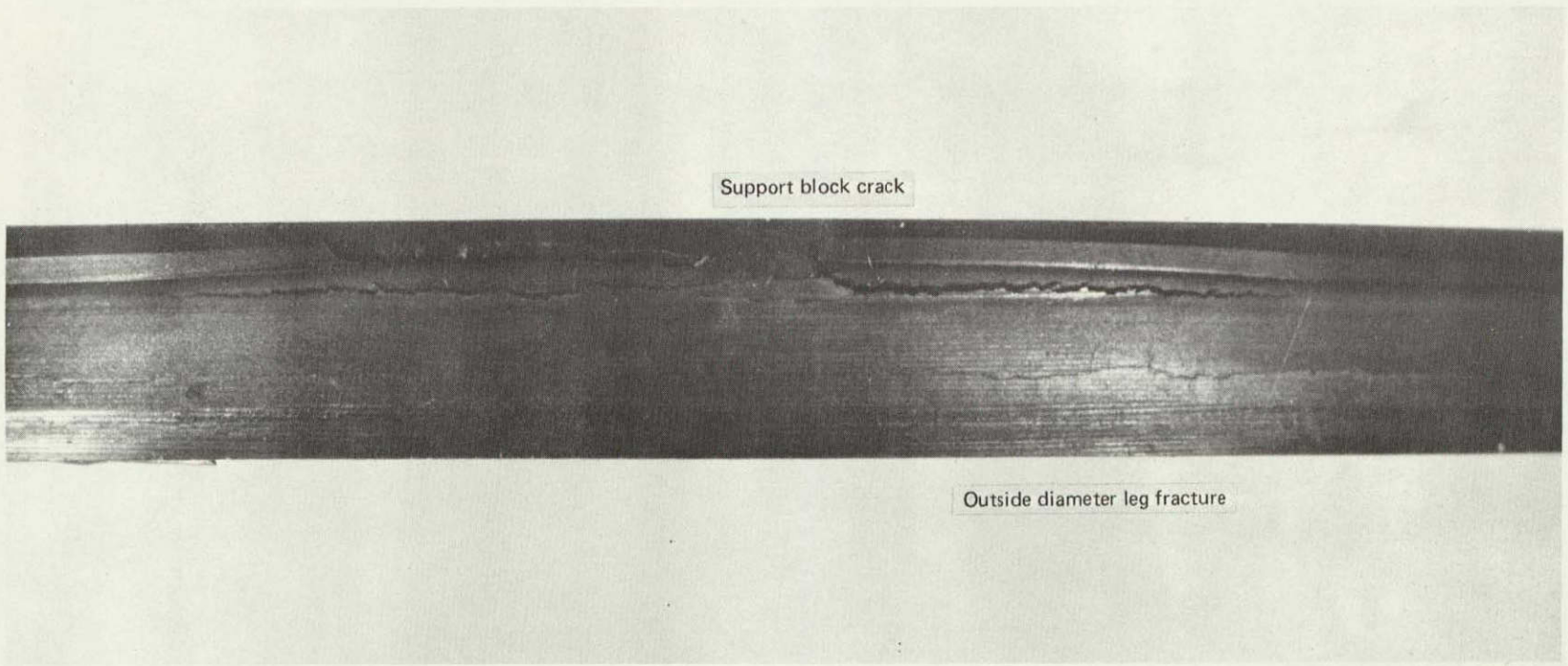


Figure 18.—Downstream Element Fracture, Endurance Test Seal

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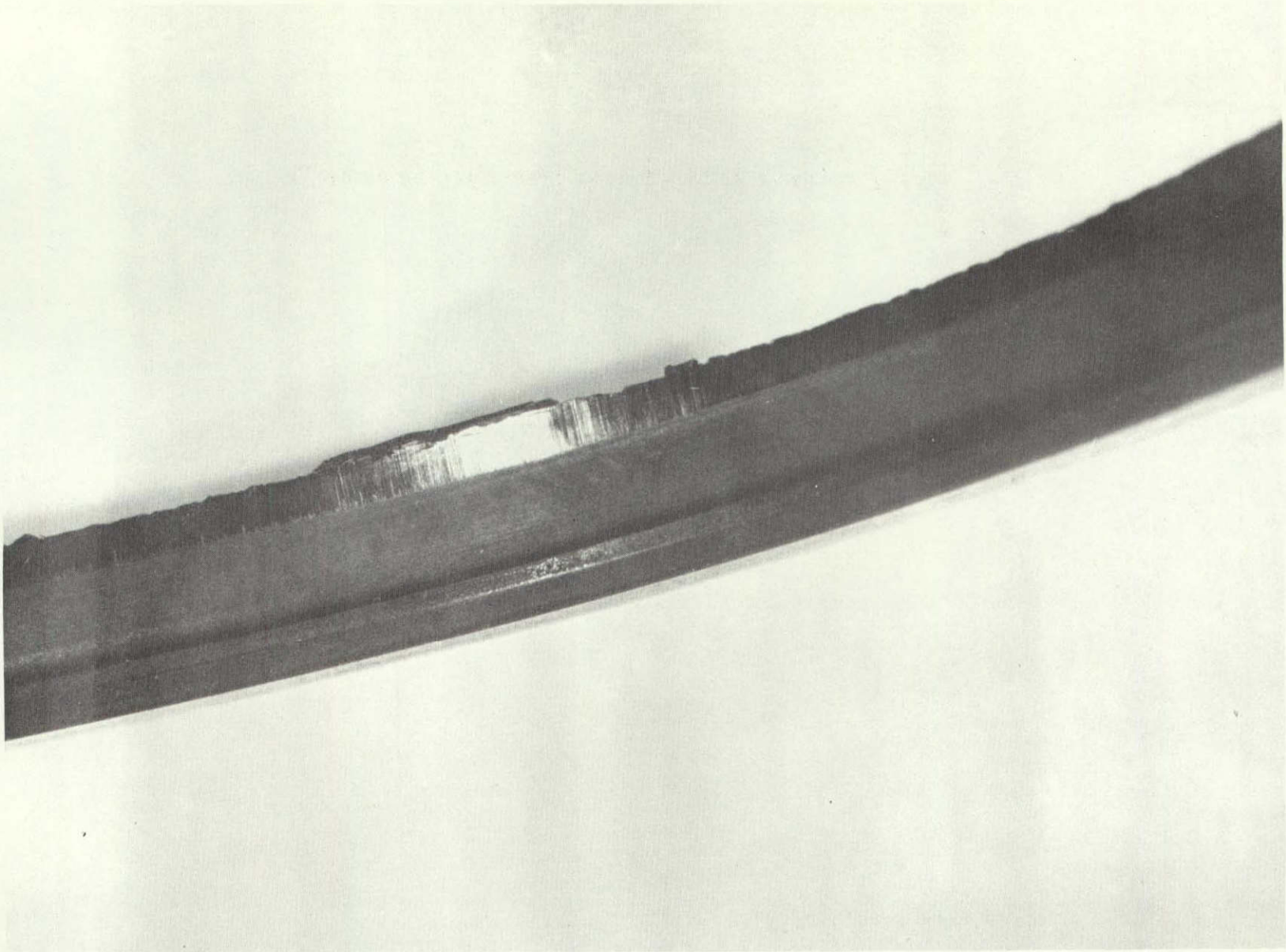


Figure 19.—Downstream Element, Inside Diameter Sealing Edge Wear

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DISCUSSION OF RESULTS

IMPULSE

There is no proven technique to translate the results of an impulse test conducted under one set of conditions to equivalent life under another set of conditions. It is therefore not possible to evaluate the impulse screening test by equating the results obtained to an equivalent life at the failure condition.

The best analysis that can be made of impulse life of the K-section seal as a function of peak impulse pressure applied to the seal is by comparing the largest number of cycles obtained in testing at various pressures. This life is shown in figure 20 and is a pessimistic analysis of the seal capability because the data points at 31.030 MPa (4500 psi) and 34.478 MPa (5000 psi) were obtained with seals that had had previous testing, and the data at 10.43 MPa (1500 psi) was not a failure condition for the seal. To obtain a true picture of impulse life, multiple samples at selected pressures would have to be tested. To arrive at an estimated life at each pressure, nonrepresentative results would be eliminated by statistical analysis.

ENDURANCE

Side loads introduced into the actuator by the torque tube-crank arm mechanism caused more severe rod/bearing and piston/cylinder wear during the single-stage seal tests than encountered during previous second-stage seal tests. This wear might be attributed to the following procedures, used in a single-stage testing, or could be only the evidence of expected wearout of parts after an accumulated 5 years of testing.

- Fluid just upstream of the single-stage seal was trapped, since there was no interstage bleed as was used with two-stage seal operation. The actuator stroke did not allow full exchange of fluid on both sides of the piston. Frictional heat generated was therefore not carried away by a constant flow of fluid over the wear area.
- The absence of the first-stage seal appeared to allow greater rod flexibility for side motion within the seal module than when a two-stage seal was installed. Wear in the module showed evidence of side loading and overheating due to frictional contact between the rod and bearing surface of the seal module.

The above conditions are suspected of being the cause for leakage developing at the balance tube seal which lies within the actuator rod (fig. 11).

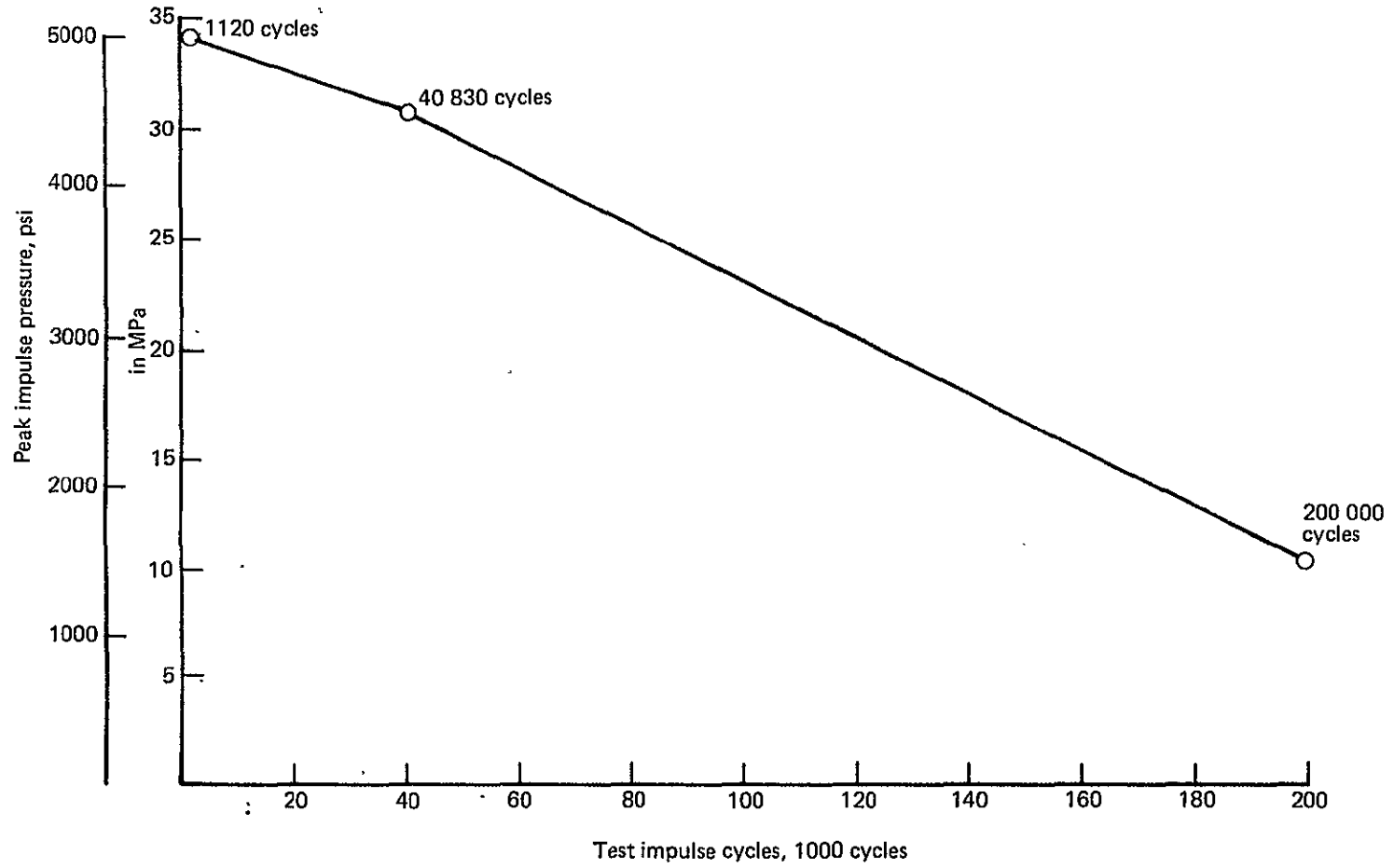


Figure 20.—Projected Impulse Life

CONCLUSIONS

The machined polyimide K-section seals that were designed for second-stage rod seal applications with a nominal differential pressure of 1.379 MPa (200 psi) have only limited life at pressures that would be encountered in single-stage seal applications. The tests conducted showed that though impulse life at higher pressures than 20.687 MPa (3000 psi) was encouraging, static pressurization for 5 minutes at these pressures would cause K-section leg fractures. Further development of single-stage seals in this geometric shape and made of polyimide material is not advocated. This conclusion does not detract from the exemplary performance of these seals under conditions for which they were designed. Continued development of polyimide seals in second-stage applications should be conducted. Adequate testing of machined seals has been completed to prove seal acceptability. Further development should be directed to provide standard dimensions for the variety of seal sizes needed in industry.

APPENDIX A

PRESSURE IMPULSE TEST, SYSTEM DESCRIPTION AND OPERATING SEQUENCE

TEST SYSTEM DESCRIPTION

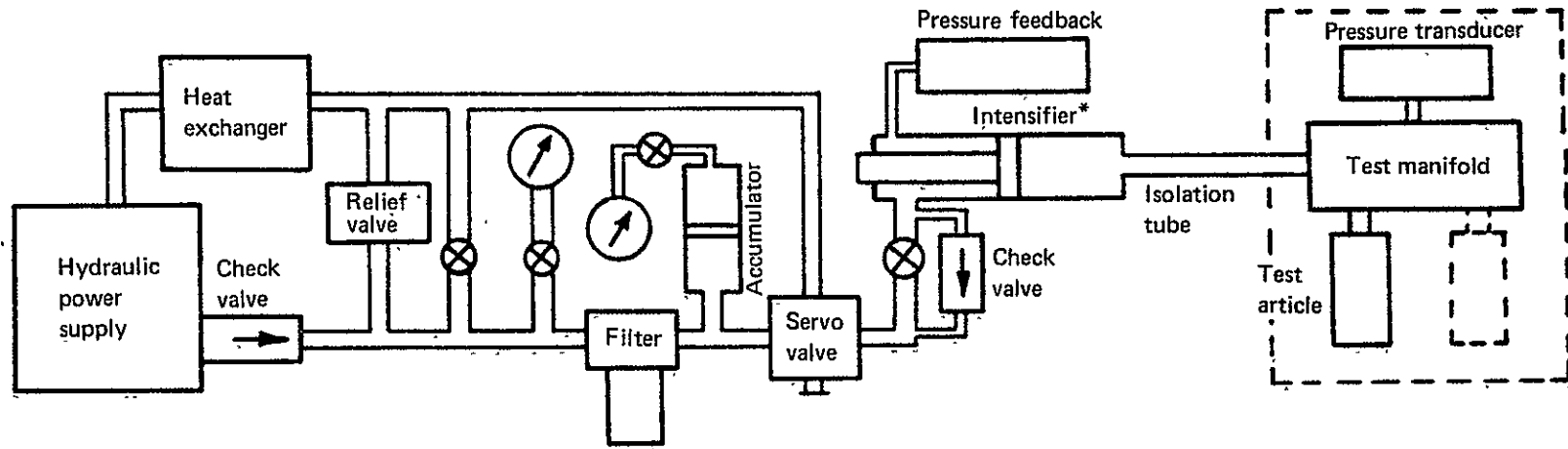
TEST OPERATION COMPONENTS

The hydraulic system shown schematically in figure 21 describes the test rig used for impulse testing. This is an existing rig developed primarily for testing of tubing, fittings, and hoses. It consists of the following major components:

Hydraulic power supply	Denison 8-gpm pump unit
Hydraulic relief valve	Denison
Hydraulic filter	Purolater, T-type (25-micron-absolute)
Servo valve block	Boeing laboratory equipment (SK11-96025)
Intensifier (3-to-1 area ratio)	Boeing laboratory equipment
Heat exchanger	Harrison, water-cooled
Accumulator	Hydrodyne, $3.785 \times 10^3 \text{ m}^3$ (1-gal), 68.94 MPa (10 000 psig)
Isolation tube	0.013-m (1/2-in.) od for first-stage test 0.0064-m (1/4-in.) od for second-stage test

The hydraulic power supply consists of a $5.047 \times 10^{-4} \text{ m}^3/\text{sec}$ (8-gpm) 34.43-MPa (5000-psig) variable-displacement pump with reservoir. A high-pressure, piston-type accumulator is located in the supply line just upstream of the servo valve manifold to provide peak flow requirements beyond the maximum dynamic response of the pump. Ports within the servo valve block are oversized to reduce pressure drop. For tests requiring pressure rise rates below 1033 MPa/sec (150 000 psig/sec), a 3-to-1 intensifier is placed between the servo valve and the test manifold. This allows the pump and servo to be operated well within their working pressure range while impulsing the test article at rather high pressure peaks.

For this series of tests reported, the fluid on the servo side of the intensifier was MIL-H-5606, and the fluid on the test article side of the intensifier was MIL-H-83282 (ref. 4). The test article temperature was provided by placing the seal-retaining housing in an environmental enclosure and controlling the ambient temperature within this enclosure. Because the fluid in the test article was almost dead-ended, no preheating of



*Shown for 2nd stage test operation, direction reversed for 1st stage tests

Figure 21.—Impulse Test Setup Schematic

the supply fluid was required. The test chamber was positioned approximately 152.4 cm (60 in.) from the intensifier and connected by a suitable section of hydraulic tubing. This tube was used to isolate the test article temperature from the intensifier.

Seals were installed by wetting the seal and gland surfaces with hydraulic fluid and using finger pressure to position the individual parts on the rod. The seal-housing bushing was then used to push the seal assembly into its proper position in the gland shown in figures 22 and 23. No sticking or binding was encountered during installation.

CONTROL CIRCUIT AND INSTRUMENTATION

The control system for impulsing was based on an electrohydraulic, closed-loop, pressure-control servo system. Components of this system were arranged as shown in figure 24. The control actuating device was the four-way, pressure-control servovalve with one cylinder port blocked. The servo controller was a Boeing-built controller with an adjustable servo loop gain from unity to a multiplication of one hundred. The controller output stage was a voltage driver that also provided damping for the servovalve.

The servovalve was driven by two superimposed square waves of variable amplitude and period. The basic wave provided a signal corresponding to the desired working, or plateau, pressure level. The second wave with the same leading edge, greater amplitude, and a shorter duration was superimposed to provide the overshoot pressure peak. The shape of the overshoot peak-pressure wave was varied between a single damped wave to that of a nearly zero-damped oscillatory wave by varying the controller loop gain. Additional fine adjustment of wave shape, rate of pressure rise, and pressure level was made by varying the servovalve input wave shape, hydraulic supply pressure, pressure loss in the supply line to the intensifier, and the test article volume. A Boeing-built, fail-safe panel provided for system shutdown at loss of 10% of the peak pressure for one cycle, or loss of 3 percent to 5 percent for several cycles.

DATA

A data system shown in figure 25 was used to determine that proper adjustment had been made to the control system for the specific impulse profile. Cycle programmer output and servovalve current were used as reference control information. Output from a data system transducer, mounted on the test specimen manifold, provided a dynamic impulse pressure trace for visual monitoring. Oven temperatures were controlled automatically and monitored on a vertical temperature indicator. Instrumentation data accuracy is reported in Appendix C.

TEST OPERATION

After the test article and data transducer were installed on the test manifold, a system pressure of 0.689 MPa (100 psig) was applied to the intensifier and test article to allow air to be bled from the system. Full system pressure was thereafter applied and the servo controller used to manually vary pressure from zero to maximum to check for system leaks and control system stability.

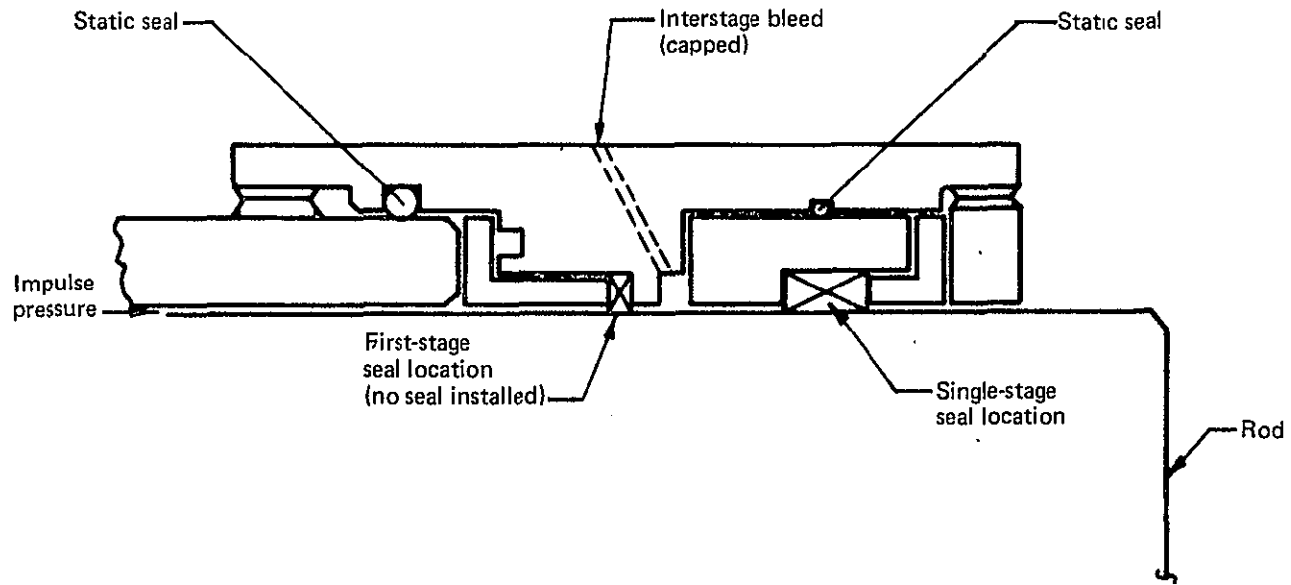


Figure 22.—Seal Installation Impulse Test

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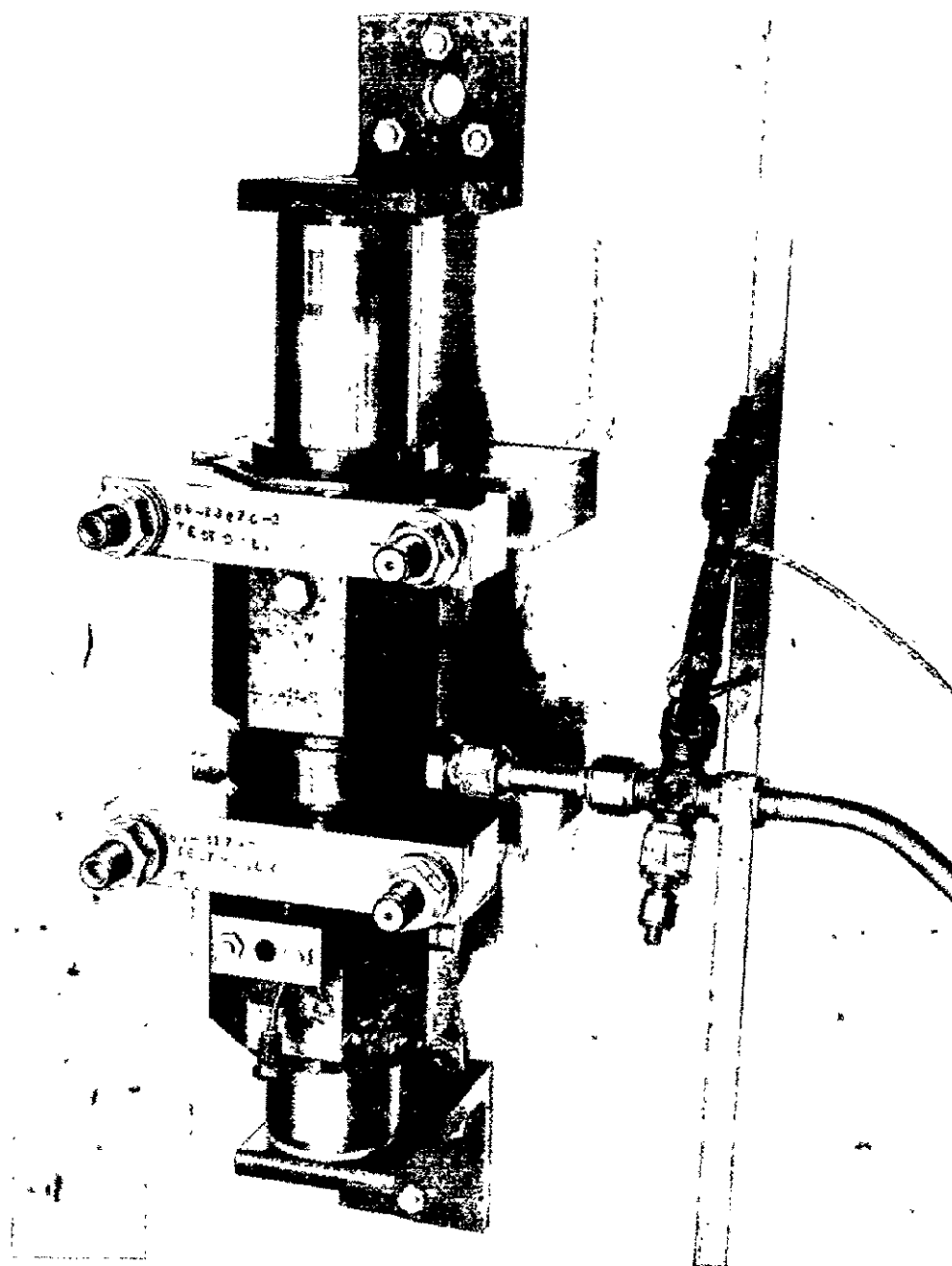


Figure 23.—Impulse Test Seal Housing

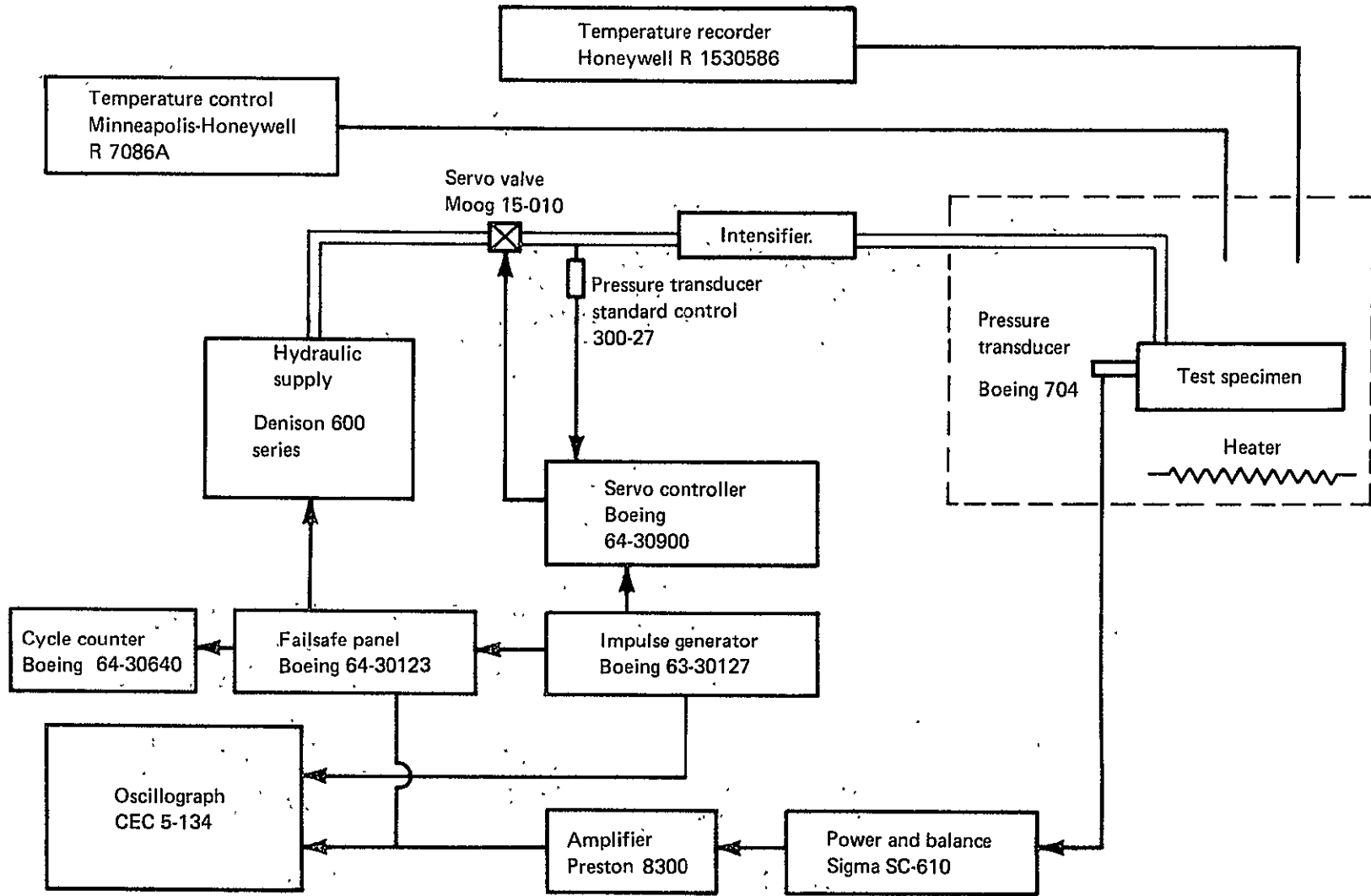


Figure 24.—Impulse Test Instrumentation Block Diagram

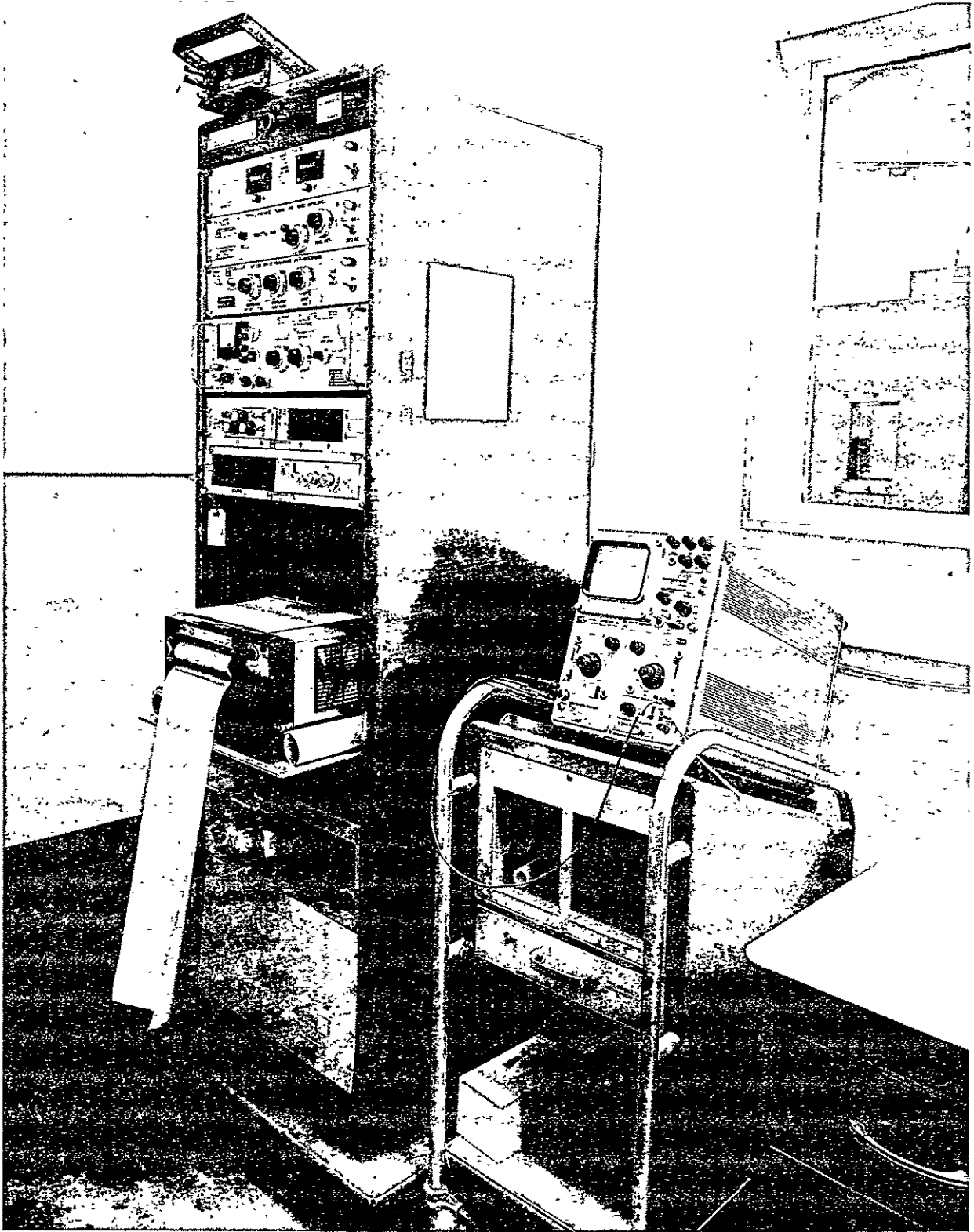


Figure 25.—Impulse Test Instrumentation

Proof pressure tests were conducted on the seal assemblies to establish preimpulse test leakage performance of the test articles. These tests were conducted by statically pressurizing the seals to 10.43 MPa (1500 psig) for 300 sec (5 min). The test was conducted at 297 K (75° F).

The test data system was calibrated and the pressure impulse profile set to the requirements of the screening or structural impulse test:

1. The cycle programmer offset control was adjusted to place the pressure plateau at the correct level.
2. The programmer leading-edge width control was opened just far enough to obtain the desired peak pressure.
3. The power supply pressure was adjusted as necessary to obtain the correct peak pressure amplitude.
4. The servo controller gain was adjusted to shape the overshoot wave to the desired profile.

Recordings were made to determine pressure rise, which was calculated as follows:

P = peak pressure in psig

$\Delta 1$ = time at 10% P (sec)

$\Delta 2$ = time at 90% P (sec)

Rate of rise in MPa/sec (psig/sec) = $(0.9P - 0.1P)/(\Delta 2 - \Delta 1)$. This is the straight line slope of the pressure-time trace.

Heater controls were adjusted to maintain seal-housing temperatures at the level prescribed for each segment of the impulse test. During testing, leakage was measured by collection in burettes or by visual monitoring where leakage was only an infrequent drop.

POSTTEST INSPECTION

The seals that completed impulse tests were examined for structural damage, cracking of the seal material, and contact surface polishing. The above were not considered as conditions of seal failure unless the leakage during the test was greater than the allowable. The inspection was performed by unaided visual observation to make a qualitative description of the seal, supplemented by observations using a microscope.

APPENDIX B

ENDURANCE TEST, SYSTEM DESCRIPTION AND OPERATING SEQUENCE

TEST SYSTEM DESCRIPTION

The endurance test installation, shown in figure 26, is an existing rig developed primarily for testing linear actuator seals. The installation consists of a load system, the hydraulic power supply with its associated plumbing, and the control electronics. The major power and loading components are as follows:

Oven--Dispatch, model 203

High-temperature power supply--Auto Controls Laboratory, Inc., model 4586 (fig. 27)

Load fixture--Boeing laboratory equipment

Filter--microporous (25-micron-absolute)

Relief valve--Vickers C-175-F

Servovalve block--Boeing laboratory equipment

Accumulator--Hydrodyne 68.95-MPa (10 000-psig)

The load system consisted of a torsion bar capable of providing resisting torque for the actuator. The torque bar length was adjusted to provide a torsional load such as to require full system pressure of 27.58 MPa (4000 psig) at full actuator stroke. The force from the actuator was reacted to the torsion bar through a lever arm and bearing assembly to simulate a flight-control-surface hinge point. Self-aligning bearings were used for the actuator head-end and rod-end connection points. No additional side load other than bearing friction was applied. The mounting base of the load system and the actuator was installed in a test oven. This installation is shown in figure 28. Due to its size, the torsion bar extended through the back of the oven and was supported externally at the extreme end by a pedestal.

Hydraulic power was supplied by a $1.262 \times 10^{-3} \text{ m}^3/\text{sec}$ (20-gpm) Auto Controls Laboratory high-temperature power supply. This unit is complete with all pressure and temperature controls. It supplied MIL-H-83282 (ref. 4) hydraulic fluid at a maximum of 27.58 MPa (4000 psig) and at the required test temperature. The $9.464 \times 10^{-3} \text{ m}^3$ (2.5-gal) accumulator was located in the supply line between the power supply and the test rig. In addition to filtration within the power supply, a 25-micron-absolute filter was located in the supply line downstream of the accumulator. The cavity between the first- and second-stage seals in the test actuator was capped for single-stage seal evaluation.

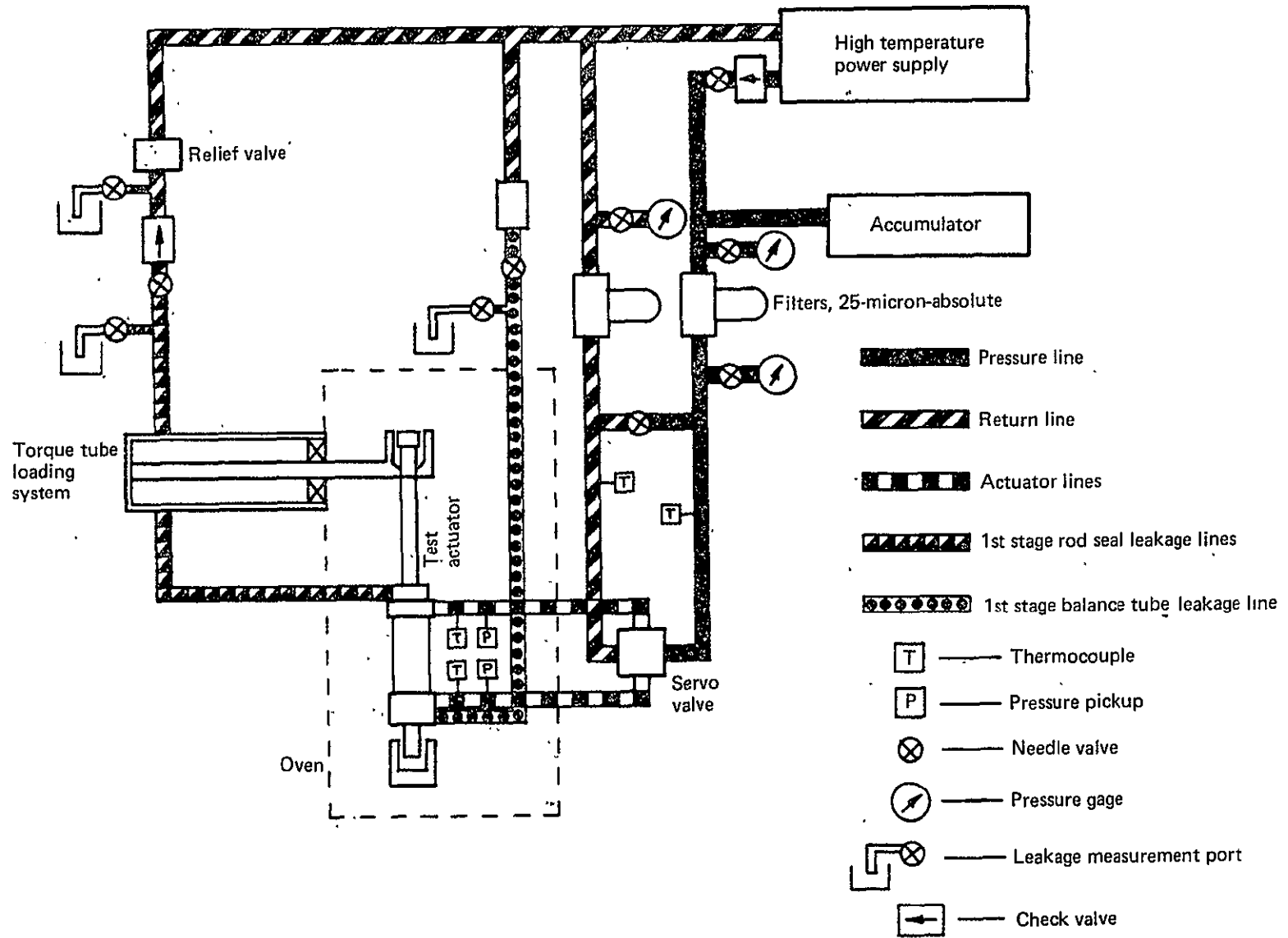
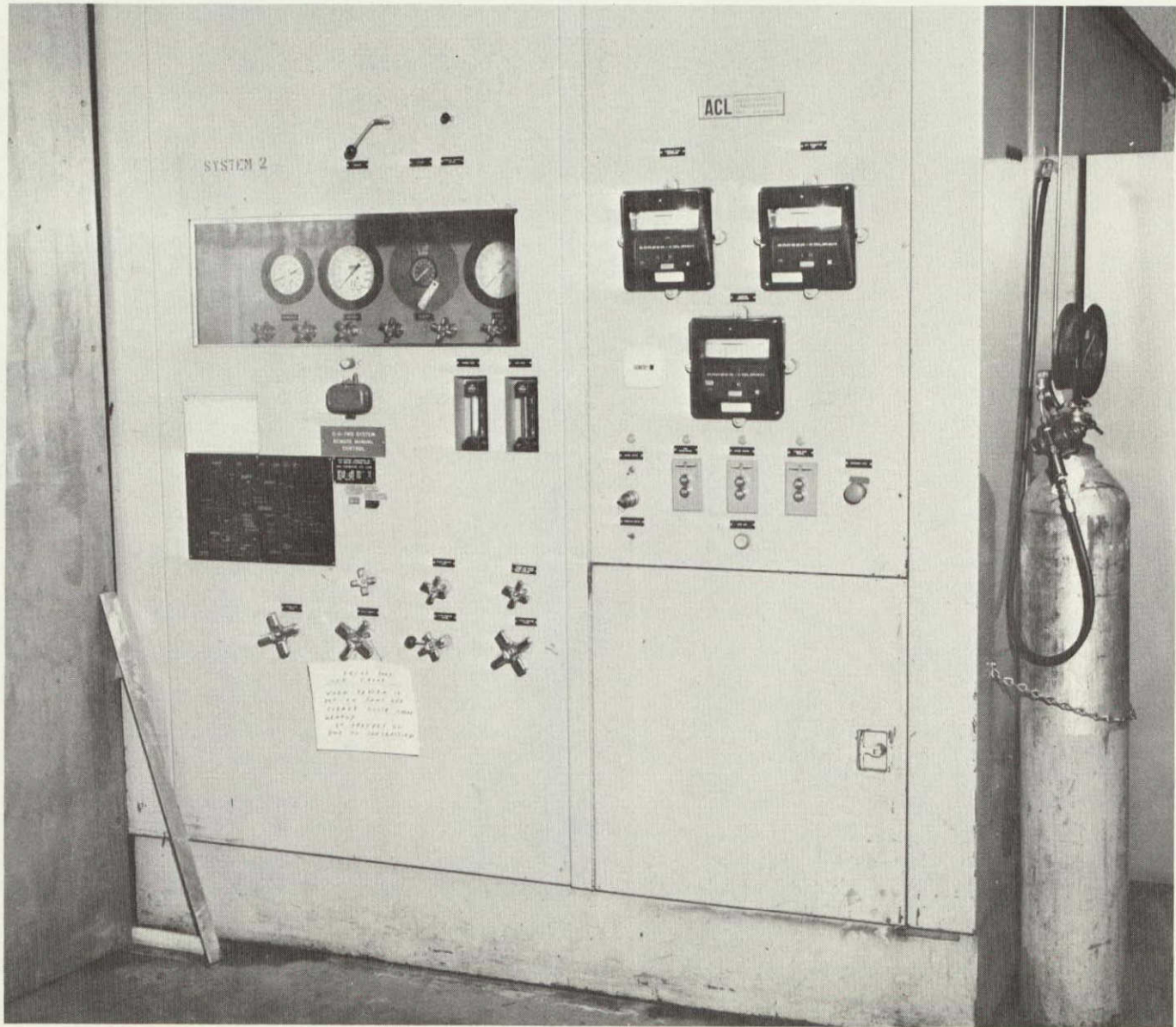


Figure 26.—Hydraulic Installation Schematic, Endurance Test



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Figure 27.—Auto Control Laboratory Power Supply

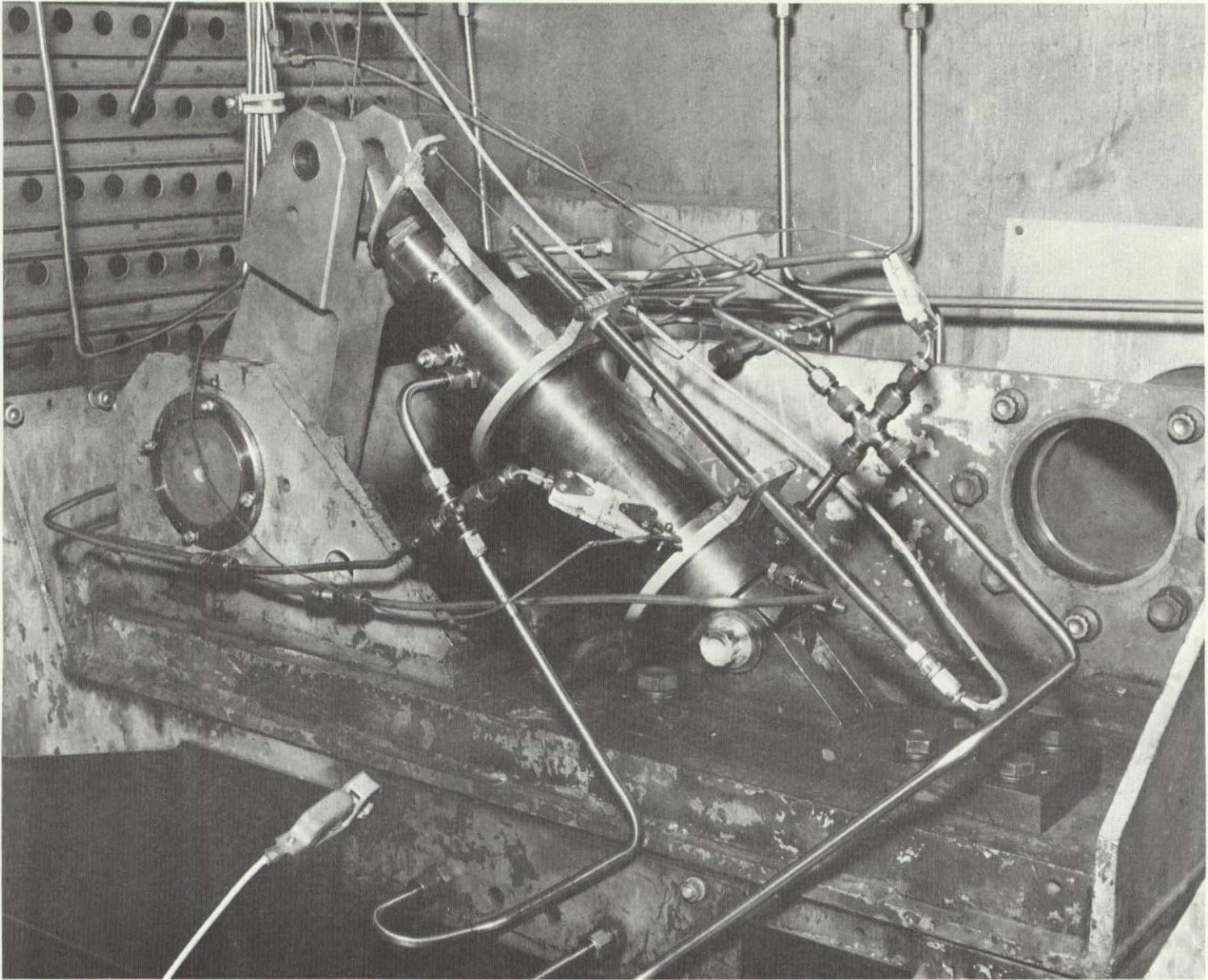


Figure 28.—Actuator Installation Endurance Test

CONTROL ELECTRONICS

The control of test operation cycling was provided by a closed-loop electrohydraulic flow control loop incorporating position feedback.

Components were arranged as shown in figure 29 and 30. The electrical loop consisted of the feedback transducer (LVDT), carrier amplifier, Boeing standard controller, and servovalve, with the total loop completed mechanically through the fluid-powered actuator rod. The servocontroller was driven with a function generator providing a sinusoidal cycle at the required period. The actuator stroke, amplitude, and position were set at the servocontroller command for the flow control servovalve.

Actuator head- and rod-end cylinder pressures were measured and recorded on a direct-write oscillograph. The actuator position was also recorded on the oscillograph and monitored during the test to ensure that proper position and stroke amplitude were maintained.

Oven ambient, oil, and component temperatures were recorded on a stamping-type temperature recorder.

Instrumentation and recorded data accuracies are reported in Appendix C.

ENDURANCE TEST PERFORMANCE SEQUENCE

TEST ARTICLE ASSEMBLY

The test seals were assembled into the second-stage cavity of the seal module of the test actuator shown in figure 11. This module was specifically designed during the NAS3-14317 program to hold both first- and second-stage seals for evaluation during endurance testing. Only the second-stage seals were used in tests for single-stage performance. The actuator was assembled and manually inspected for binding. A proof pressure test was then conducted and preendurance test leakage rates established for the seals at room temperature.

TEST OPERATION

After the test actuator and data transducers were installed in the loading fixture, a reservoir pressure of 0.344 MPa (50 psig) was applied and air was bled from the hydraulic system. A room temperature checkout was conducted, starting with a system pressure of 6.894 MPa (1000 psig) and increasing in incremental steps to working pressure while cycling. Testing was performed in the sequence defined in the table below, and test conditions were established by adjusting:

1. The hydraulic power supply to test temperature and nominal working pressure
2. The oven controls to maintain the test temperature for the mass of the actuators and fixture

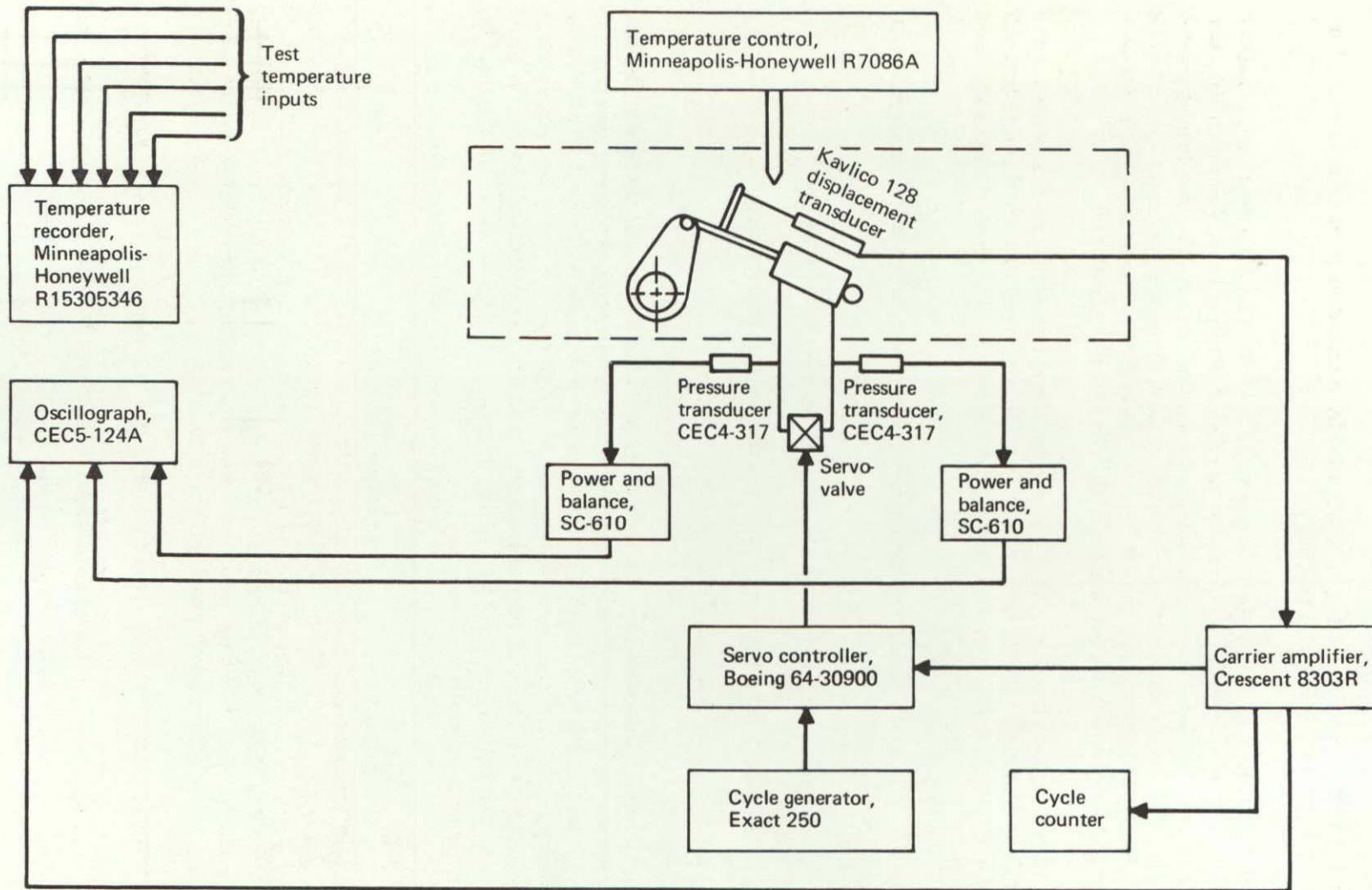


Figure 29.—Electrohydraulic Control Loop, Endurance Test

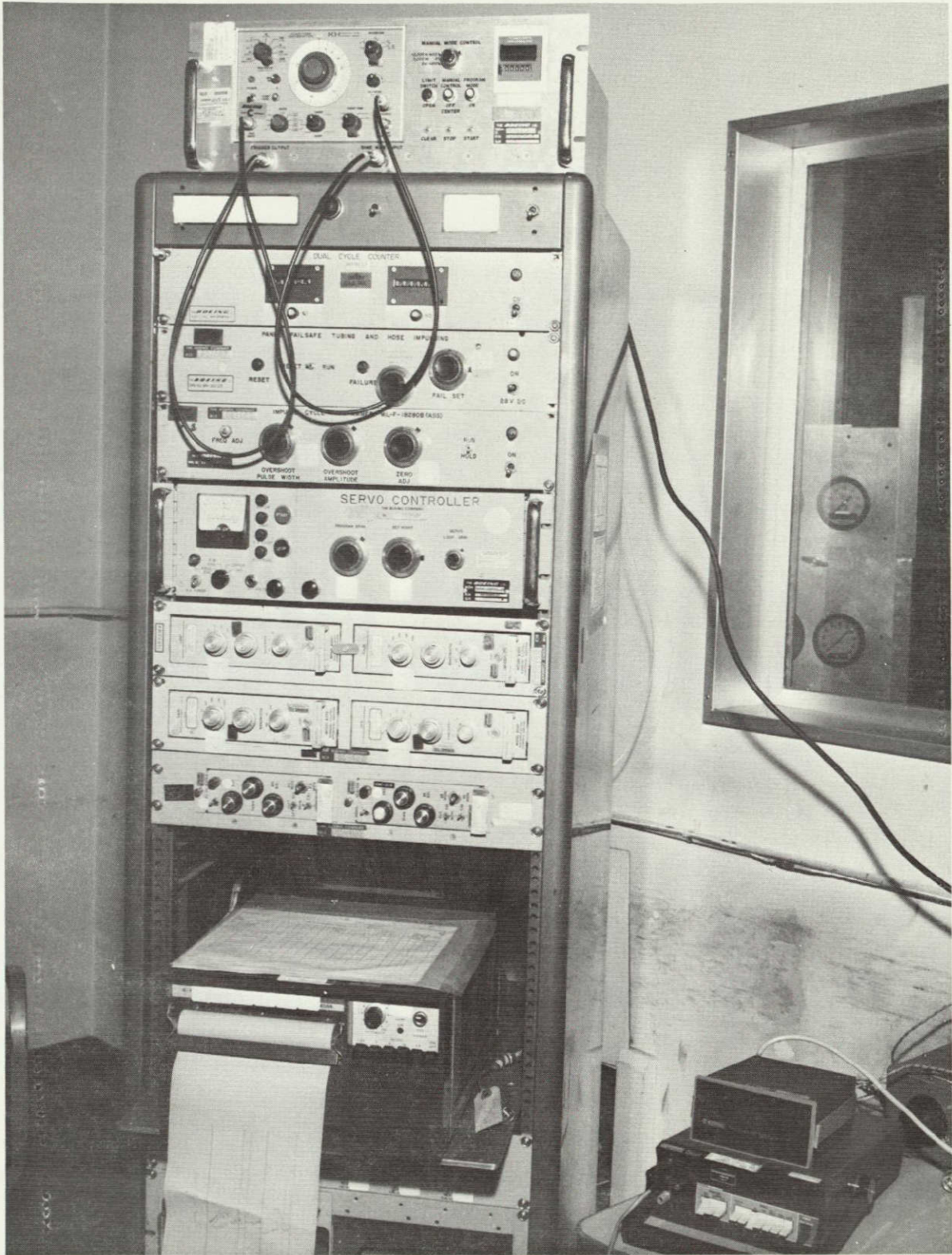


Figure 30.—Endurance Test Instrumentation

3. The function generator to the cycle rate required by the test schedule
4. The servocontroller to provide the desired actuator neutral cycling point and percent of rod stroke

ENDURANCE TEST SEQUENCE

Sequence number	Cycles	% load and stroke (see note 4)	Maximum cycle rate, Hz	Actuator temperature	
				K	°F
1	7.5×10^5	2	6	450	350
2	5000	25	0.83	450	350
3	10000	50	0.67	450	350
4	5000	100	0.56	450	350

Note:

1. All cycles are to be run around actuator midstroke position.
2. A portion of the cycles from sequences 2, 3, and 4 are to be randomly interspersed during performance of sequence 1.
3. Testing spectrum is to consist of five consecutive runs in the sequence shown (ie., 1, 2, 3, 4, 1, 2, 3, 4, 1, 2...) with the sum of sequences 1+2+3+4 equalling one run.
4. 6.35-cm (2.5-in.) actuator: 100% stroke = 7.62 cm (3.0 in.); 100% load = 88.9964 N (20 000 lbf)

During testing, leakage was measured by its collection in buretts.

POSTTEST INSPECTION

The seals that completed endurance tests were examined for structural damage, cracking of the seal material, contact surface polishing, and unusual wear. This was conducted by unaided visual observation supplemented by observations using a microscope.

APPENDIX C

INSTRUMENTATION CALIBRATION AND DATA ACCURACY

Test instrumentation equipment calibrations are traceable through the Boeing flight test calibration laboratory to the National Bureau of Standards. Strain gage, bridge-type transducers were calibrated to determine nonlinearity, hysteresis, and R-shunt calibration transfer values. Position transducers were end-to-end calibrated in place by a calibrated scale/visual technique.

Pressure

Transducer accuracy within	$\pm 0.75\%$ full scale
Power and balance/conditioning within	$\pm 0.1\%$ full scale
Oscillograph accuracy within	$\pm 2.0\%$ full scale
Pressure-measuring system accuracy (RSS) within	$\pm 2.1\%$ full scale

Displacement

Transducer accuracy within	$\pm 0.1\%$ full scale
Signal conditioning within	$\pm 0.2\%$ full scale
Oscillograph accuracy within	$\pm 2.0\%$ full scale
Displacement measuring system accuracy (RSS) within	$\pm 2.0\%$ full scale

Temperature

Thermocouple accuracy within	± 1.1 K ($\pm 2^\circ$ F)
Temperature recorder within	± 2.2 K ($\pm 4.5^\circ$ F)
Temperature measuring system accuracy (RSS) within	± 2.5 K ($\pm 4.0^\circ$ F)

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4. Military Specification, Hydraulic Fluid, Fire Resistant Synthetic Hydrocarbon Base, Aircraft. MIL-H-83282A (USAF), February 1974.

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