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FINAL REPORT

DEVELOPMENT OF SPIRAL-GROOVE SELF-ACTING SEALS FOR HELICOPTER ENGINES

by

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16. Abstract

A spiral-groove, self-acting face seal was rig tested at advanced gas turbine operating conditions to determine wear and leakage rates. The spiral-groove, self-acting geometry was located in the rotating seal seat. Seal component wear induced by start-stop operation was measured after subjecting the test seal to 176 start-stop cycles. Wear occurring during normal operation was documented throughout a 75-hour endurance test. Seal air leakage was also measured. During endurance operation, the seal was subjected to operating conditions bounded by the values below.

Surface Speed 244 m/s (800 ft/sec)

Air Pressure - 148 N/cm^2 abs (215 psia)

Air Temperature - 622 K (660°F)

The post-test condition of the seal components was documented. Wear data is presented in tabular form, while seal air leakage is presented graphically, as a function of pressure and speed.

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FOREWORD

This program was funded by the U. S. Army Air Mobility Research and Development Laboratory. Program management was by the Lewis Research Center of the National Aeronautics and Space Administration under Contract NAS 3-20795. The period of performance was 10 June 1977 to 31 December 1978.

Technical direction was provided by the NASA Project Manager, Mr. Lawrence P. Ludwig of the Fluid Systems Components Division. Mr. Leonard W. Schopen, NASA Lewis Research Center, was the Contracting Officer.

The Avco Lycoming Program Manager was Mr. Michael O'Brien. The test program was conducted by Mr. Harry Thornton.

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SUMMARY

A rig test simulating advanced gas turbine engine operation was performed on a spiral-groove, self-acting face seal which incorporated the spiral-groove geometry in the rotating seal seat. Seal air leakage and seal component wear rates were determined. The rig test included two parts. The first phase was a determination of the sensitivity of seal face wear to repeated start-stop operation. During this phase, a seal was subjected to 176 start-stop cycles, after which seal face wear was documented. The second phase of the test consisted of 75 hours of endurance operation. Operating conditions during the endurance test reached surface speeds of 244 m/s (800 ft/sec), air pressures of 148 N/cm^2 (215 psia) and air temperatures of 622 K (660°F).

Carbon primary ring wear was characterized with two parameters. First, the overall wear was established; then any additional local surface variations were determined. Generally, both the sealing dam and the larger flat land area which interfaces with the spiral grooves assumed a tapered wear characteristic after operation (coverging as distance from the seal centerline increased). Maximum wear of the carbon primary ring observed after the start-stop cycles was .0010 cm (.0004 in.). Maximum taper was .00068 cm (.00027 in.), occurring on the land area. No spiral-groove seat wear was measurable. The endurance test featured the same seal hardware, and after 22.5 hours of operation, total wear of the carbon primary ring was found to be a maximum of .00177 cm (.0007 in.) with maximum taper of .00315 cm (.00125 in.) occurring on the dam; no spiral groove wear was measurable on the seal seat. Maximum test conditions during this phase of the endurance test encompassed surface speeds of 168 m/s (550 ft/sec), sealed air pressures of 31 N/cm^2 (45 psia), and air temperatures of 600K (620°F). A new primary sealing element was used for the balance of the endurance test (52.5 hr) because of damage to the original sealing element, which was chipped during reassembly. At the completion of the endurance test, overall carbon primary ring wear was .0004 cm (.0015 in.) with a maximum taper occurring on the seal land of .0046 cm (.0018 in.); wear of the self-acting geometry on the seal seat was not determinable due to disturbance of the chrome-carbide surface caused by an apparent momentary rub during operation.

Seal air leakage was at time unstable during testing. This was attributed to binding because of a marginally low clearance between the carbon sealing element and the seal housing. A representative air leakage at 148 N/cm^2 (215 psia) is .002 kg/sec (.005 lb/sec).

INTRODUCTION

Advanced gas turbine engines impose increasingly severe demands on main bearing compartment shaft seals. Higher shaft speeds accompanied by elevated air pressures and temperatures make difficult the task of maintaining seal heat generation, air leakage, and operating life within acceptable limits.

The purpose of this program was to evaluate the wear and leakage characteristics of a spiral-groove, self-acting face seal configured to be accommodative in the gas producer turbine bearing compartment of an advanced gas turbine engine. The seal design differs from those previously tested (Reference 1) by locating the spiral-groove geometry on the rotating seal seat. This is an alternative to the more traditional location on the mating face of the carbon sealing element. Spiral grooves located in the chrome-carbide surface of the seal seat have the potential for increased wear resistance when compared to spiral grooves located in the carbon sealing element.

Self-acting or film-riding seals offer an alternative to conventional contacting carbon seals and to labyrinth type clearance seals. Conventional contacting carbon seals may not be adequate at the operating conditions of future high-performance gas turbine engines. Labyrinth seals operating at these future conditions will likely be multistage devices, incorporating pressurization and venting passages. These are not only expensive but also require relatively large amounts of space compared with carbon seals and are difficult to accommodate in small, high-performance engines. Labyrinth seals also allow higher air leakage overboard and into the bearing compartments than carbon seals, placing greater demands on the lubrication system and impacting engine performance.

Self-acting or film-riding seals allow operation in a noncontacting mode except during engine startup and shutdown, at which time they become contacting. During operation in the noncontacting mode, the dynamic sealing surfaces are separated by a small gap which effectively limits air leakage. The fact that the sealing surface are noncontacting minimizes heat generation and seal wear.

The experimental evaluation and endurance test was carried out in a test rig that simulated engine conditions of an advanced gas producer turbine bearing location.

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1. O'Brien, M., DEVELOPMENT OF SPIRAL - GROOVE SELF-ACTING FACE SEALS, Avco Lycoming Report LYC 77-41, NASA CR 135303, June 1977.

APPARATUS AND PROCEDURE

Test Vehicle

The test rig used during the test program is illustrated in Figure 1. The test bearing and seal compartment which is shown in detail in Figure 2, illustrates the arrangement of the bearing and test seal.

The test rig prime mover is a 74.57 kw (100 hp), 30,000 rpm steam turbine. A 1:3 ratio speed increasing gearbox connects the steam turbine to the test rig. The test installation is shown in Figure 3. The test rig shaft is supported by a 35x62x14 mm split inner race ball bearing adjacent to the test seal (test bearing compartment) and by a 35x 55x10 mm split inner race ball bearing at the opposite end of the shaft (support bearing compartment). Both bearings are hydraulically mounted with thrust loading accomplished by coil springs acting on the outer race of the support bearing. A single batch of MIL-L-23699 oil was used throughout the test program. Oil flow to the test bearing compartment was varied as a function of shaft speed as illustrated in Figure 4. Oil jet location and orientation are shown in Figure 2. Oil feed temperature into the test bearing compartment was maintained at 355 ± 6K ($180^{\circ} \pm 10^{\circ}$F) during the endurance test. During the start-stop cycles, the oil feed temperature was maintained at 339 ± 6K ($150^{\circ} \pm 10^{\circ}$F).

A reciprocating compressor in conjunction with electric air heaters supplied pressurized air to the seal cavity at the desired temperature and and pressure.

The volume flow rate of the air leaking past the seal was measured with rotameters to provide an indication of seal performance. The air-oil mixture from the bearing compartment passed through the test rig scavenge system (minimum area 93 mm^2 (1.44 $in.^2$) and into a static air-oil separator prior to the airflow measurement. Averaged values of air leakage are presented.

Seal Wear Measurement Technique

Seal wear measurement was accomplished by montoring carbon sealing element length at three indexed locations in the vicinity of the anti-rotation lug slots. Variation in the dam and land surface profile was also documented at these three locations.

Wear of the seal seat and any accompanying reduction of spiral groove

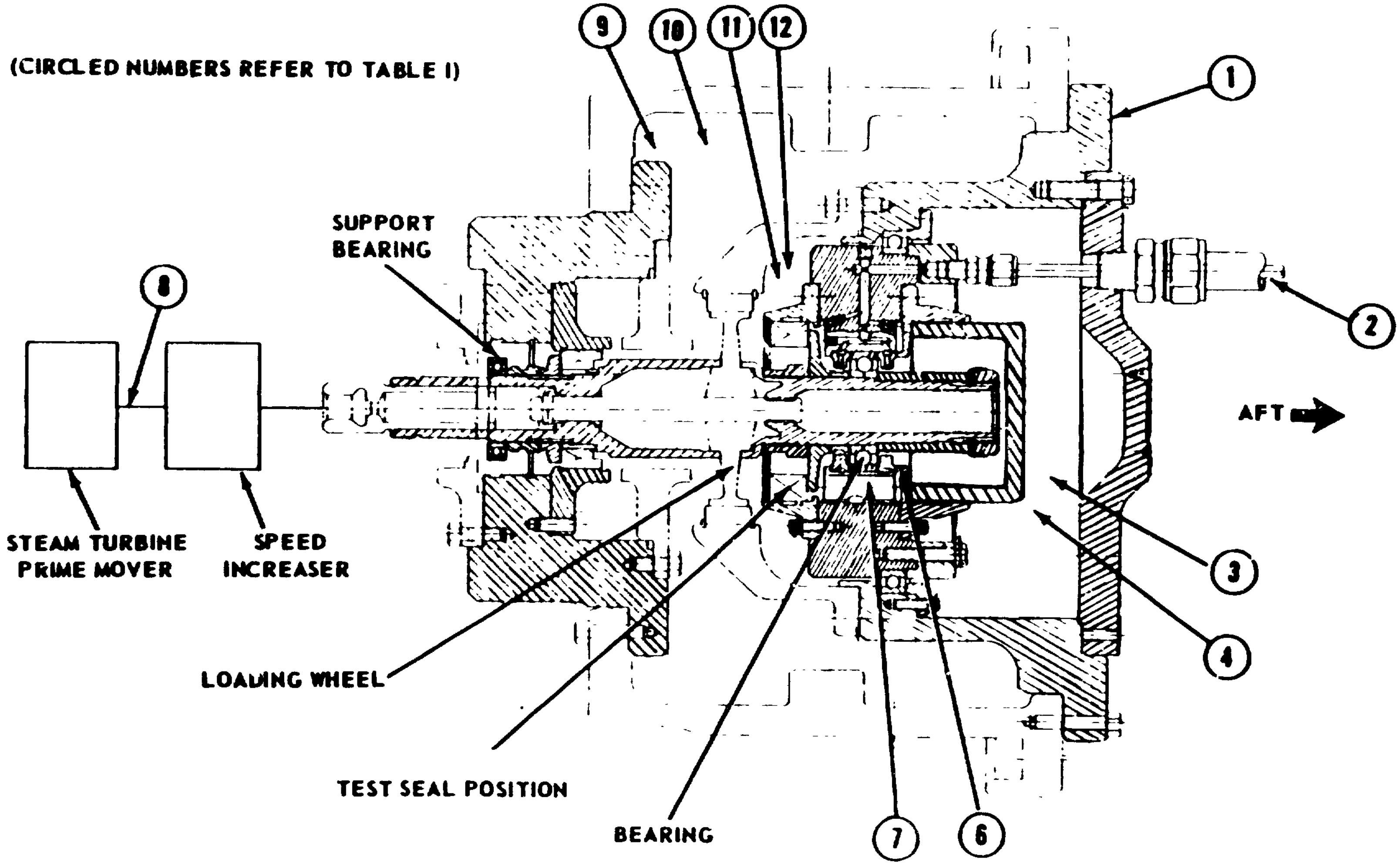


Figure 1. Test Rig Schematic.

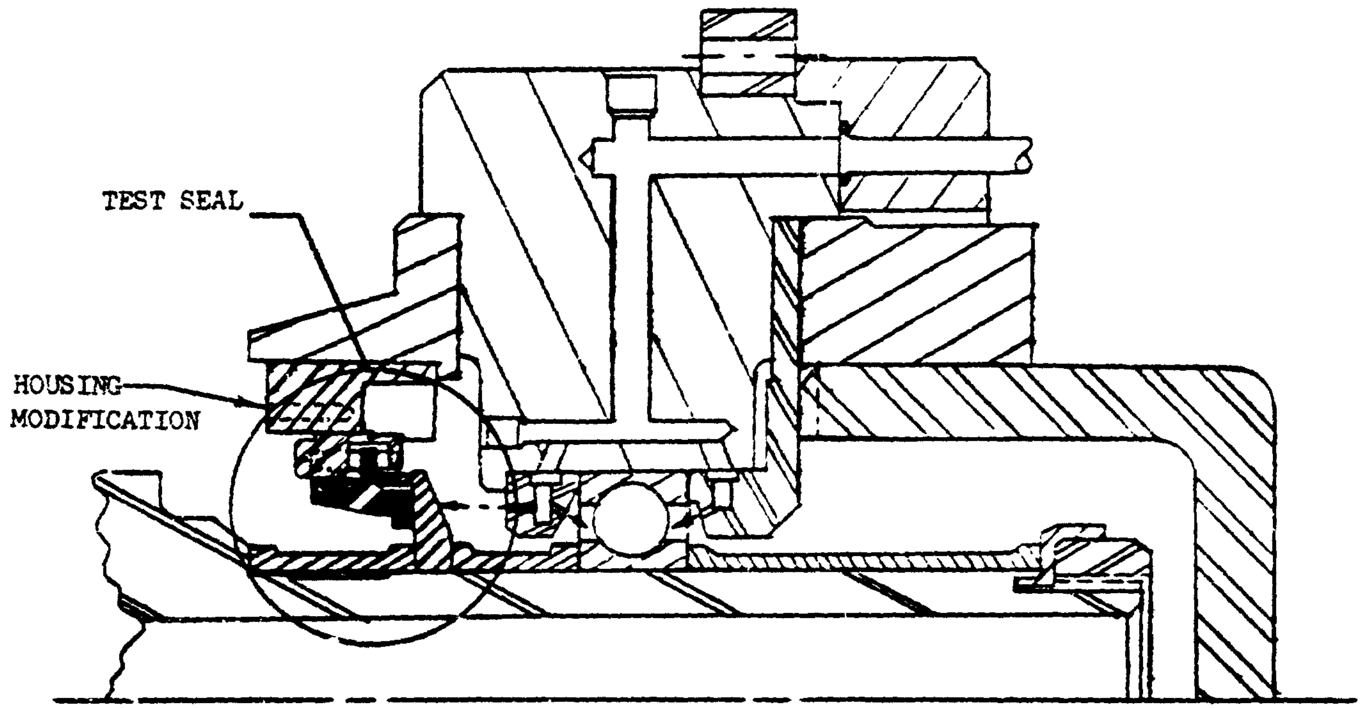


Figure 2. Test Seal Bearing Compartment.

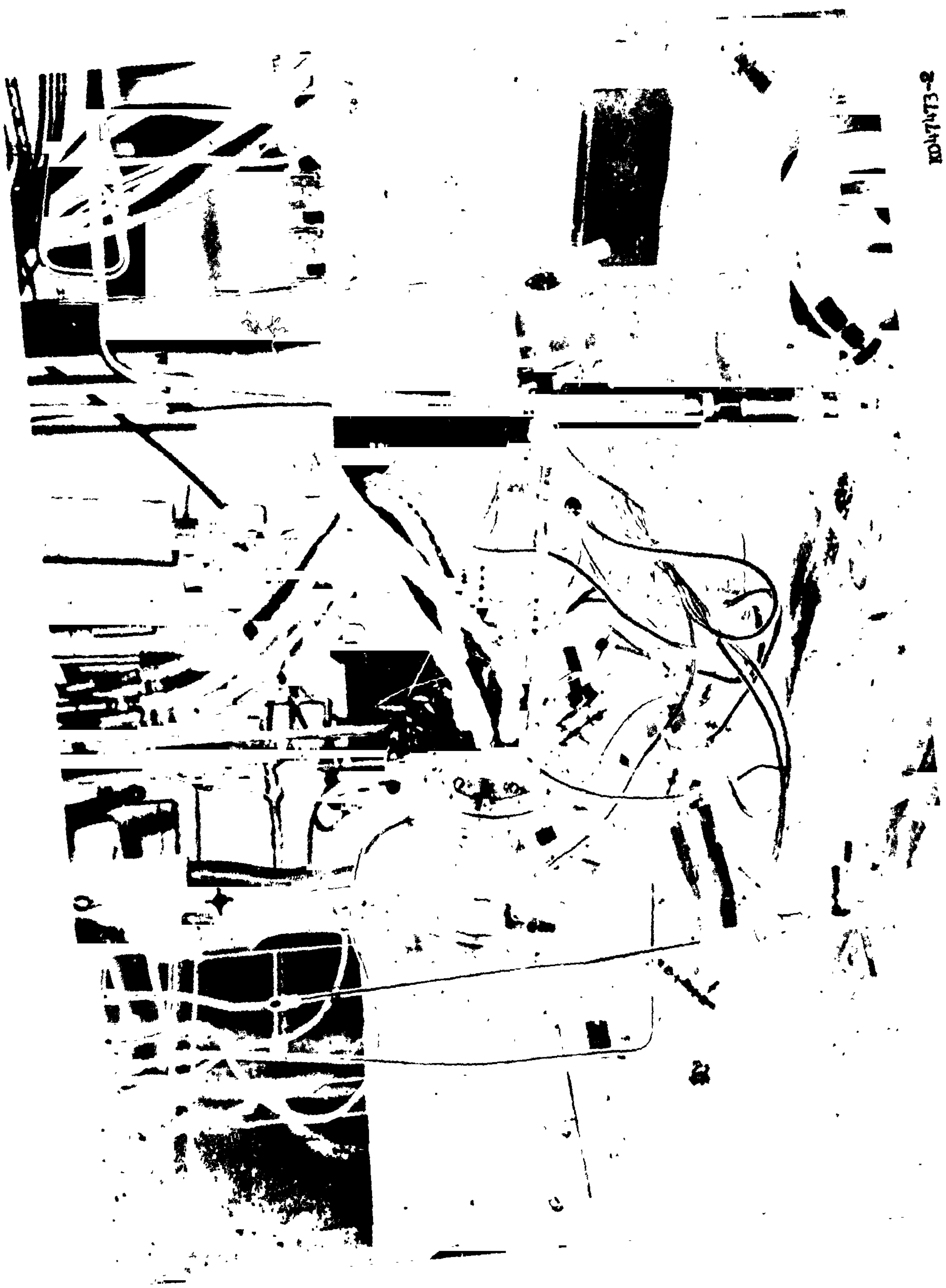


Figure 3. Test Installation.

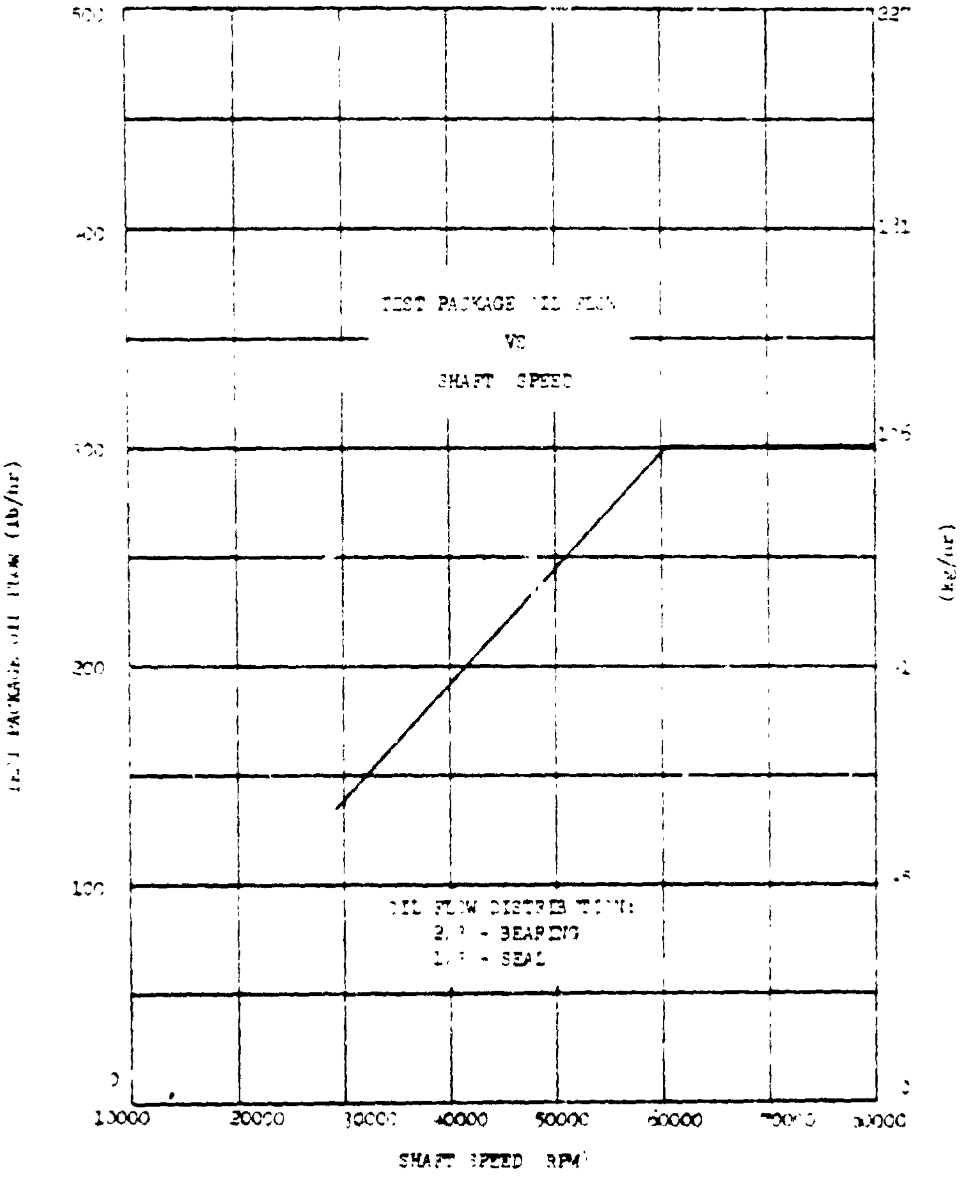


Figure 4. Oil Flow Versus Shaft Speed.

depth was documented through Indiron traces at two diametral locations; one corresponding to an outboard spiral groove location, and another inboard near the beginning of the spiral grooves. Figure 5 illustrates the locations of these wear measurements.

Recorded Parameters

Instrumentation incorporated in the test rig is listed in Table 1. The location of the pertinent instrumentation is shown in Figure 1. All measurements were made with instruments calibrated in English units that were then converted to SI units.

SPIRAL-GROOVE SELF-ACTING SEAL DESIGN

The test seal, illustrated in Figure 6, includes the following components:

- The seal utilizes a primary sealing element fabricated from carbon graphite material. The face of the element contains the sealing dam and a land surface which will oppose the spiral-groove lift geometry location in the seal seat. Pressure feed holes communicate sealed pressure to the annulus separating the sealing dam from the land surface. Anti-rotation provisions are made by three slots in the sealing element which engage pins in the seal housing.

- The secondary seal is a straight-cut, pressure-balanced piston ring which is carried in a groove in the primary sealing element and seals against a bore located in the seal housing.

- Coil springs within the seal housing serve to load the primary sealing element against the seal seat.

- The seal seat is manufactured from AMS6322 material and incorporates a flame sprayed chrome-carbide sealing surface. The spiral-groove geometry (.0005-.0010 in. deep) is also located on this surface of the seal seat. The spiral groove is outward pumping and extends from below the carbon ring inside diameter to within (.102 cm (.040 in.) of the annular inside diameter.

The design of the primary sealing element is such that an increase in closing force is produced as sealed pressure is increased. During operation, this closing force plus the axial springs load is balanced by the force produced by the pressure generating capability of spiral grooves. The spiral-groove pressure generation, for a given groove geometry, is a function of sliding velocity, the sealed fluid viscosity, and the separation between the sealing element and the seal seat.

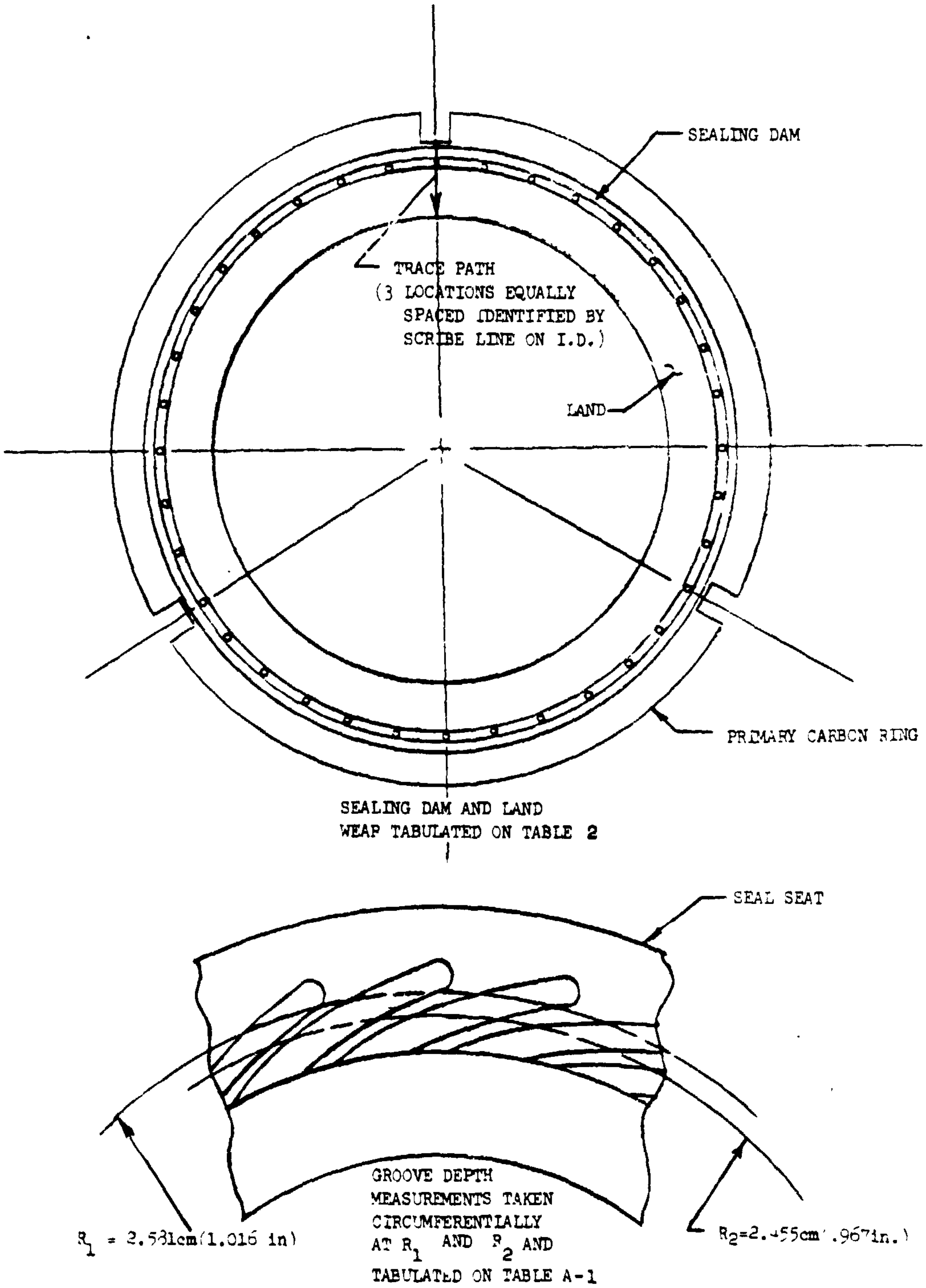
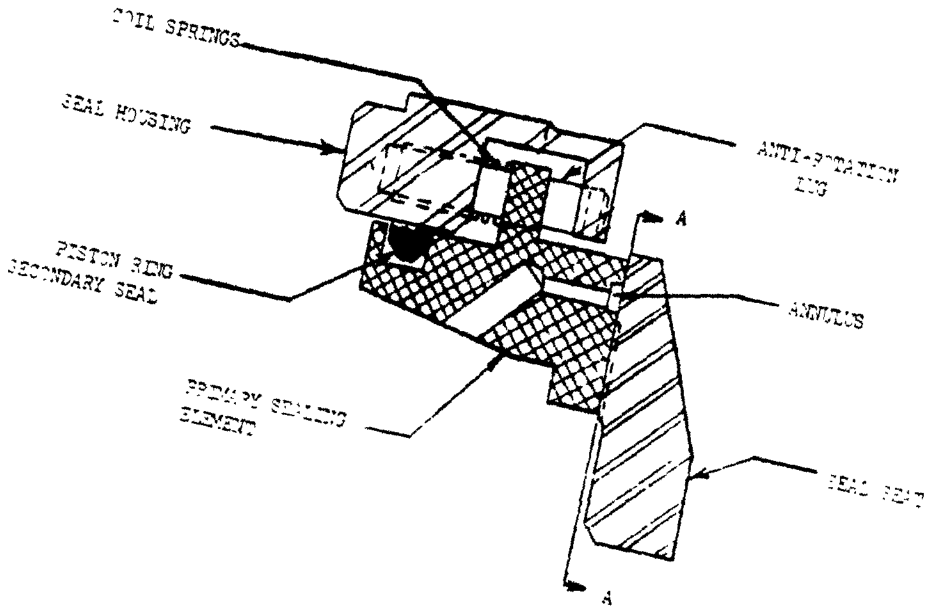


Figure 5. Location of Wear Measurements.

TABLE 1. INSTRUMENTATION PLAN

Parameter To Be Measured	Sensing Device	Location	Corresponding Number in Figure 1
Shaft Speed	Magnetic pickup	Steam turbine Shaft	8
Air Pressure	Gage	Fwd wheel cavity	9
	Gage	Seal cavity	12
	Gage	Aft cavity	3
Air Temperature	Thermocouple	Fwd wheel cavity	10
	Thermocouple	Seal cavity	11
	Thermocouple	Aft cavity	4
Seal Air Leakage	Glass tube rotameter	Scavenge air-oil mixture is passed through a static separator and the dry airflow is passed through the flowmeter	7
Oil Temperature	Thermocouple	Oil feed line	2
	Thermocouple	Scavenge line	7
Oil Flow	Glass tube rotameter	Oil feed line	2
Oil Pressure	Gage	Oil feed line	2
Bearing Cavity Pressure	Gage	Within bearing cavity	6
Scavenge Pressure	Gage	Scavenge line	7
Vibration	Velocity pickup		1
Chips	Chip detector	Scavenge line	7



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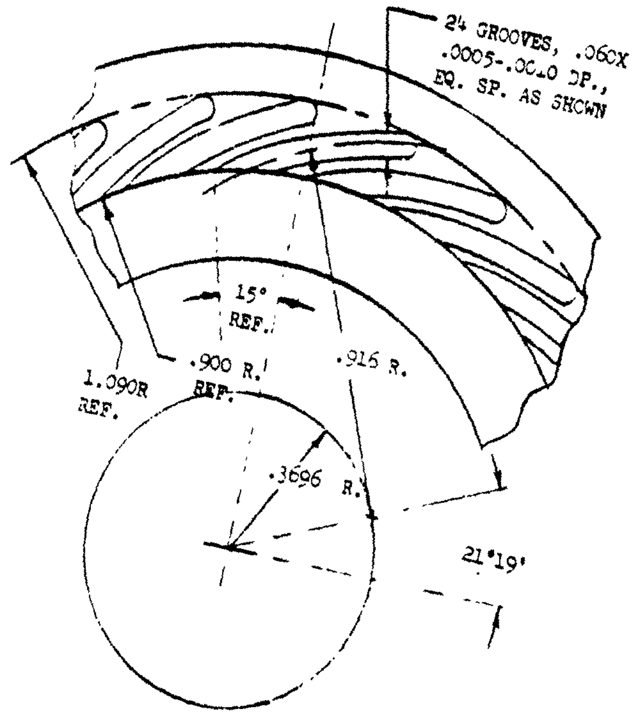

Figure 6. Test Seal.

When the seal is operating at a particular sliding velocity, sealed pressure, and temperature, the separation between the sealing element and the seal adjusts until the closing force is balanced. This establishes the leakage clearance. Ideally, this clearance should be as small as possible possible to minimize air leakage, but practical consideration such as assembled seat and primary sealing element flatness, along with pressure, temperature and speed-induced distortions of these items limit achievable minimum operating clearance. In practice, this operating clearance is on the order of .005 cm (.0002 in.)

TEST PROGRAM

The test program comprised two main parts. First, in order to assess the effect of start-stop operation on seal wear, the seal was subjected to 176 start-stop cycles where shaft speed was repeatedly varied from 0 to 29,000 rpm with the sealed air pressure maintained at 20.7 N/cm^2 abs (30 psia). The seal was inspected at the completion of the start-stop testing to determine sealing element and seat wear. The second phase of the test program subjected the seal to an endurance test. The first 22.5 hours simulated operating conditions of an actual engine seal position. An inspection was performed at the completion of this testing. The remainder of the endurance test was 52.5 hours in duration at increasingly severe operating conditions. Seal sliding velocity was varied from 167.6 to 243.8 m/s (550 to 800 ft/sec), and sealed pressures varied from 20.7 to 148.2 N/cm^2 (30 to 215 psia). Air leakage rates were measured at the various test conditions. During the endurance test, the seal was inspected three times: first, at the 22.5 hour point; next, at an unscheduled stop (33 hours) due to a bearing failure; and lastly at the completion of the test. Photographs were taken before testing, during inspections, and at the completion of the test. Details of the test program follow.

Build I - Start - Stop Operation

Test Description

Testing consisted of 176 starts and stops, accelerating from 0 to 29,000 rpm or 91.6 m/s (300.5 ft/sec). External air pressure was set at 20.7 N/cm^2 abs (30 psia) throughout the test. Air temperature outside the seal was maintained in the 335.9 to 341.5K (145° to 155°F) range. Seal air leakage was not measured. Primary sealing element wear and seal seat wear were documented at the completion of the test.

Pretest photographs documenting the appearance of the test seal are presented in Figures 7 and 8. Figure 7 illustrates the assembled seal, flanked by two spiral-groove seal seats. The seat on the right (AMS 6322 material) was used throughout the test program. The seat on the left was a backup design fabricated from TZM material (chosen for its thermal properties), but since the AMS6322 seat performed adequately, it was not tested. Figure 8 illustrates the disassembled seal components, showing from left to right: the seal housing with springs installed; the piston ring secondary seal and anti-rotation lugs; and the primary sealing element.

The posttest appearance of the seal components is shown in Figure 9 (overall appearance), Figure 10 (close-up of primary sealing element), and Figure 11 (close-up of the seal seat).

Test Results

Component Wear - No seal seat wear was measurable; however, wear of the dam and land area of the primary sealing element did occur. Wear results are compiled in Table 2. Surface profile traces of the monitored areas are presented in the appendix.

Character of Observed Wear (Sealing Element) -

Sealing Dam Wear - Wear was maximum at the dam inside diameter, and produced a converging leakage passage.

Land Wear (Opposing Spiral Grooves) - Wear was maximum in the central region of the land, minimum at the inside diameter, and at an intermediate level at the land outside diameter.

Discussion of Results

The amount of carbon primary ring wear observed, .00102 cm (.00040 in.), is significant with respect to altering the surface profile. The significance would have been greater had the self-acting geometry been located in the primary sealing element, as it was in designs evaluated during previous test programs (Reference 1). The variations in surface profile observed would be expected to negatively influence the pressure-generating capacity of the spiral-groove geometry. Dam wear is typical of that observed during previous programs (Reference 1) and has been explained as the result of the abrasive action of contaminants in the sealed medium (air), which are hypothesized to accumulate at the sealing dam inside diameter. The land wear can be explained in a similar manner since the dead end region of the spiral grooves would be expected to

Figure 7. Assembled Seal, Prior to Test.

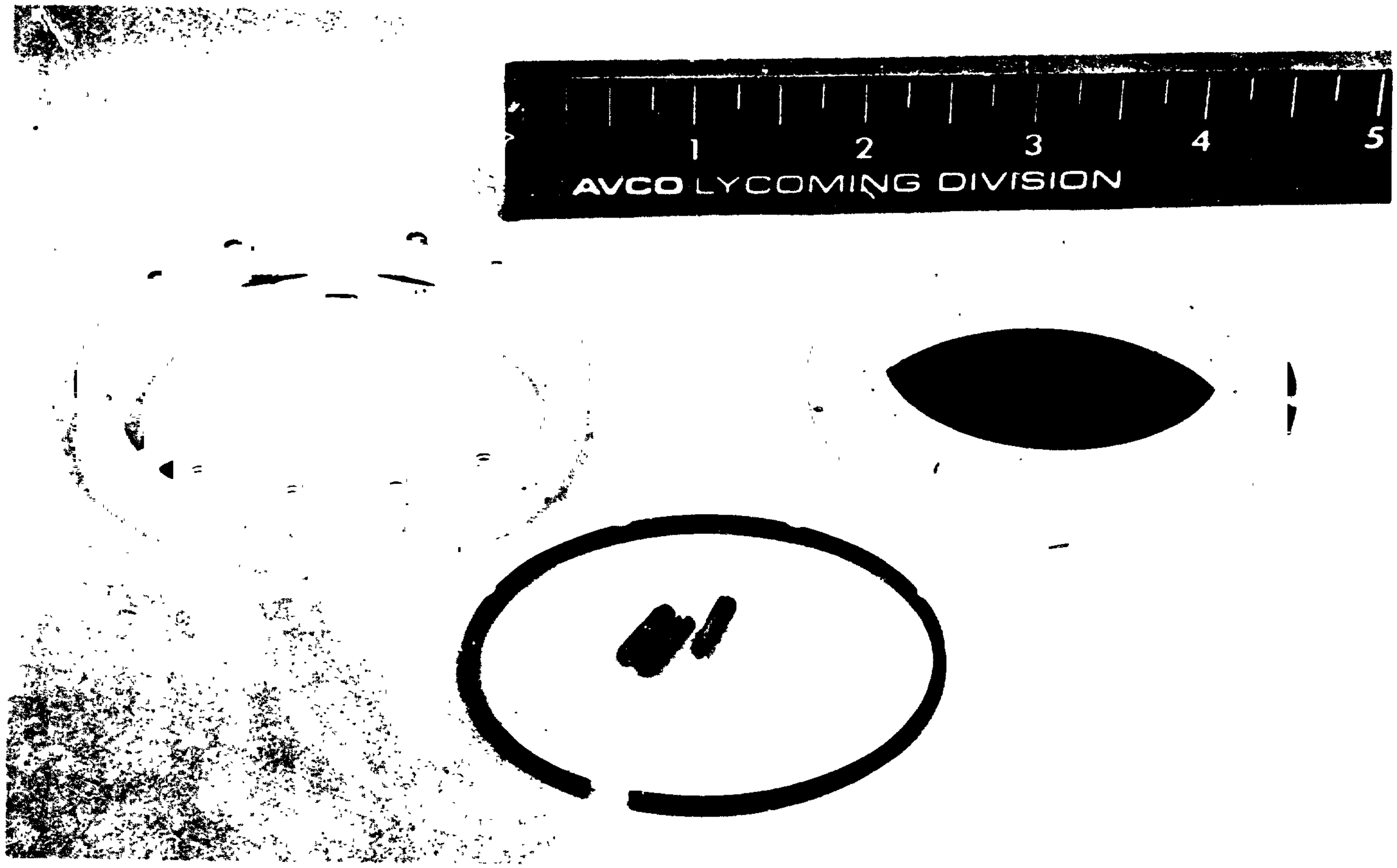

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Figure 8. Disassembled Seal, Prior to Test.

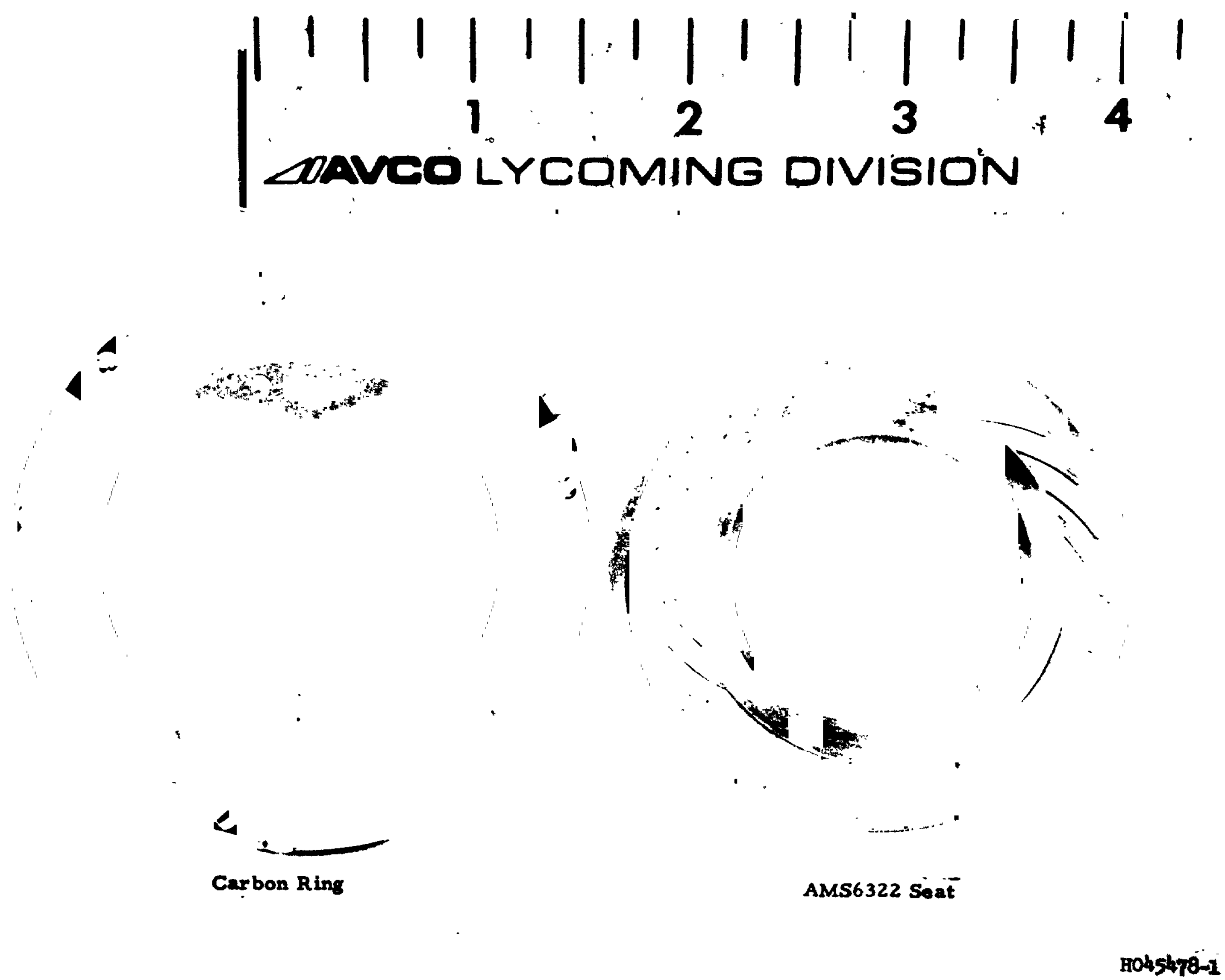

Figure 9. Assembled Seal, After Start-Stop Test.

Figure 10. Primary Sealing Element, After Start-Stop Test

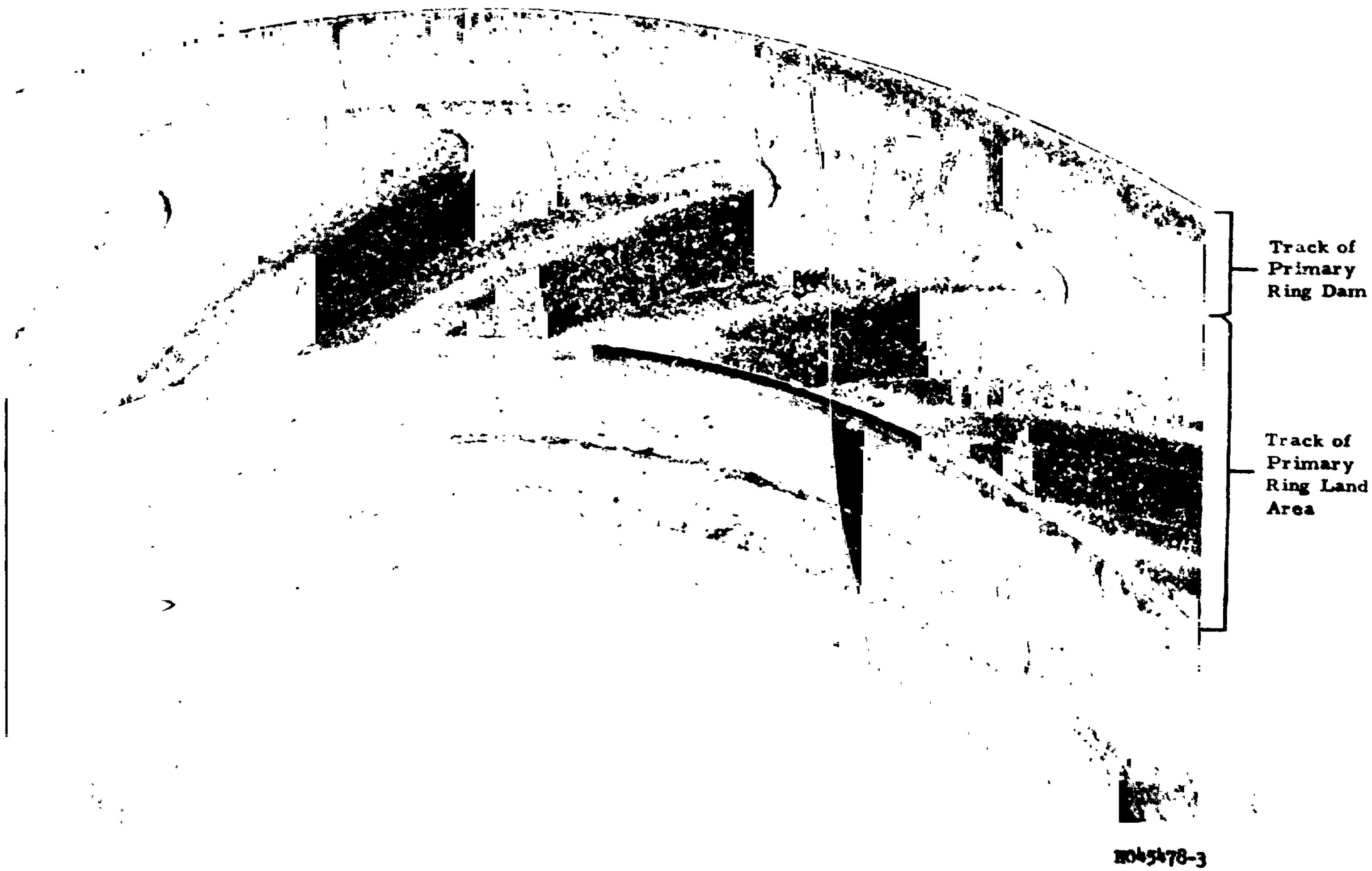

Figure 11. Seal Seat. After Start-Stop Test.

TABLE 2. TABULATED SEAL WEAR

PRIMARY SEALING ELEMENT NO. 2

ITEM/ LOCATION	FEATURE	NEW cm (in)	AFTER 176 STARTS AND STOPS cm (in)	AFTER RUNS 1-15 cm (in)
LOCATION 1	LENGTH OF DAM	1.29032 (.5080)	1.28930 (.5076)	1.28854 (.507[illegible])
	LENGTH OF LAND	1.29032 (.5080)	1.28930 (.5076)	1.29007 (.5079)
	LOCAL SURFACE VARIATION OF LAND	.00004 (.000014)	.00023 (.000090)	.00025 (.00010)
	LOCAL SURFACE VARIATION OF DAM	.00004 (.000014)	.00051 (.00020)	.00170 (.00067)
LOCATION 2	LENGTH OF DAM	1.29032 (.5080)	1.28930 (.5076)	1.28930 (.5076)
	LENGTH OF LAND	1.29032 (.5080)	1.28930 (.5076)	1.29032 (.5080)
	LOCAL SURFACE VARIATION OF LAND	.00005 (.000018)	.00069 (.00027)	.00069 (.000270)
	LOCAL SURFACE VARIATION OF DAM	.00006 (.000024)	.00013 (.00005)	.00216 (.00085)
LOCATION 3	LENGTH OF DAM	1.29032 (.5080)	1.28930 (.5076)	1.28930 (.5076)
	LENGTH OF LAND	1.29032 (.5080)	1.28930 (.5076)	1.28905 (.5075)
	LOCAL SURFACE VARIATION OF LAND	.00004 (.000016)	.00022 (.000085)	.00102 (.0004)
	LOCAL SURFACE VARIATION OF DAM	.00003 (.000011)	.00036 (.00014)	.00318 (.00125)

PRIMARY SEALING ELEMENT NO. 3

ITEM/ LOCATION	FEATURE	NEW cm (in)	AFTER RUN 22 cm (in)	AT END OF TEST cm (in)
LOCATION 1	LENGTH OF DAM	1.2884 (.50725)	1.2880 (.5071)	1.2880 (.5071)
	LENGTH OF LAND	1.2884 (.50725)	1.2880 (.5071)	1.2880 (.5071)
	LOCAL SURFACE VARIATION OF LAND	.00003 (.000013)	.0008 (.00030)	.0043 (.00170)
	LOCAL SURFACE VARIATION OF DAM	.00003 (.000010)	.0002 (.00007)	.0005 (.0002)
LOCATION 2	LENGTH OF DAM	1.2884 (.50725)	1.2885 (.5073)	1.2880 (.5071)
	LENGTH OF LAND	1.2884 (.50725)	1.2885 (.5073)	1.2880 (.5071)
	LOCAL SURFACE VARIATION OF LAND	.00002 (.000008	.00064 (.00025)	.00457 (.0018)
	LOCAL SURFACE VARIATION OF DAM	.00002 (.000007)	.00005 (.00002)	.00038 (.0015)
LOCATION 3	LENGTH OF DAM	1.2884 (.50725)	1.2885 (.5073)	1.2880 (.5071)
	LENGTH OF LAND	1.2884 (.50725)	1.2885 (.5073)	1.2880 (.5071)
	LOCAL SURFACE VARIATION OF LAND	.00002 (.000008)	.00051 (.00020)	.00464 (.00183)
	LOCAL SURFACE VARIATION OF DAM	.00002 (.000006)	.00010 (.00004)	.00032 (.00012[illegible])

trap particles of a size range on the order of the groove depths. From this as ., grooves which are fed radially inward should be superior to the grooves which are fed radially outward as used in this design.

Build II - Endurance Test - Engine Simulation Phase (22.5 Hours)

Test Description

Testing consisted of obtaining air leakage data for test points indicated in Runs 1 through 15 which are illustrated in Table 3. The test points duplicate operating conditions occurring in an actual engine seal position. Seal sliding velocity was varied from 91.6 m/s (300 ft/sec) to 175.3 m/s (575 ft/sec) and sealed pressure ranged between 20.7 N/cm^2 abs (30 psia) and 31.0 N/cm^2 abs (45 psia). Sealed air temperature varied between 385.4 and 551K (234^o and 532^{o}F). The seal assembly from the previous test sequence was utilized for this portion of the endurance test.

Test Results

Component Wear - Reduction in spiral-groove depth on the order of .00025 cm (.00010 in.) was observed at the 4.910 cm (1.933 in.) diameter location. Essentially no change was observed at the 5.160 cm (2.031 in.) diameter location. Figure 12 illustrates the overall condition of the seal seat after test. Figure 13 illustrates carbon build-up forming on the groove edge of the seat. Table A-1 in the appendix illustrates actual measurements for each groove. An overall reduction in primary sealing element length was observed, along with a change in surface characteristics. The results of the wear are compiled in Table 2. Only one of three monitored locations of the land area indicated a length reduction of .00102 cm (.00040 in.).

Local surface variations of the dam and land areas both increased in magnitude when compared to that observed during start/stop testing. Local surface variations up to .00051 cm (.0002 in.) were observed on the dam. Maximum land surface variation was .00069 cm (.00027 in.). Surface profile traces of the dam and land area are presented in the appendix. Figure 14 and 15 show the condition of the assembled seal after test. Figure 16 illustrates a close-up view of the sealing dam and land area. Local deposits are apparent forming at the sealing dam inside diameter.

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TABLE 3. SUMMARY OF TEST POINTS

RUN	SEALED PRESSURE N/cm² abs (psia)	SHAFT SPEED RPM	SURFACE SPEED M/S (ft/sec)	AIR LEAKAGE kg/s	AIR LEAKAGE (lb/sec)	AIR LEAKAGE SCFM	DURATION HOURS
0	20.7 (30.0)	0-29000-0	91.4 (300)	.00030	(.00060)	.47	1.5
1	20.7 (30.0)	29000	91.4 (300)	.00030	(.00060)	.47	
2	27.6 (40.0)	38599	121.9 (400)	.00030	(.00060)	.47	
3	31.0 (45.0)	55486	175.3 (575)	.00030	(.00060)	.47	
4	20.7 (30.0)	28949	91.4 (300)	.00030	(.00060)	.47	
5	27.6 (40.0)	38599	121.9 (400)	.00030	(.00060)	.47	
6	31.0 (45.0)	55486	175.3 (575)	.000[illegible]5	(.00136)	1.47	
7	20.7 (30.0)	28949	91.4 (300)	.00040	(.00089)	.79	
8	27.6 (40.0)	38599	121.9 (400)	.00109	(.00240)	1.87	
9	31.0 (45.0)	55486	175.3 (575)	.00198	(.00437)	3.43	
10	20.7 (30.0)	28949	91.4 (300)	.00072	(.00159)	1.25	
11	27.6 (40.0)	38599	121.9 (400)	.00146	(.00322)	2.53	
12	31.0 (45.0)	55486	175.3 (575)	.00234	(.00515)	4.04	
13	20.7 (30.0)	28949	91.4 (300)	.00073	(.00161)	1.27	
14	27.6 (40.0)	38599	121.9 (400)	.00106	(.00234)	1.83	
15	31.0 (45.0)	55486	175.3 (575)	.00331	(.00730)	5.73	
16	31.0 (45.0)	52900	167.0 (548)	.00030	(.00066)	.47	
17	79.3 (115.0)	52900	167.0 (548)	.00042	(.00093)	.76	
18	79.3 (115.0)	57899	182.9 (600)	.00133	(.00293)	2.30	
19	79.3 (115.0)	67548	213.4 (700)	.00132	(.00290)	2.28	
20	113.8 (165.0)	55486	175.3 (575)	.00202	(.00446)	3.50	
21	113.8 (165.0)	57898	182.9 (600)	.00195	(.00430)	3.38	
22	113.8 (165.0)	67548	213.4 (700)	.00240	(.00529)	4.15	
23	148.2 (215.0)	55486	175.3 (575)	.00288	(.00634)	4.98	
24	148.2 (215.0)	57898	182.9 (600)	.00280	(.00618)	4.85	

TABLE 3 - Continued

RUN	SEALED PRESSURE N/cm^2 abs (psia)	SHAFT SPEED RPM	SURFACE SPEED M/S (ft/sec)	AIR LEAKAGE kg/s	AIR LEAKAGE (lb/sec)	AIR LEAKAGE SCFM	DURATION HOURS
25	148.2 (215.0)	67548	213.4 (700)	.00261	(.00575)	4.51	1.5
32	79.3 (115.0)	57898	182.9 (600)	.00183	(.00404)	3.17	
33	79.3 (115.0)	67548	213.4 (700)	.00166	(.00365)	2.87	
34	113.8 (165.0)	57898	182.9 (600)	.00304	(.00670)	5.26	
35	113.8 (165.0)	67548	213.4 (700)	.00294	(.00647)	5.08	
36	148.2 (215.0)	57898	182.9 (600)	.00363	(.00800)	6.28	
37	148.2 (215.0)	67548	213.4 (700)	.00204	(.00449)	3.52	
42	148.2 (115.0)	57898	182.9 (600)	.00150	(.00331)	2.60	
43	148.2 (115.0)	67548	213.4 (700)	.00198	(.00436)	3.42	
44	113.8 (165.0)	57898	182.9 (600)	.00120	(.00265)	2.08	
45	113.8 (165.0)	67548	213.4 (700)	.00372	(.00821)	6.44	
46	148.2 (215.0)	57898	182.9 (600)	.00177	(.00390)	3.06	
47	148.2 (215.0)	67548	213.4 (700)	.00164	(.00361)	2.83	
	DATA POINTS 26, 27, 28, 29, 30, 31, 38, 39, 40, 41, 48, 49 50, 51 WERE REDEFINED AS LISTED BELOW:						
A	127.6 (185.0)	60200	190.20 (624)	.00278	(.00612)	4.80	6.0
B	113.8 (165.0)	57898	182.88 (600)	.00335	(.00739)	5.80	6.25
C	148.2 (215.0)	57898	182.88 (600)	.00121	(.00268)	2.10	.75
D	113.8 (165.0)	67548	213.36 (700)	.00367	(.00811)	6.36	1.[illegible]
E	113.8 (165.0)	72300	228.30 (749)	.00337	(.00743)	5.83	6.5
F	113.8 (165.0)	75500	238.35 (782)	.00121	(.00268)	2.10	.25
G	113.8 (165.0)	76200	240.79 (790)	.00364	(.00803)	6.30	1.0
H	113.8 (165.0)	77200	243.84 (800)	.00364	(.00803)	6.30	2.0
I	148.2 (215.0)	70700	223.42 (733)	.00138	(.00306)	2.40	.25

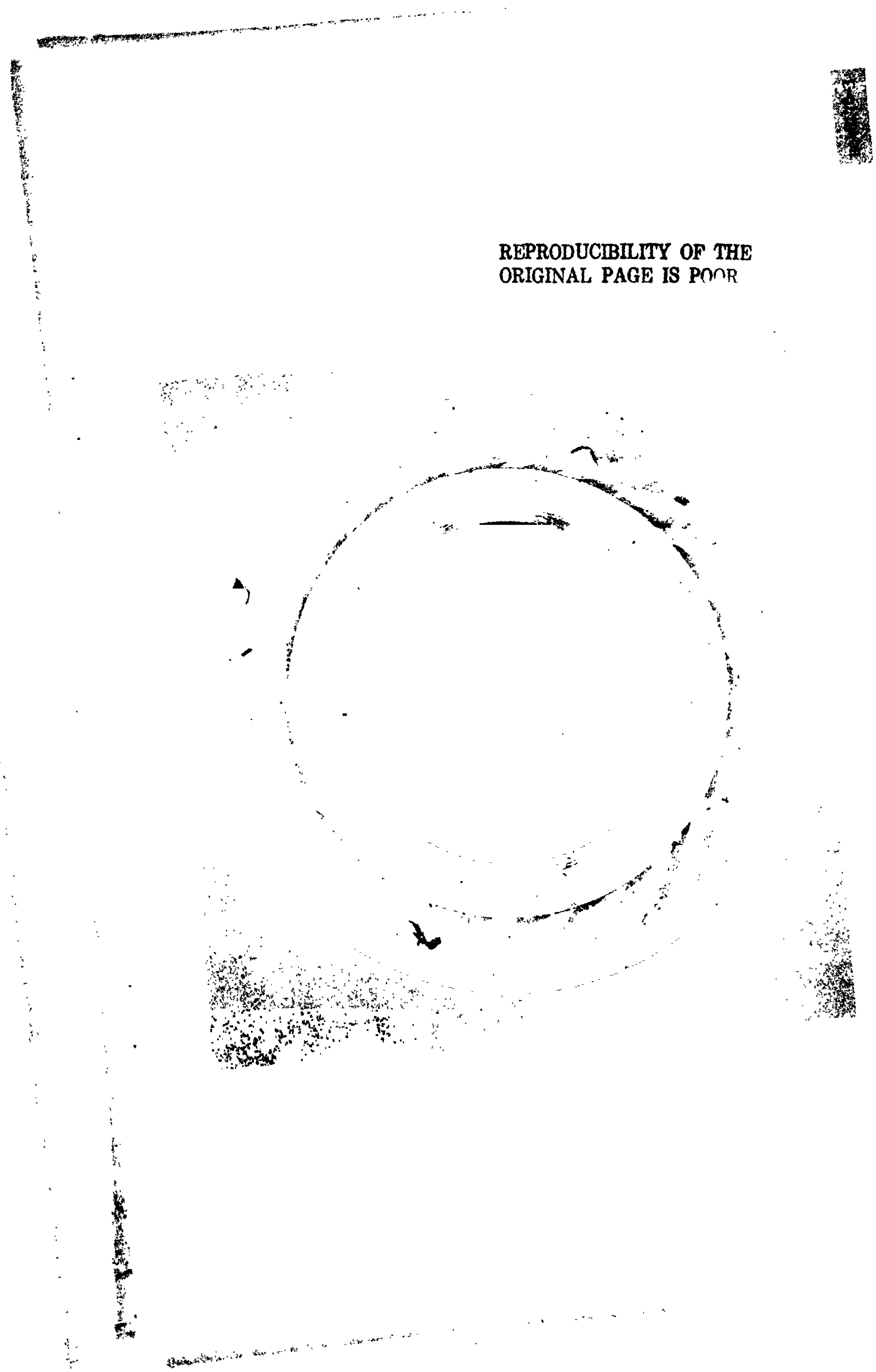

Figure 12. Seal Seat After 22.5 Hour Endurance Testing.

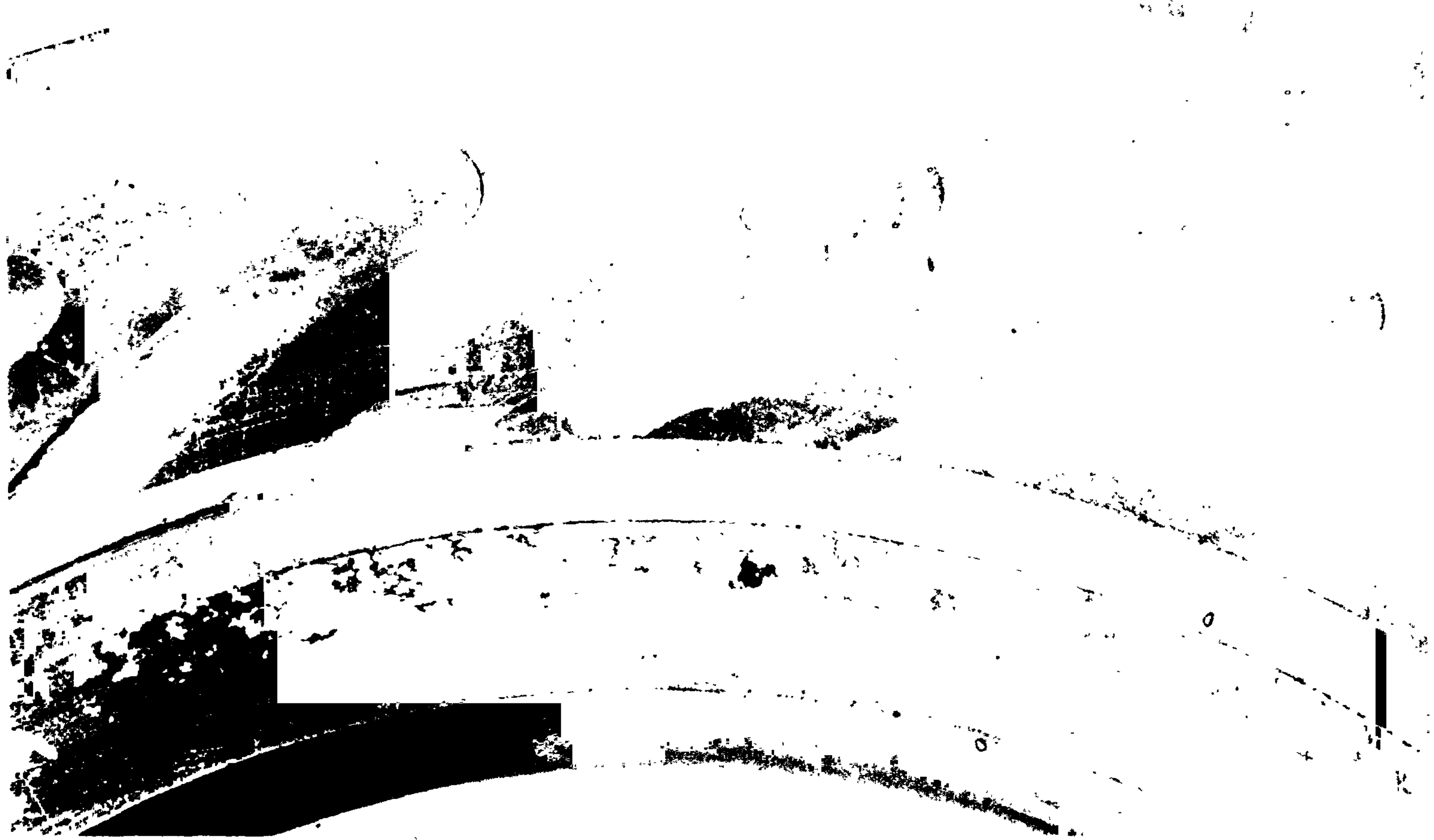

Figure 13. Close-up of Seal After 22.5 Hour Endurance Test.

Figure 14. Seal Assembly (Front) After 22.5 Hour Endurance.

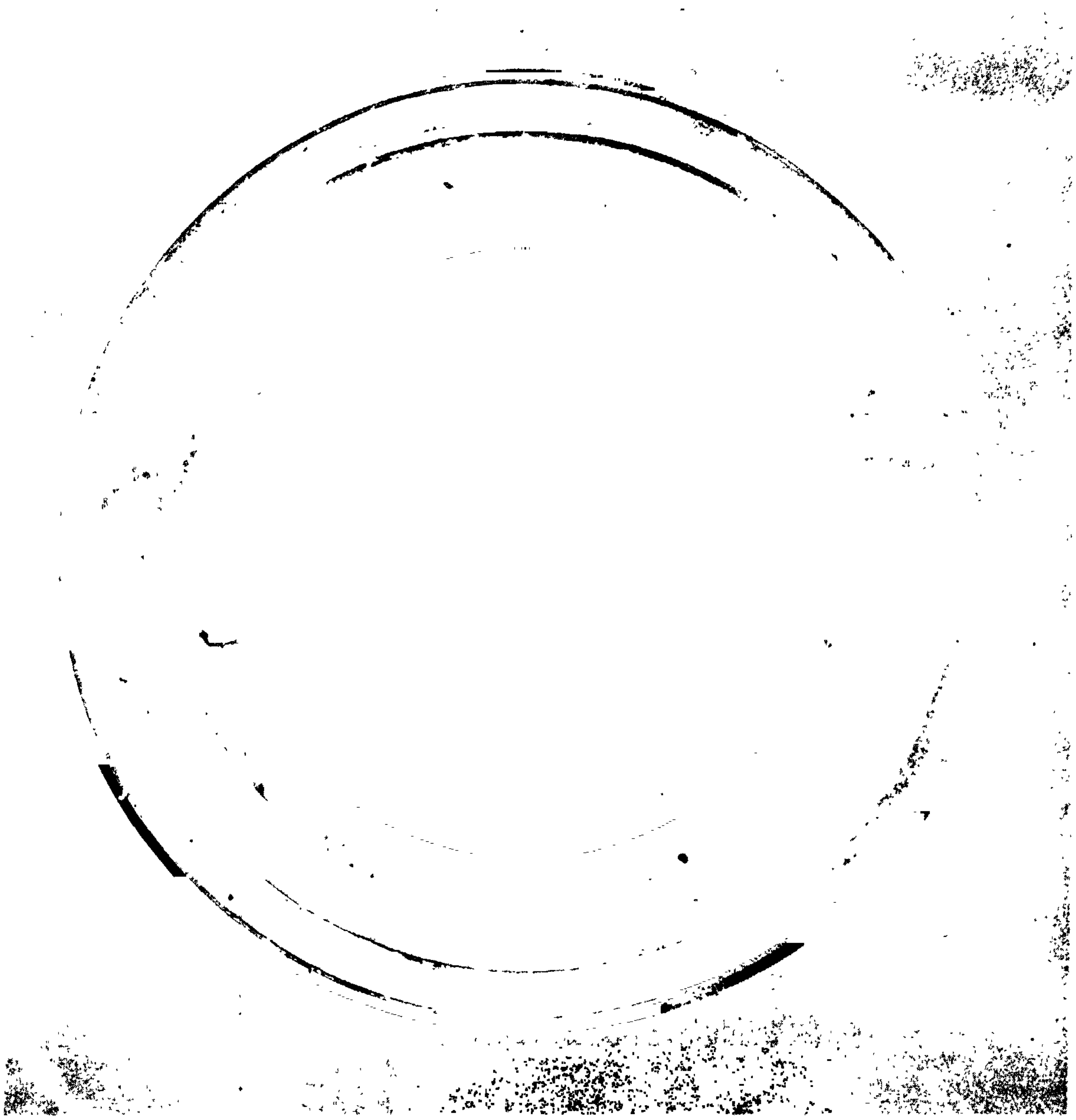

Figure 15. Seal Assembly (Rear) After 22.5 Hour Endurance Test.

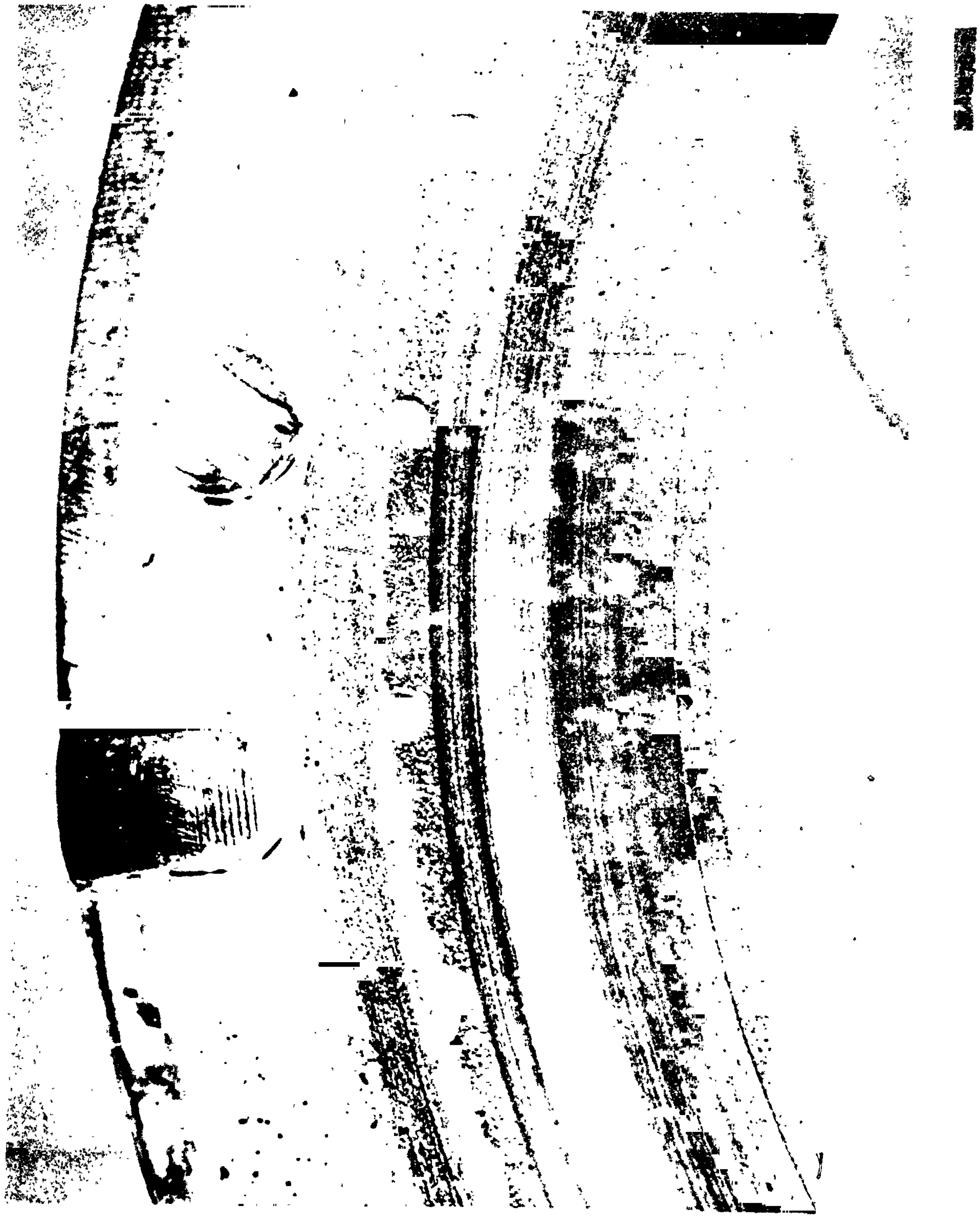

Figure 16. Primary Sealing Element After 22.5 Hour Endurance Test.

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Character of Observed Wear (Sealing Elements) -

Sealing Dam Wear - Wear was maximum at inside diameter and produced a converging leakage passage similar to that observed after Build I testing.

Carbon Ring Land Wear - Wear occurred both in the region opposing the terminus of spiral grooves and at the land inside diameter. Wear in these regions was of similar magnitudes.

Seal Air Leakage - Air leakage measurements throughout this and subsequent phases of the test program were impaired due to a marginal operating clearance between the primary sealing element and the seal housing. This was due to a combination of the reduction of the existing clearance due to press fit deflections of the seal housing which resulted from installation into the test rig and also the deflections caused by exposure to the various pressures and temperatures of the test points. Although no binding occurred at assembly, further deflections apparently resulting from the operating conditions were sufficient to cause intermittent binding of the primary sealing element during testing. Often, a low and high leakage characteristic were observed at a particular test point. On all air leakage plots, an estimated air leakage characteristic is presented (dashed line) along with actual data points. Data groups with significantly varying leakage rates for a specific operating condition are tabulated in Table 3, but are not plotted. Air leakage results from this phase of testing are presented in Figure 17.

Discussion of Results

The overall reduction of the length of the primary sealing element was not significant, but the magnitude of variations in the local surface increase significantly. An increase in leakage rate was observed after the sixth run. This can be due to either changes in seal pressure distribution resulting from the surface variation or the tendency of sealing element to bind, as previously described. Because of this, air leakage rates are high considering the sealed pressure levels tested.

Build III Endurance Operation - Increased Pressures and Speeds

Test Description

Testing consisted of obtaining air leakage data for test points indicated by Runs 16 through 47 and for redefined test points indicated Runs A

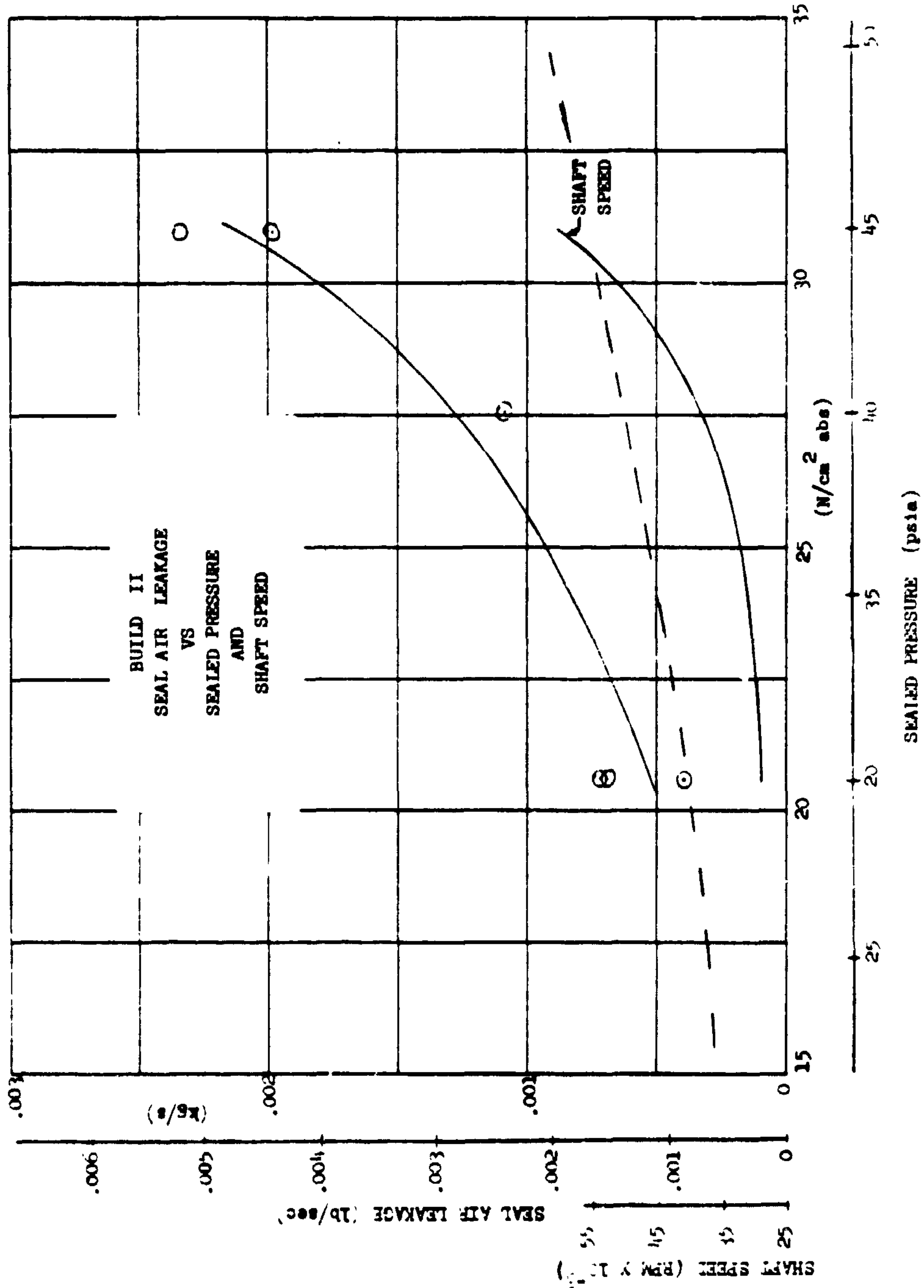

Figure 17. Air Leakage for Runs 1 Through 15.

through I. Redefinition of test points was necessary due to foregoing operation above 148.2 N/cm^2 abs (215 psia) because of high pressure air compressor problems. Build III testing was interrupted at Run 22 by a test rig bearing failure, necessitating a fourth build to complete testing. Endurance test seal operating conditions were varied between sliding velocities of 175.3 m/s and 243.8 m/s (575 ft/sec and 800 ft ft/sec) and sealed pressures of 31.4 and 150.2 N/cm^2 abs (45 and 215 psia). Maximum air temperature reached was 589 K (600°F). The primary sealing element was changed prior to the beginning of Build III operation due to chipping of the sealing dam occurring during inspection. The new primary sealing element was used for the balance of the endurance test. The test rig housing receiving the seal assembly was reworked as shown by the dashed lines in Figure 2 to reduce seal housing deflections in order to minimize binding of primary sealing element.

Test Results (Build III)

Component Wear - The test rig was disassembled after a failure of the support bearing during Run 22. The test seal components were undamaged. At this time the sealing element and seal seat wear were redocumented. Spiral-groove depth increased approximately .00015 cm (.00006 in.), indicating the probable existence of a surface deposit. Actual dimensions for each groove are presented in the appendix. The seal seat, illustrated in Figure 18 exhibits an appearance tending to confirm the existence of a surface deposit. The primary sealing element exhibited axial wear at one location of the sealing dam and the land of .00038 cm (.00015 in.). Wear was not measurable at the remaining two locations. Local surface variations of the sealing dam increased from a maximum of .00003 cm (.00001 in.) to .00018 cm (.00007 in.). The surface variation of the land region increased from a maximum of .00003 cm (.000013 in.) to .00076 cm (.00030 in.). The sealing element is illustrated in Figure 19. A region of chipped carbon material can be observed at the carbon sealing element inside diameter. Since the chip was at the location of the entrance of the spiral grooves, it was considered superficial, and the carbon sealing element was used for the balance of the endurance test.

Character of Observed Wear (Sealing Element) -

Sealing Dam Wear - Wear was slight and assumed no characteristic profile as was observed previously (sealing element new prior to test).

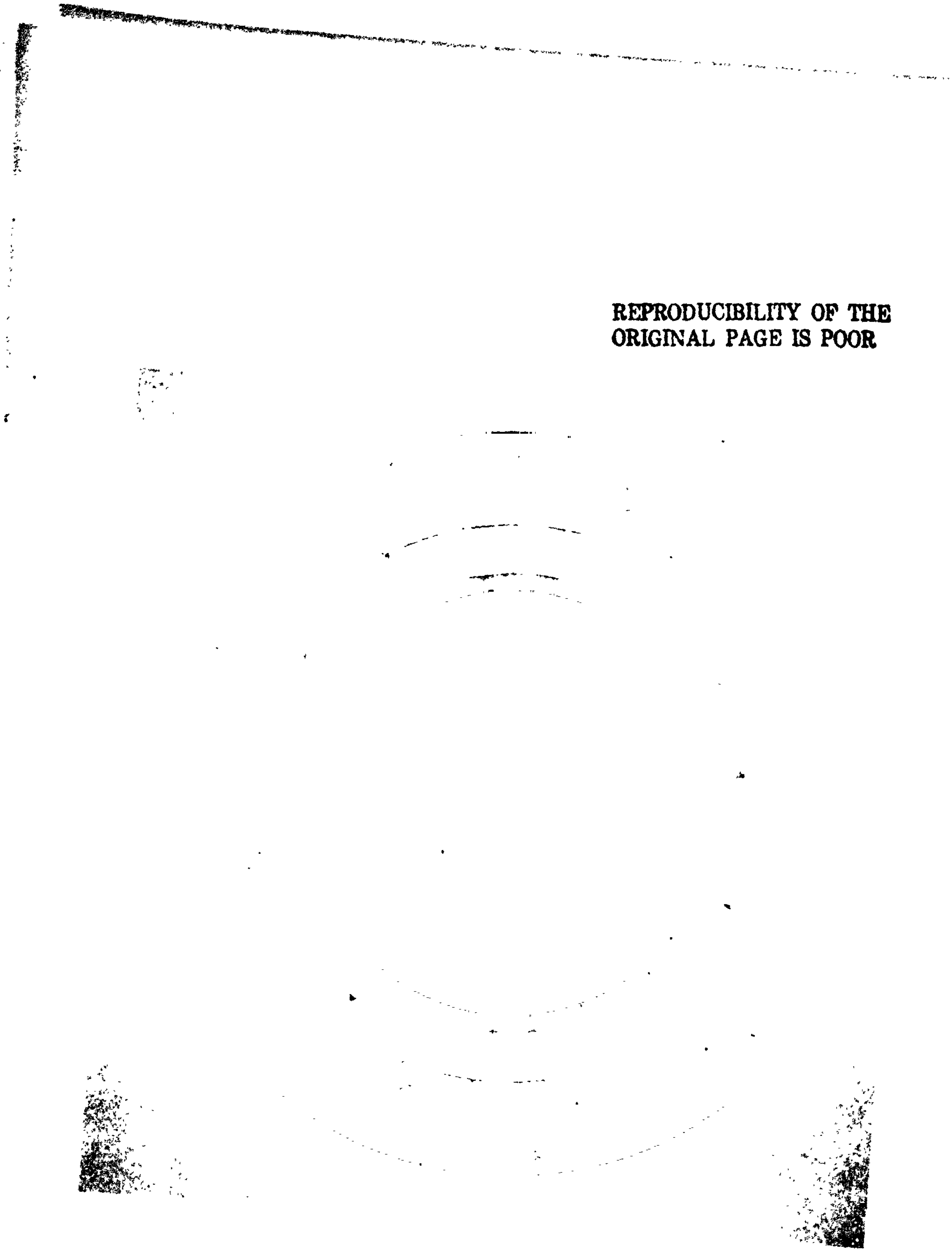

Figure 18. Seal Seat After Run 22.

Figure 19. Primary Sealing Element After Run 22.

Land Wear - Wear was maximum at the inside diameter with slight indications of wear in the region opposing the terminus of the spiral grooves.

Seal Air Leakage - Air leakage data is presented in Figure 20, along with the balance of the data accumulated during the remainder of the endurance test (Build IV). Endurance test results are discussed at the completion of Build IV testing.

Build IV - Continued Endurance Operation - Increased Pressures and Speeds

Test Description

Testing consisted of obtaining data for the remaining Runs 23 through 47 and A through I. Seal components from Build III were used to complete the endurance test.

Test Results

Component Wear - The chrome-carbide coating on the seal seat showed evidence of abnormal rubbing and heat generation. Figure 21 illustrates this condition. Measurements of spiral grooves indicated an increase of approximately .00025 cm (.0001 in.) in depths resulting from the disturbed condition of the surface of the chrome-carbide coating. An anomaly during test rig operation manifested as a step decrease in air leakage observed during Run 37, and may have indicated momentary contact between the seat and the sealing element, causing this surface damage.

Carbon primary ring sealing dam length and land length were reduced in two locations by .00051 cm (.00020 in.). The remaining location showed no change.

Local surface variations of the dam increased to a maximum of .00051 cm (.00020 in.) from a previous maximum of .00018 cm (.00007 in.). Local surface variations of the land increased from a previous maximum of .00076 cm (.00030 in.) to .00465 cm (.00183 in.). The appearance of the assembled seal and seat is shown in Figures 22 and 23. A close-up of the sealing dam and land area is shown in Figure 24. Figures 25 and 26 illustrate the disassembled seal components.

Character of Observed Wear - Both the sealing dam wear and land wear were greatest at their respective inside diameters and minimum at the

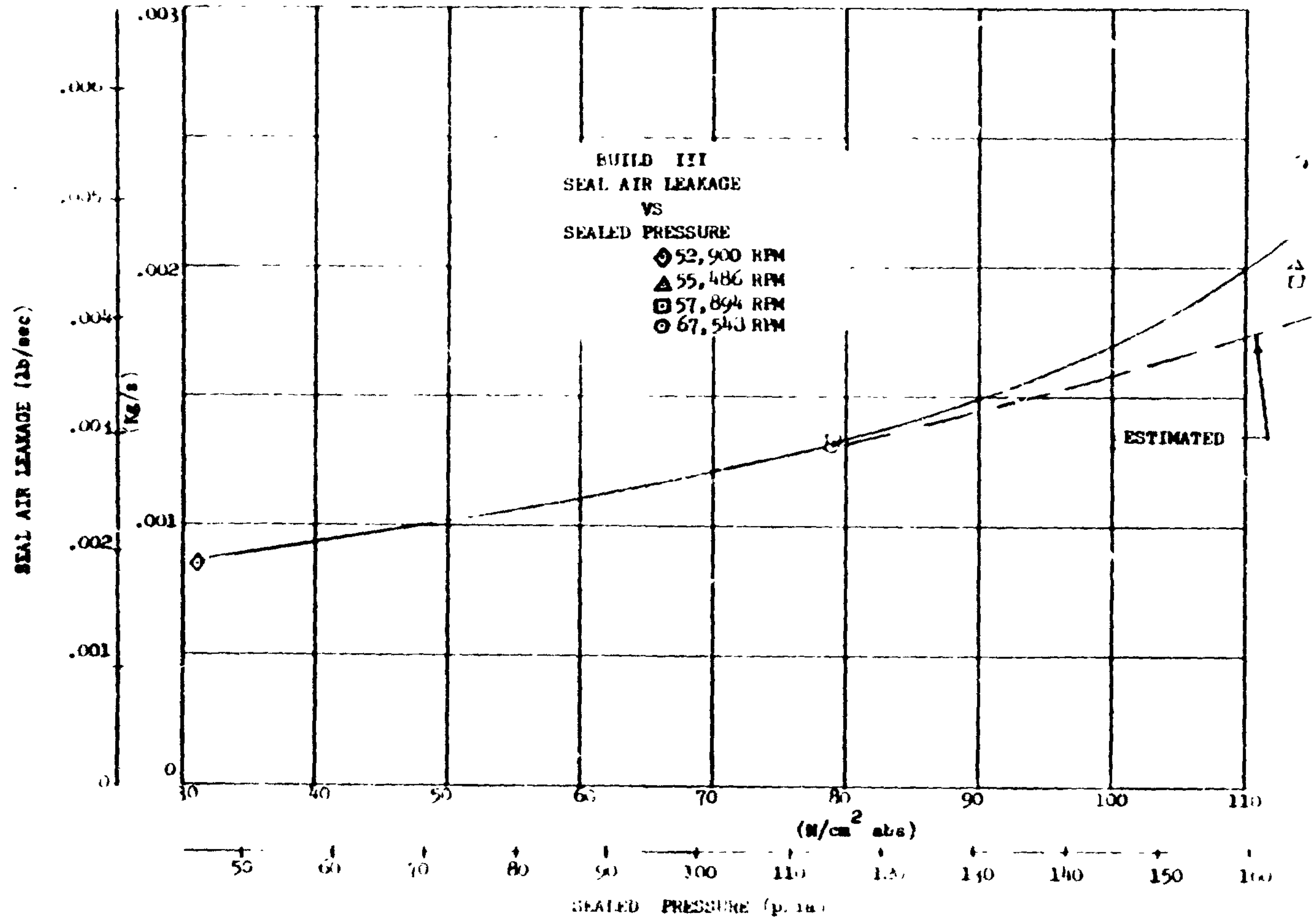

Figure 20. Air Leakage for Runs 16-22.

Figure 21. Seal Seat at Completion of Endurance Test.

Figure 22. Assembled Seat at Completion of Endurance Test.

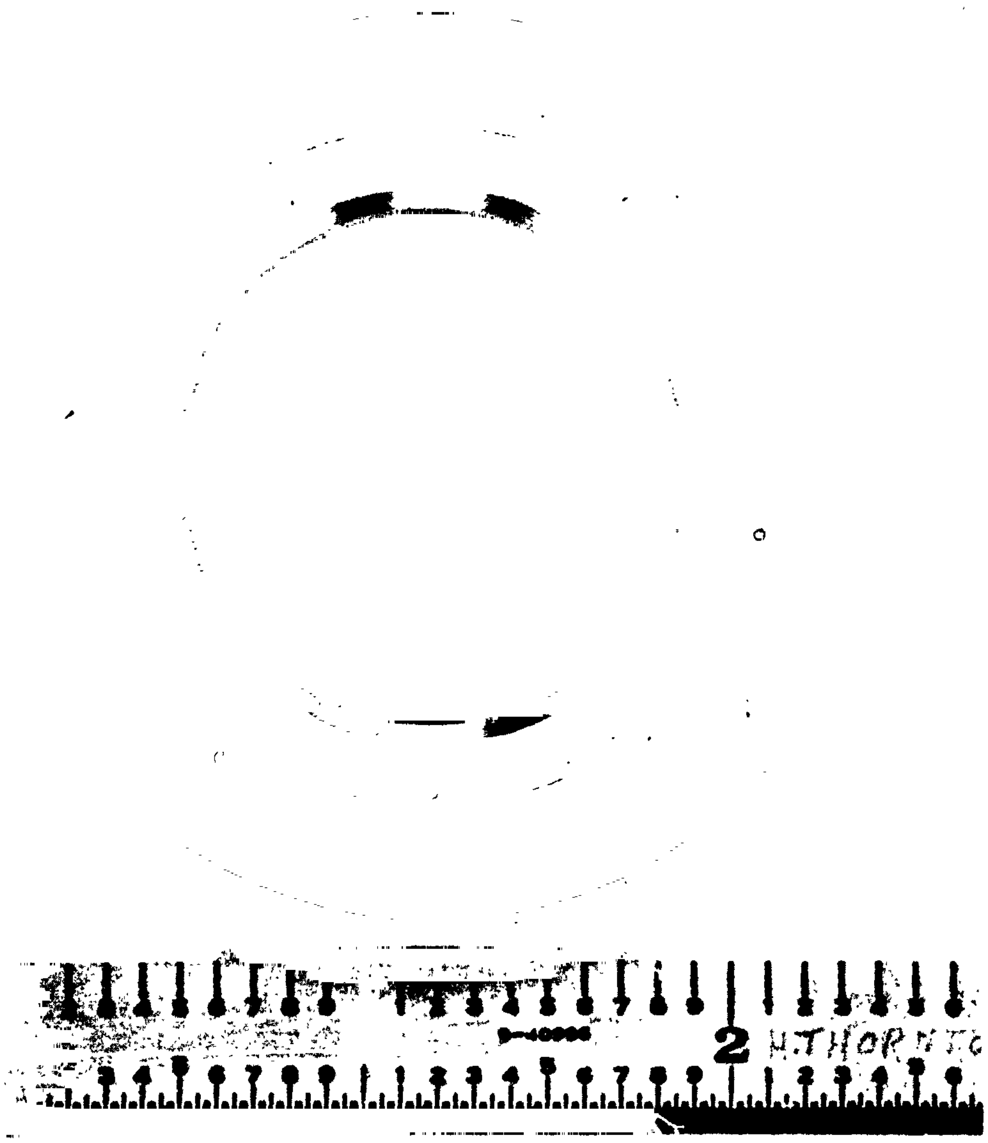

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Figure 23. Seal Seat at Completion of Endurance Test.

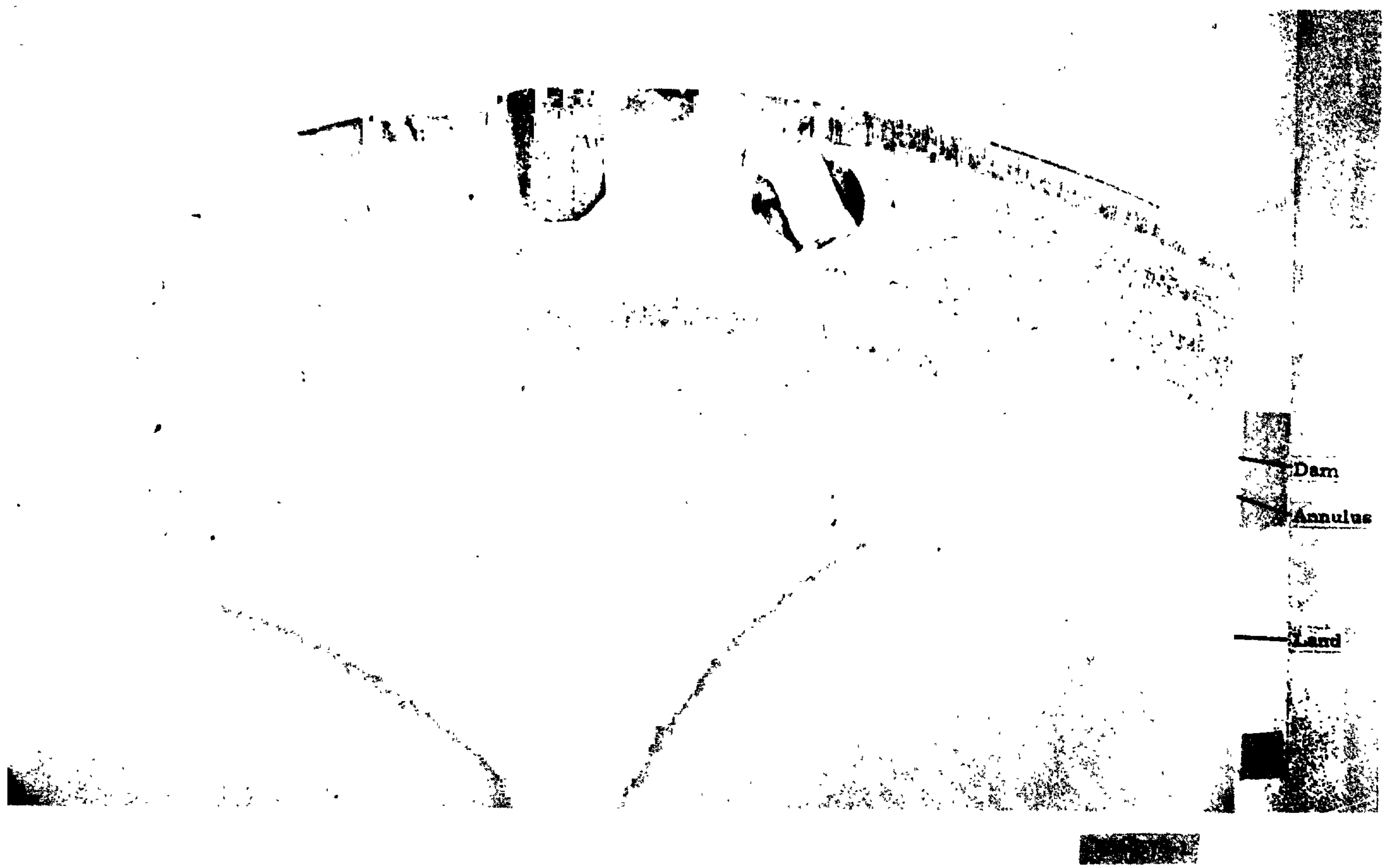


Figure 24. Sealing Dam and Land After Endurance Test.

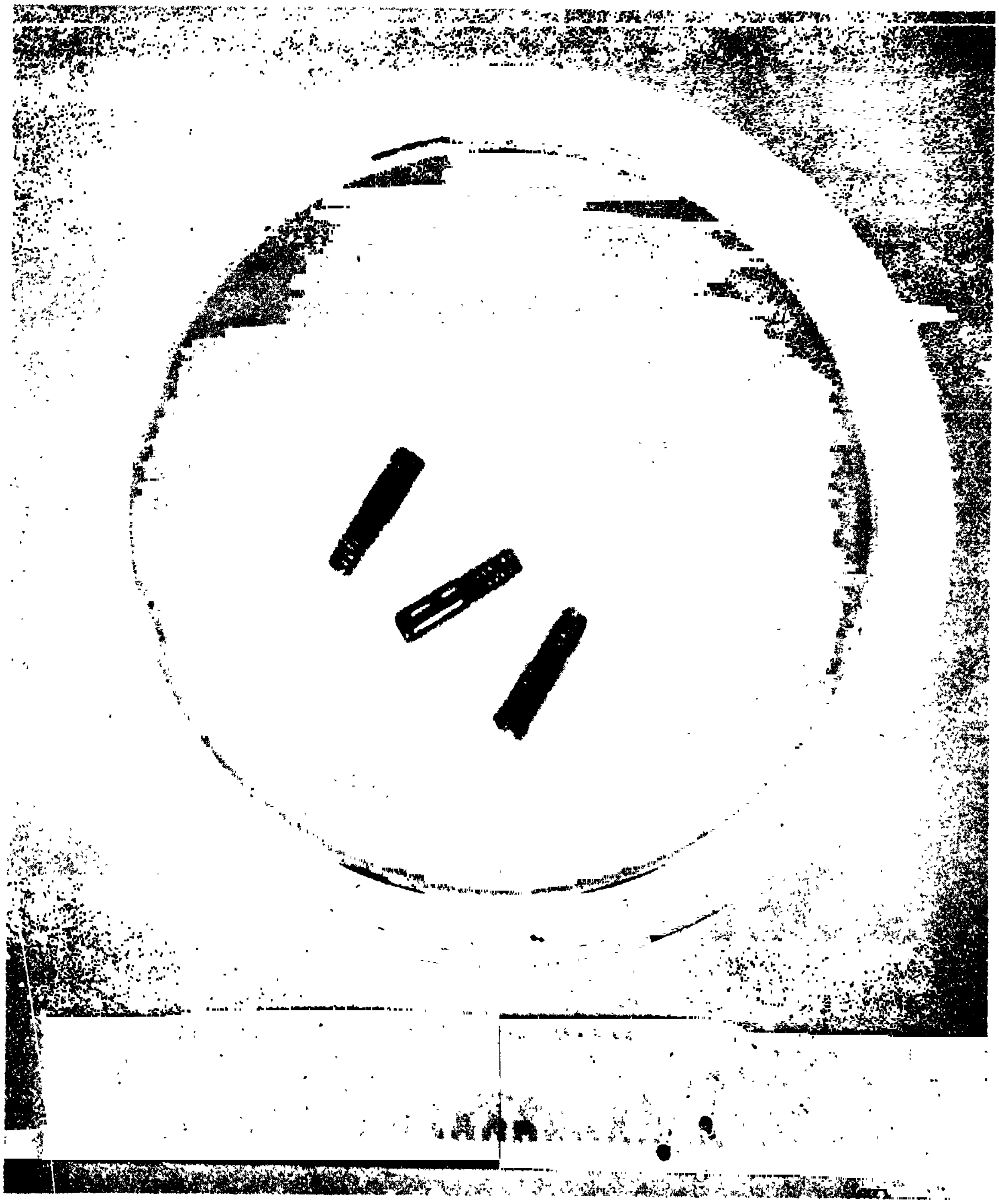


Figure 25. Seal Housing After Endurance Test.

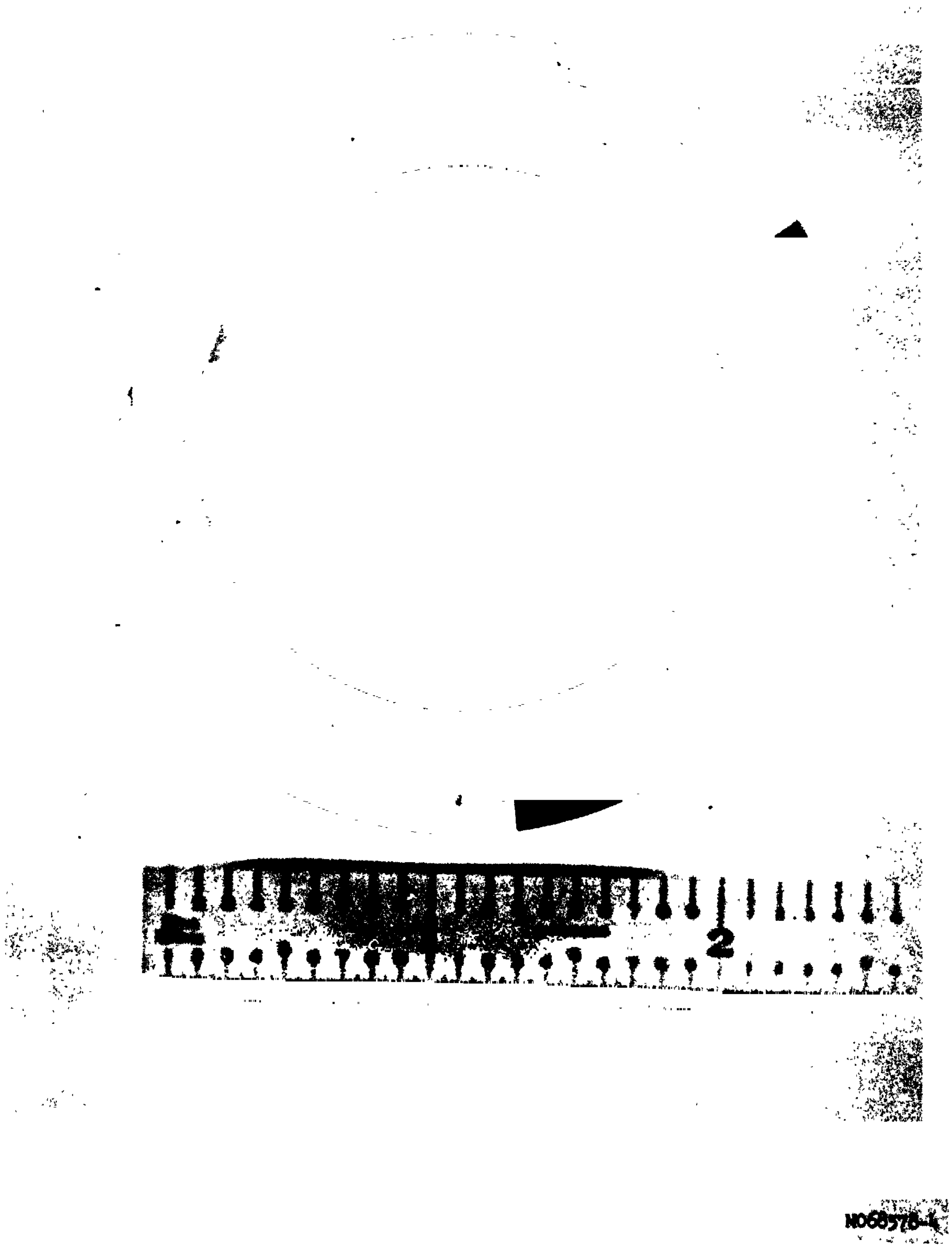


Figure 26. Rear View of Primary Sealing Element After Endurance Test.

outside diameters with a gradual transition between them. Actual wear traces are presented in the appendix.

Seal Air leakage - Air leakage is presented in Figure 27. A significant variation, attributed to a sticking sealing element, is apparent in the plotted data. An estimated air leakage characteristic for a free sealing element is shown as a dashed curve on the graph. The estimated leakage rate is at a level considered acceptable for gas turbine engine operation.

Discussion of Results

Wear measurements indicate a small reduction in length of the carbon ring primary sealing element, but the local surface variations of both the land and dam regions increased throughout the test to significant levels. The greatest increase in local surface variations occurred during the portion of the endurance test after Run 22 where speeds and pressure were maximum and where an operational contact of seal seat and sealing element is suspected to have occurred. Less of a change in local surface variation was observed at the inspection performed at Run 22, where sealed pressures were limited to 113.8 N/cm^2 abs (165 psia) and speeds to 182.9 m/s (600 ft/sec), and no apparent operational contact between the seal seat and sealing element occurred. The wear rate of the primary sealing element over the course of the endurance test (76.5 hours total running time) was 4.98×10^{-6} cm/hr (1.96×10^{-6} in./hr). Assuming local surface variations would not impair seal operation, a reduction of sealing element length of .00498 cm (.00196 in.) would be expected per 1000 hours of operation.

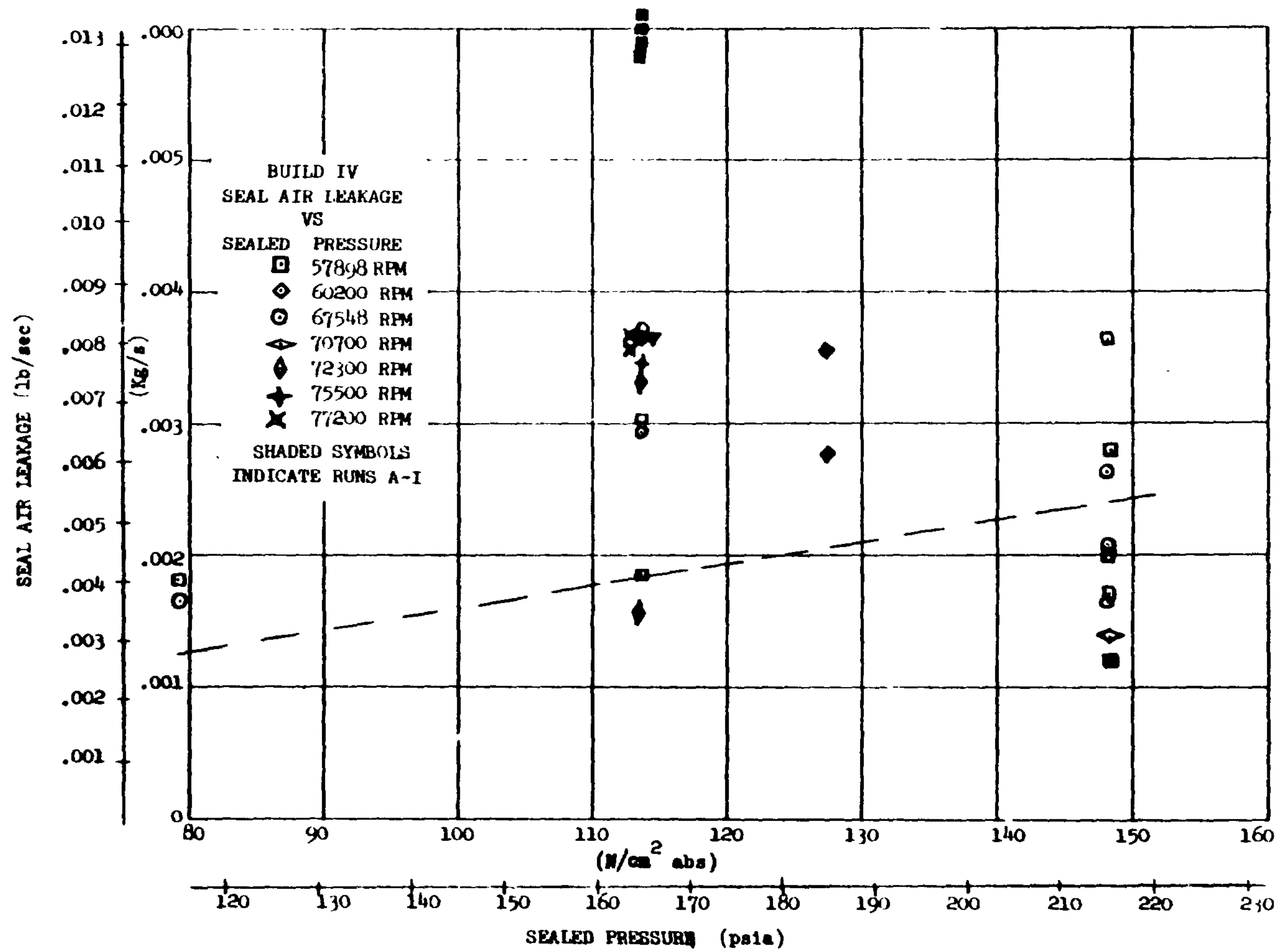


Figure 27. Seal Air Leakage for Runs 23 Through 47 and A Through I.

CONCLUSIONS

- The test seal demonstrated the ability to operate successfully at surface speeds up to 243.8 m/s (800 ft/sec) and sealed pressures to 148.2 N/cm^2 abs (215 psia).

- Fluctuating air leakage rates were observed and are suspected to be the result of binding during operation between the seal housing inside diameter and the adjacent primary sealing element outside diameter.

- The measured seal wear rate during the endurance test was at an acceptable level of 4.98×10^{-6} cm/1000 hr (1.96×10^{-6} in./1000 hr.).

- Significant variations in primary sealing element surface profile were observed during testing, and will result in seal operation with non-flat surfaces on primary sealing element. This may be due to abrasive wear or could be related to the suspected binding between the primary sealing element and seal housing.

- Wear occurring during start - stop operation is not as significant as local surface profile changes which were observed during steady state operation.

APPENDIX

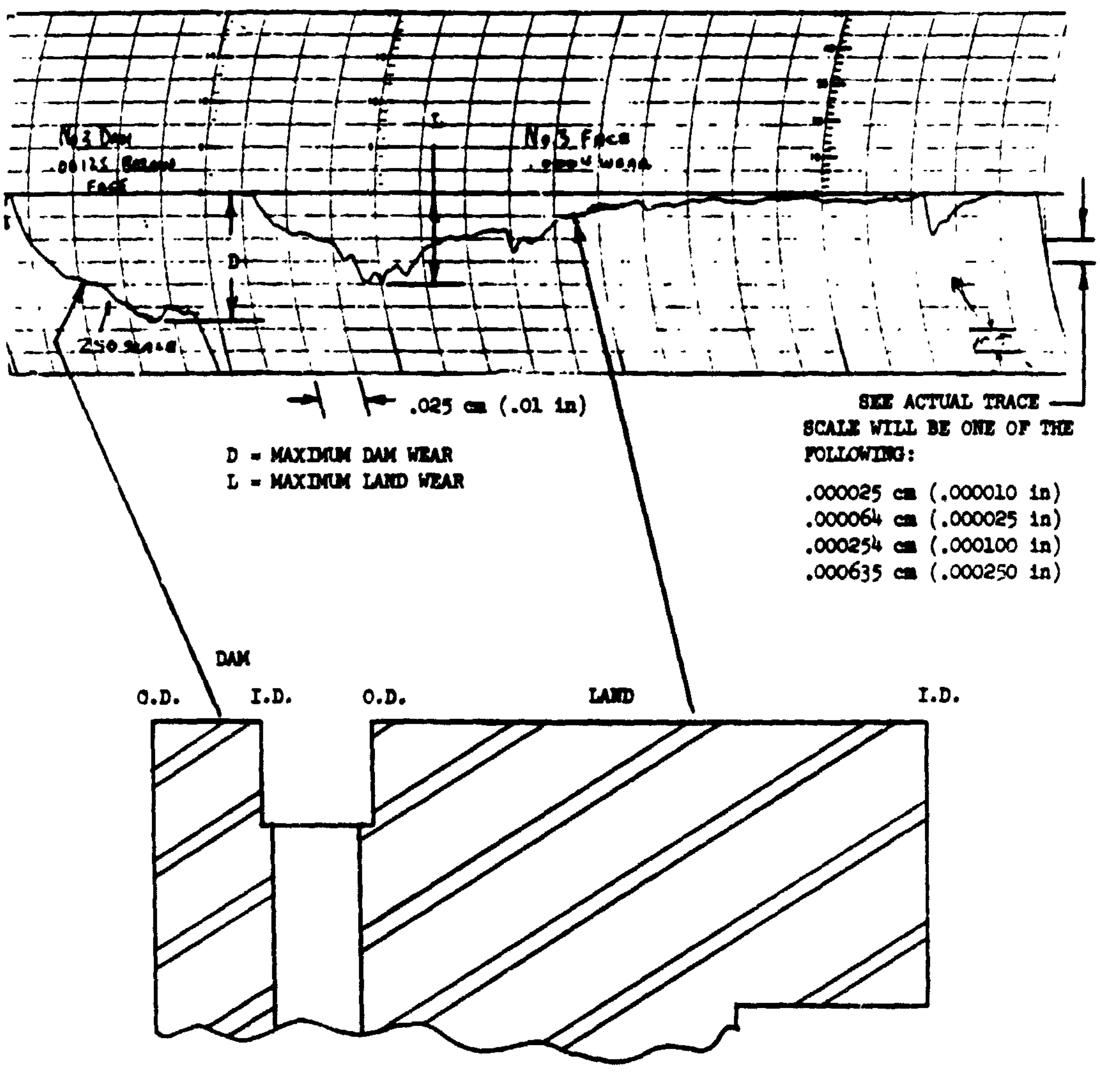
This appendix contains the following contents:

- Seal Face Trace Explanation
- Primary Sealing Element Wear Traces
- Primary Sealing Element Finish Traces
- Seal Seat Finish Traces
- Table A-1. Spiral Groove Depths
- Critical Seal Dimensions

SEAL FACE TRACES

SEAL FACE TRACES WERE TAKEN AT THREE EQUALLY SPACED LOCATIONS PROCEEDING FROM THE O.D. TOWARDS THE I.D.

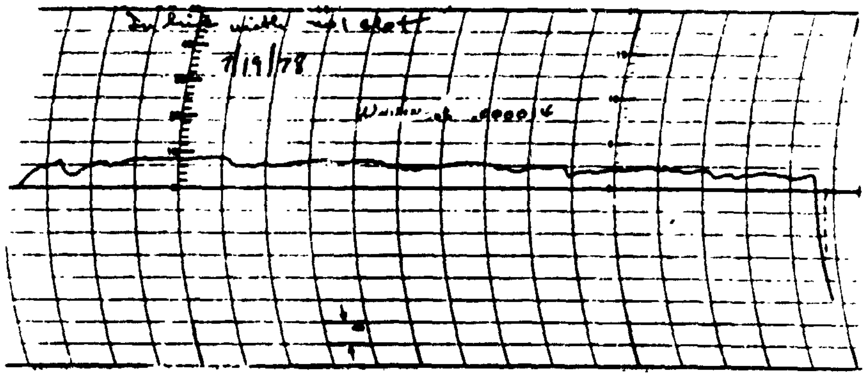
TYPICAL TRACE



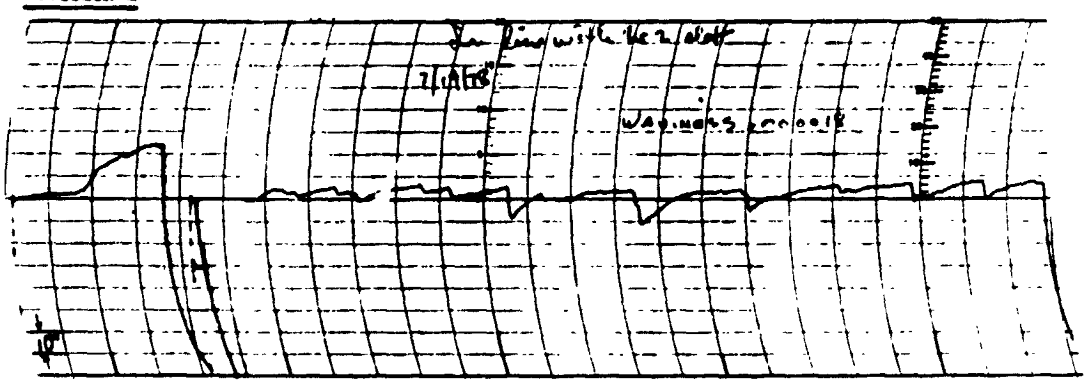
TRACES ARE PRESENTED IN SERIES ILLUSTRATING RELATIVE CHANGES FROM BUILD TO BUILD

PRIMARY SEALING ELEMENT
NO. 2 PRIOR TO RUN 0
(NEW)

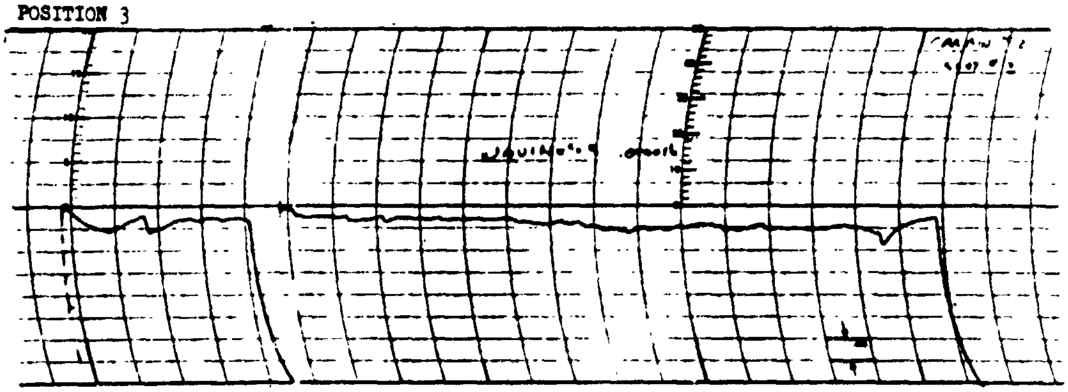
POSITION I



POSITION 2



POSITION 3



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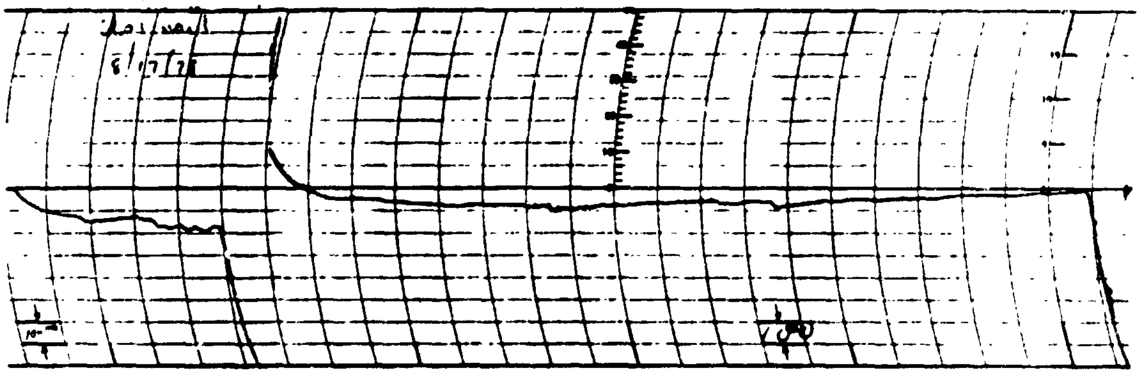
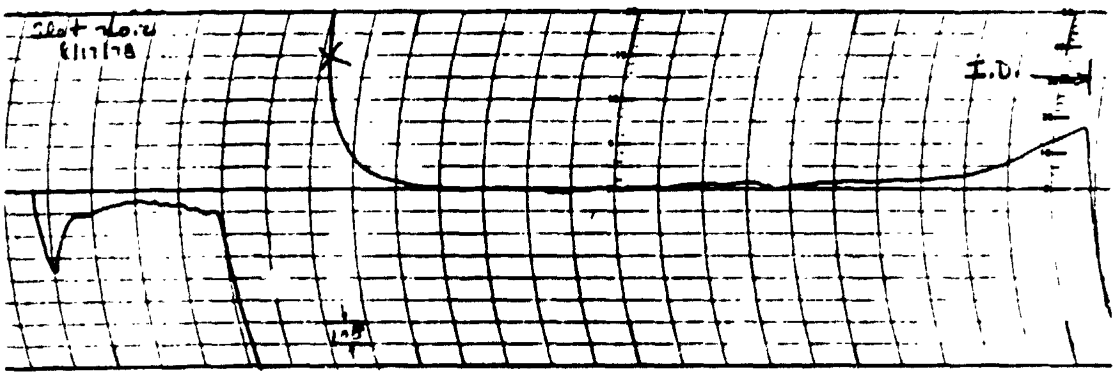
PRIMARY SEALING ELEMENT NO. 2
AFTER 176 STARTS AND
STOPS (RUN 0)

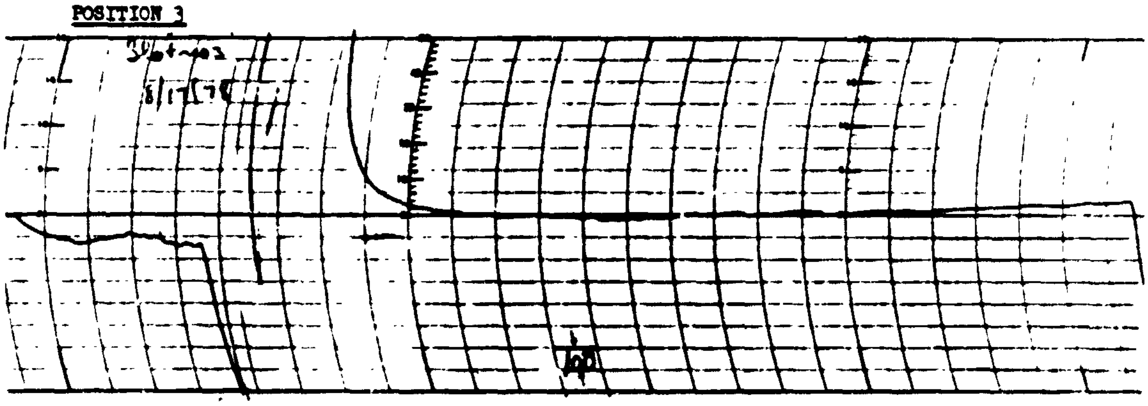
POSITION 1



POSITION 2

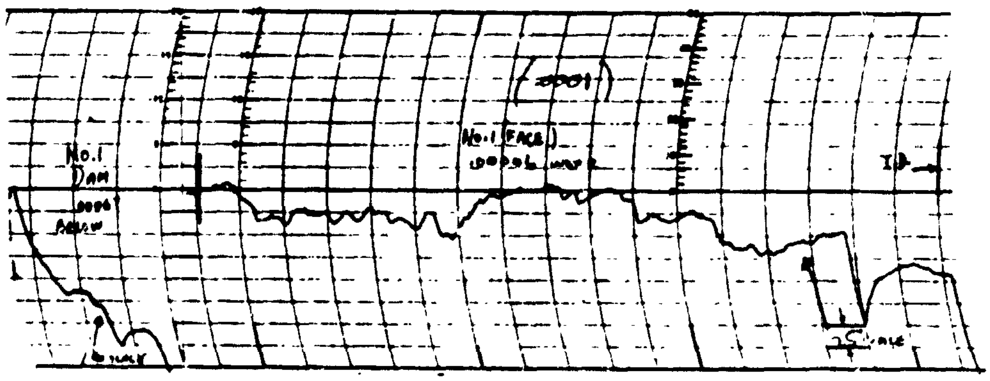


POSITION 3

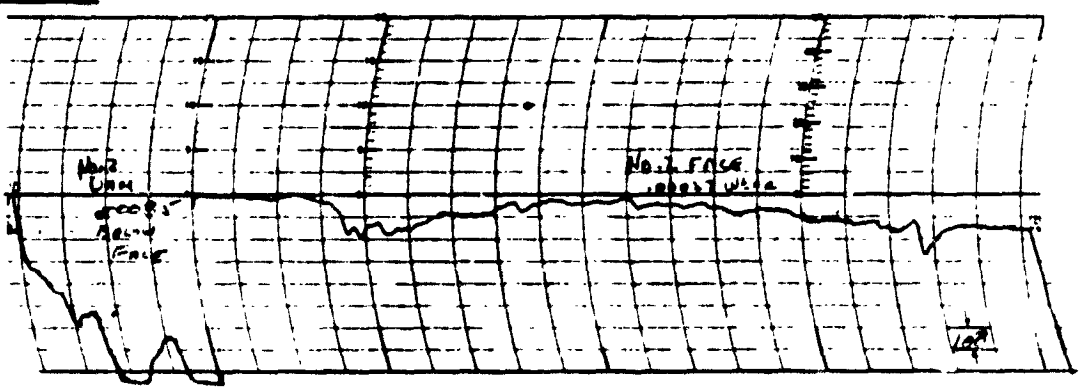


PRIMARY SEALING ELEMENT NO. 2
AFTER RUN 15

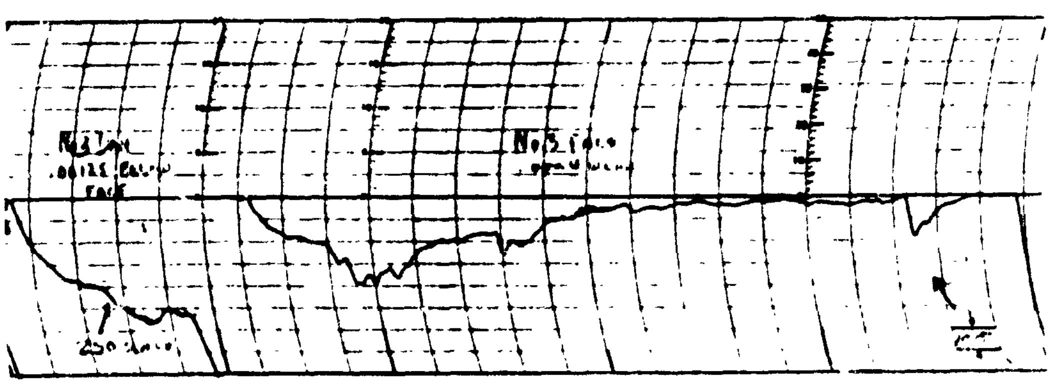
POSITION 1



POSITION 2

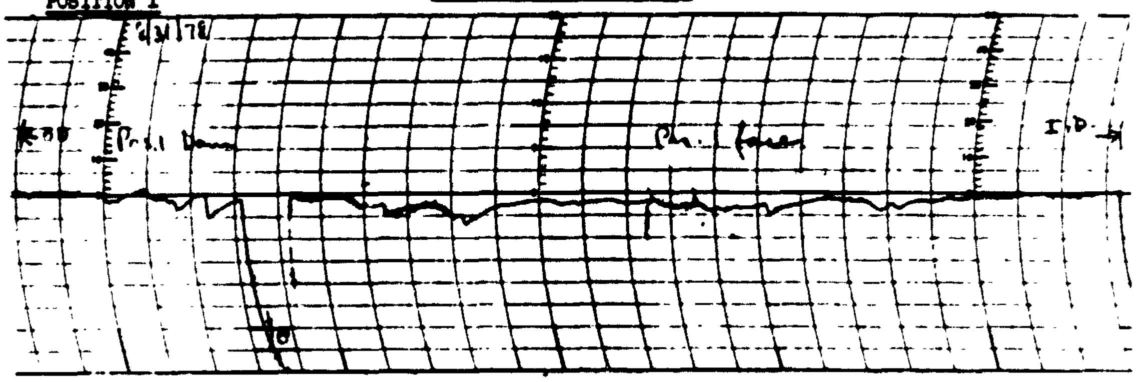


POSITION 3

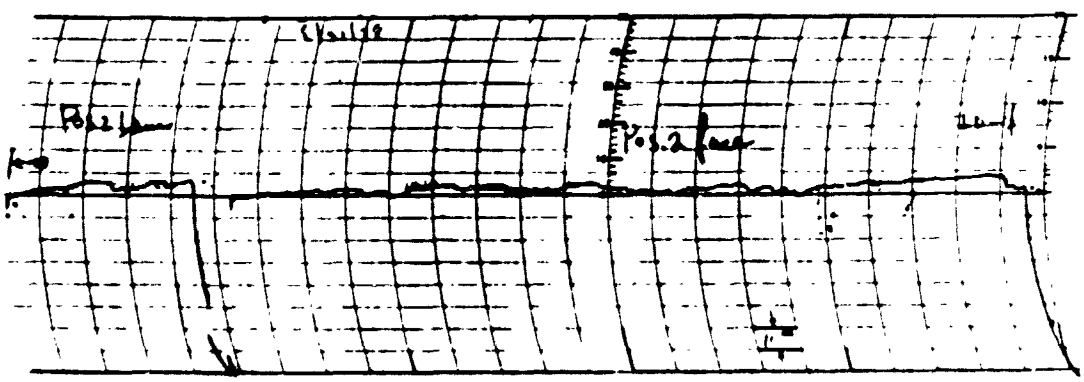


PRIMARY SEALING ELEMENT
NO. 3 PRIOR TO RUN 16
(NEW)

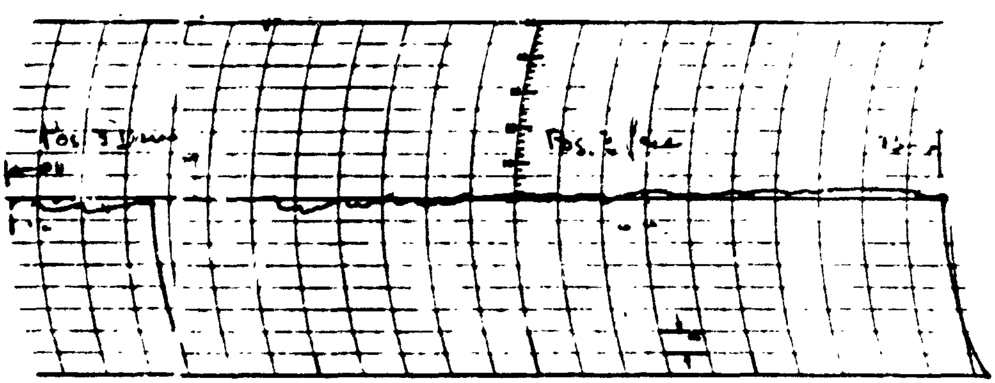
POSITION 1



POSTION 2



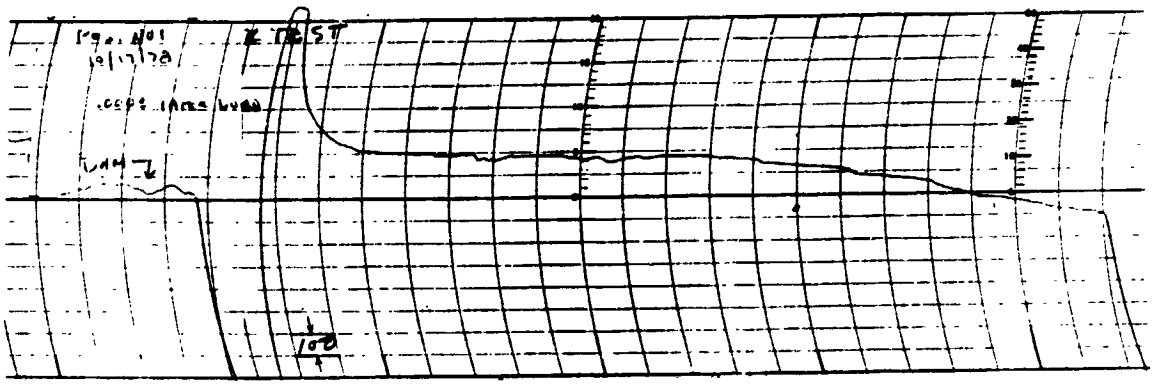
POSITION 3



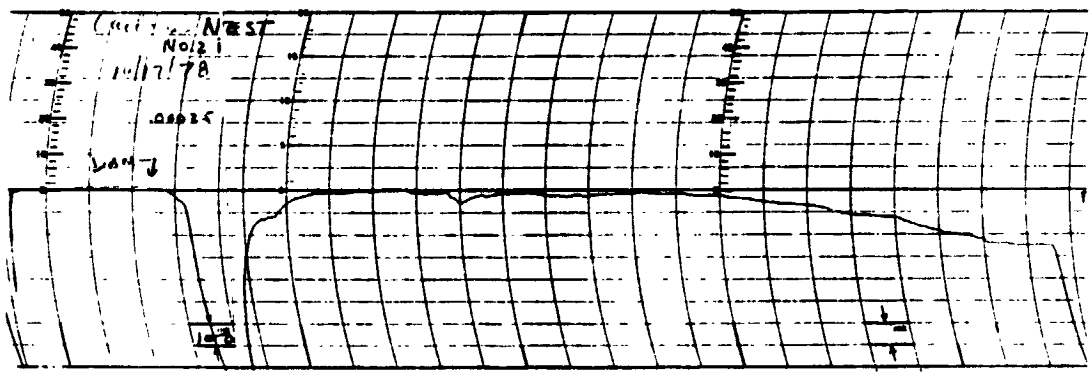
PRIMARY SEALING
ELEMENT NUMBER 3

AFTER RUN 22

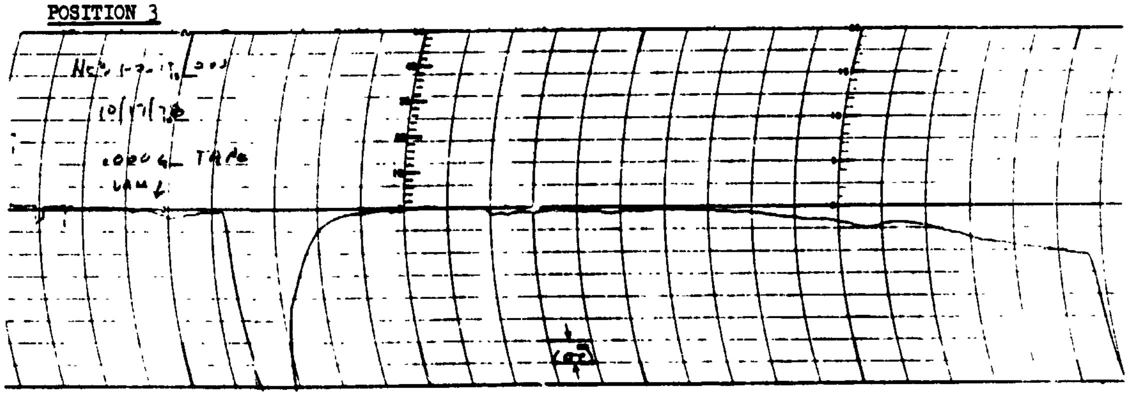
POSITION 1



POSITION 2

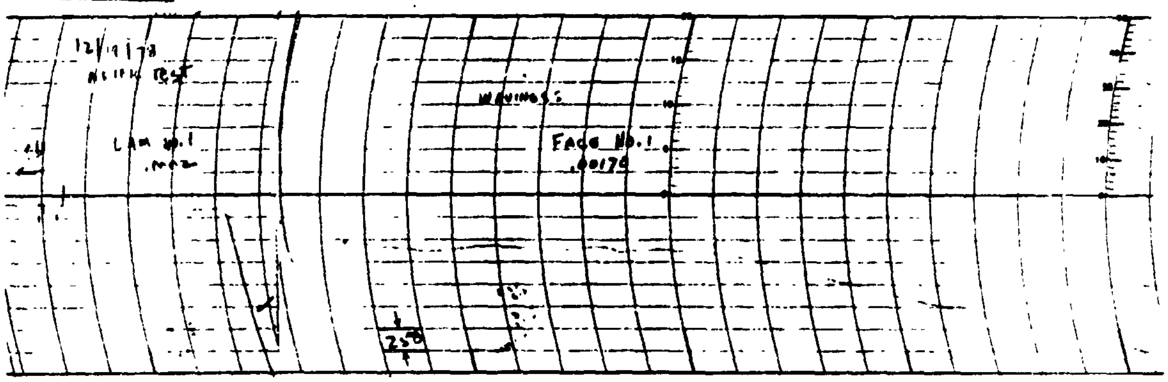


POSITION 3

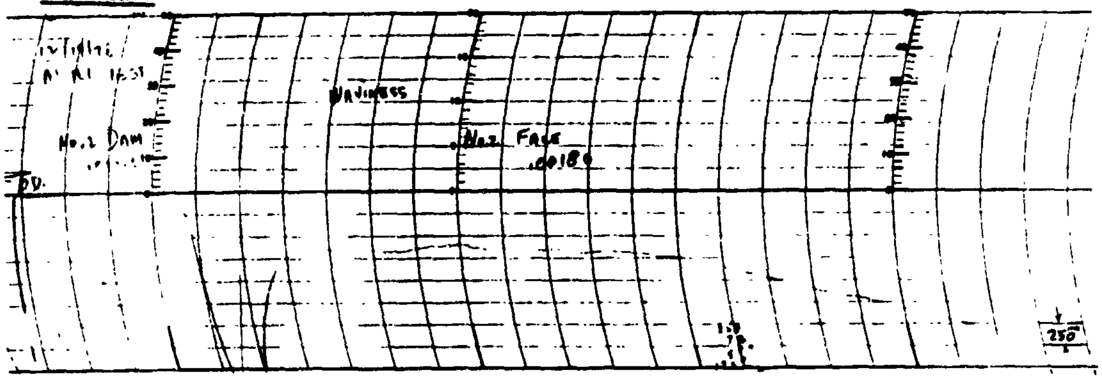


PRIMARY SEALING ELEMENT NO. 3 AT COMPLETION OF ENDURANCE TEST

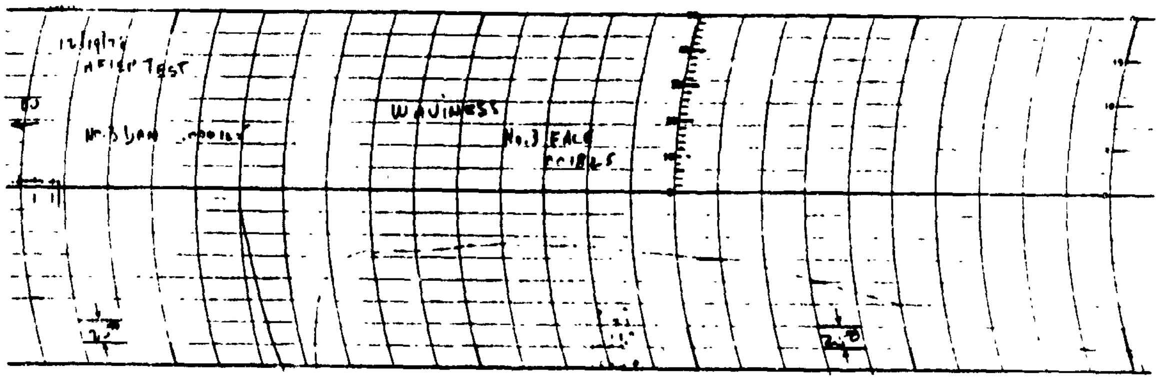
POSITION 1



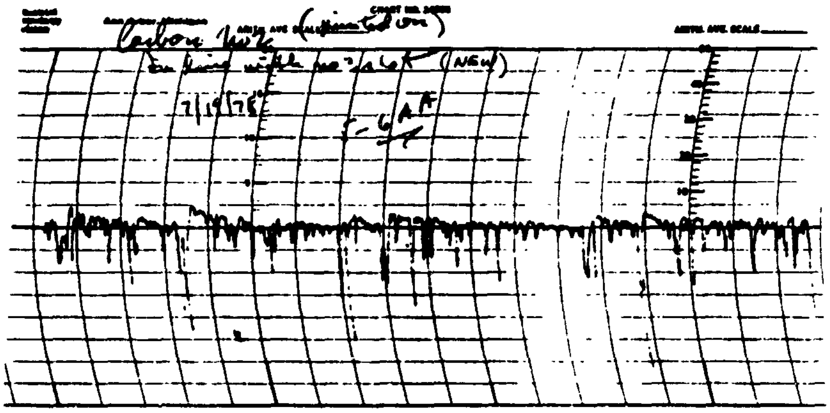
POSITION 2



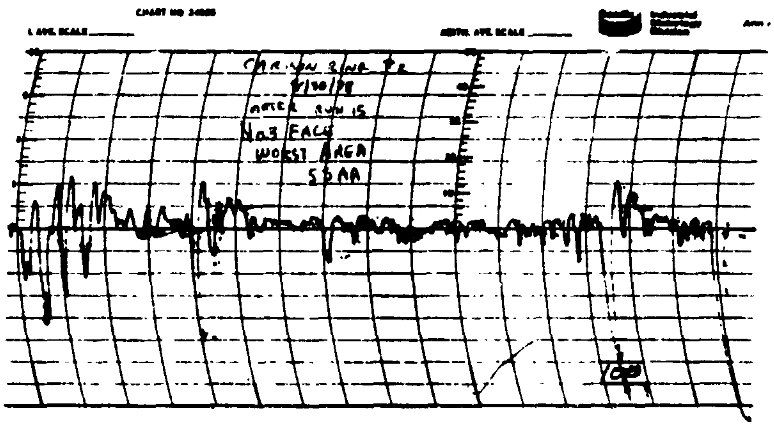
POSITION 3



PRIMARY SEALING ELEMENT
NO. 2 SURFACE FINISH

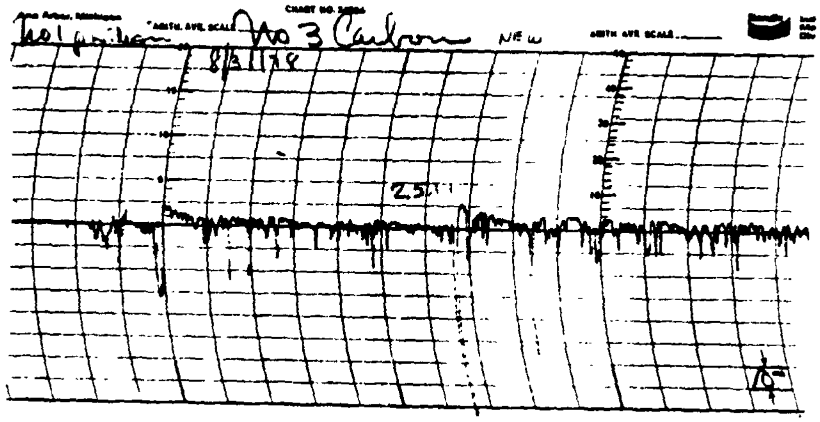


PRIOR TO RUN 0 (NEW)

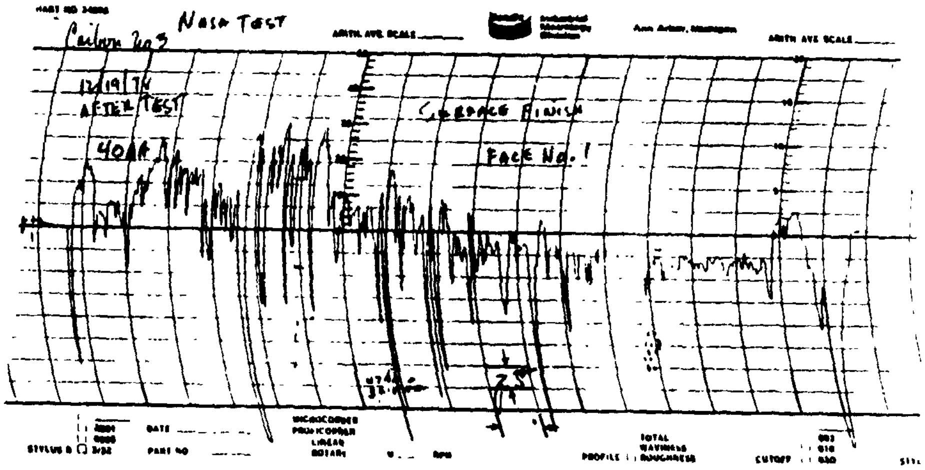


AFTER RUN 15

PRIMARY SEALING ELEMENT
NO. 3 SURFACE FINISH

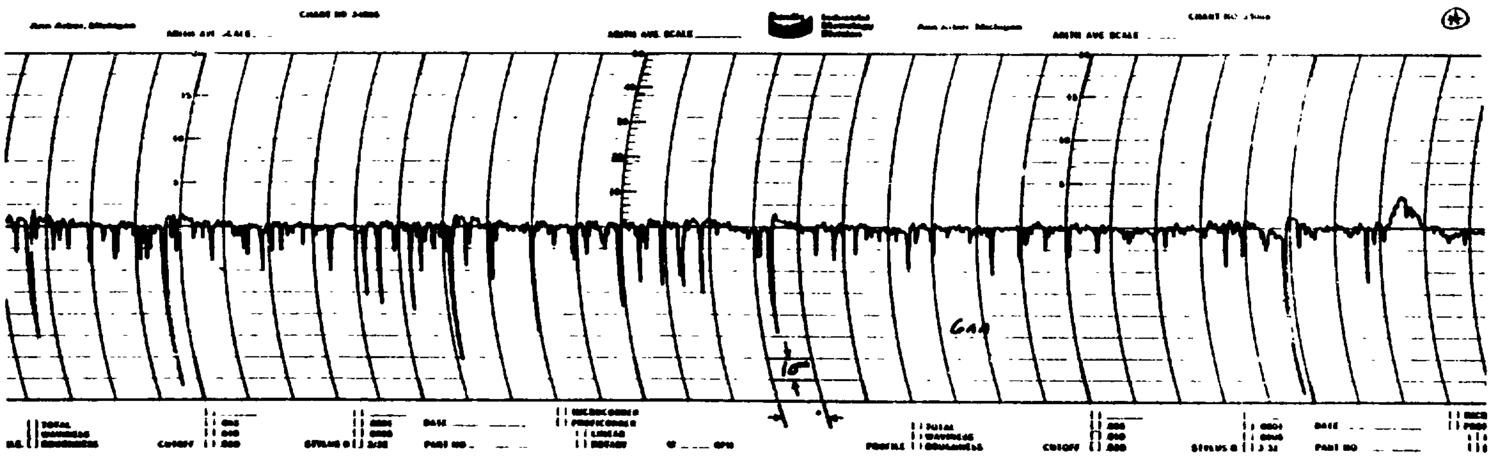


PRIOR TO RUN 16 (NEW)

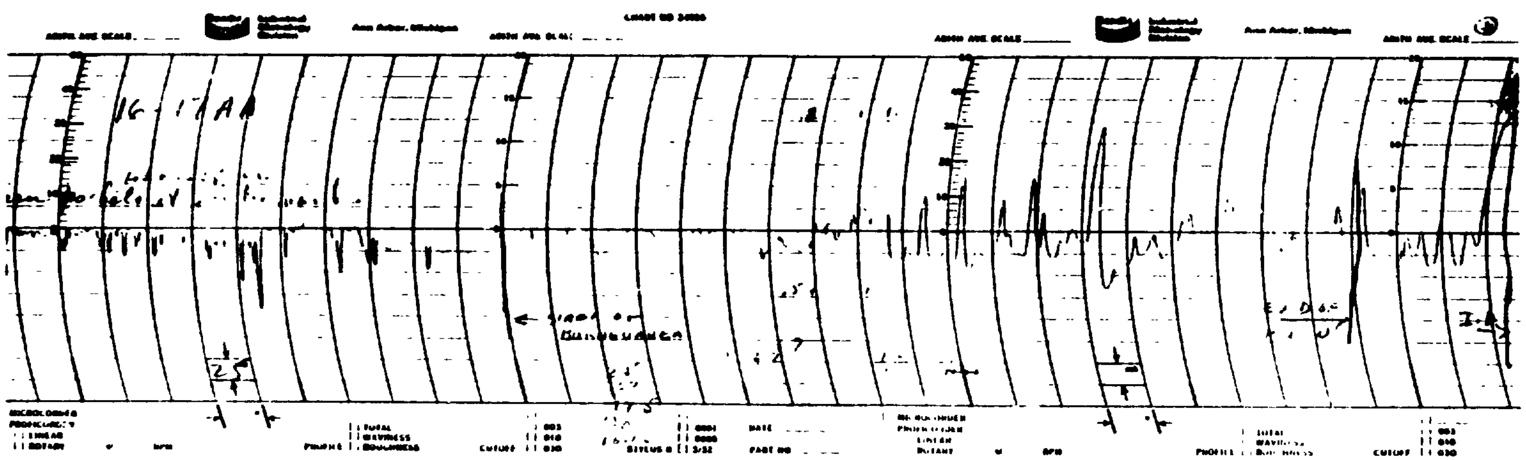


AT END OF ENDURANCE TEST

SEAL SEAT SURFACE FINISH



PRIOR TO RUN O (NEW)



AT END OF ENDURANCE TEST

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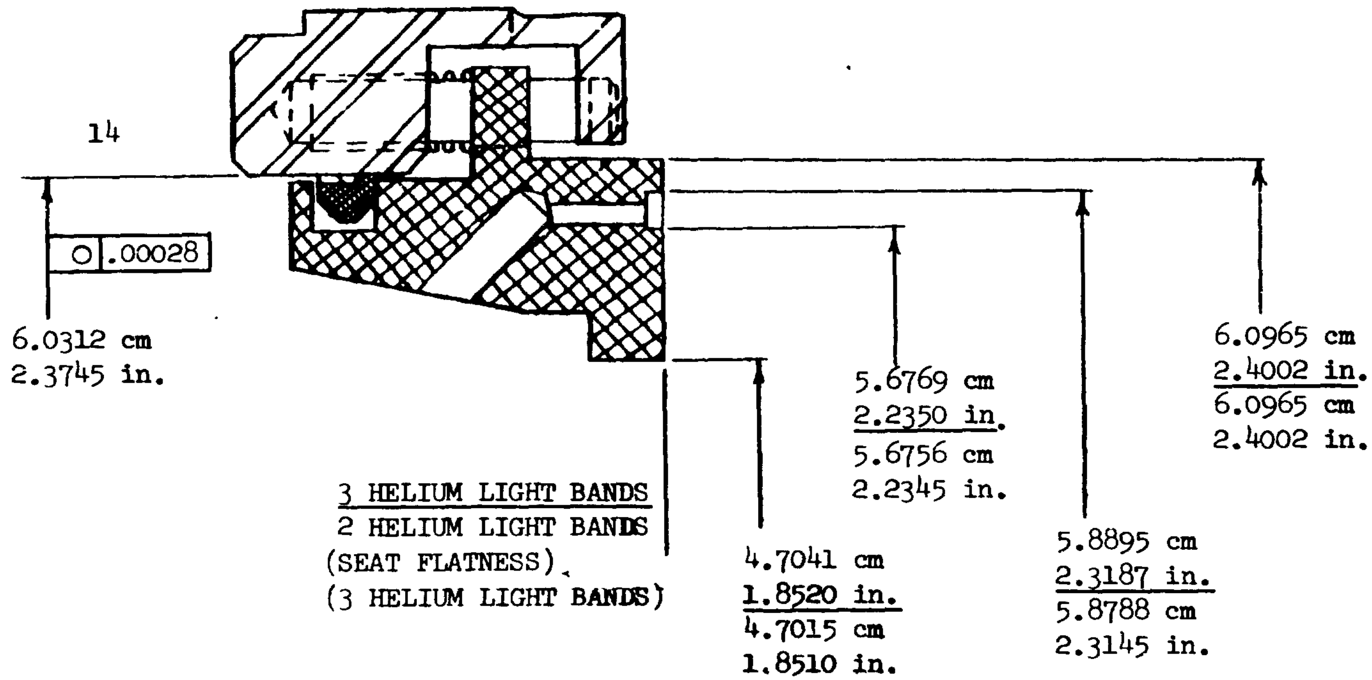
TABLE A-1. SPIRAL GROOVE DEPTHS - SEAT S/N 00001

POCKET	NEW DEPTH @ R_1 cm (in)	NEW DEPTH @ R_2 cm (in)	AFTER RUN 15 DEPTH @ R_1 cm (in)	AFTER RUN 15 DEPTH @ R_2 cm (in)	AFTER RUN 22 DEPTH @ R_1 cm (in)	AFTER RUN 22 DEPTH @ R_2 cm (in)	AT COMPLETION OF TEST DEPTH @ R_1 cm (in)	AT COMPLETION OF TEST DEPTH @ R_2 cm (in)
1	.00133 (.00053)	.00184 (.00073)	.00133 (.00053)	.00155 (.00061)	.00180 (.00071)	.00171 (.00068)	.00234 (.00092)	.00236 (.00093)
2	.00165 (.00065)	.00146 (.00058)	.00165 (.00065)	.00175 (.00069)	.00191 (.00075)	.00191 (.00075)	.00229 (.00090)	.00229 (.00090)
3	.00159 (.00063)	.00208 (.00080)	.00171 (.00068)	.00180 (.00071)	.00184 (.00073)	.00213 (.00084)	.00203 (.00080)	.00203 (.00080)
4	.00168 (.00066)	.00216 (.00085)	.00164 (.00067)	.00191 (.00075)	.00210 (.00083)	.00211 (.00083)	.00193 (.00076)	.00236 (.00093)
5	.00191 (.00075)	.00237 (.00094)	.00189 (.00075)	.00206 (.00081)	.00184 (.00073)	.00229 (.00090)	.00216 (.00085)	.00229 (.00090)
6	.00178 (.00075)	.00232 (.00092)	.00187 (.00074)	.00203 (.00080)	.00178 (.00070)	.00226 (.00089)	.00193 (.00076)	.00198 (.00078)
7	.00165 (.00065)	.00178 (.00070)	.00165 (.00065)	.00159 (.00063)	.00201 (.00079)	.00175 (.00069)	.00178 (.00070)	.00178 (.00070)
8	.00188 (.00074)	.00201 (.00079)	.00171 (.00068)	.00180 (.00071)	.00194 (.00077)	.00201 (.00079)	.00210 (.00083)	.00213 (.00084)
9	.00183 (.00072)	.00193 (.00076)	.00182 (.00072)	.00175 (.00069)	.00184 (.00073)	.00192 (.00076)	.00208 (.00082)	.00211 (.00083)
10	.00169 (.00067)	.00165 (.00065)	.00169 (.00067)	.00152 (.00060)	.00151 (.00060)	.00161 (.00064)	.00229 (.00090)	.00229 (.00090)
11	.00137 (.00054)	.00146 (.00058)	.00127 (.00050)	.00133 (.00053)	.00179 (.0007)	.00140 (.00055)	.00203 (.00080)	.00203 (.00080)
12	.00165 (.00065)	.00182 (.00072)	.00168 (.00066)	.00165 (.00065)	.00178 (.00070)	.00178 (.00070)	.00279 (.00110)	.00274 (.00108)
13	.00159 (.00063)	.00171 (.00068)	.00163 (.00064)	.00152 (.00060)	.00197 (.00078)	.00171 (.00068)	.00193 (.00076)	.00198 (.00078)
14	.00178 (.00070)	.00191 (.00075)	.00178 (.00070)	.00170 (.00067)	.00178 (.00070)	.00185 (.00073)	.00211 (.00083)	.00239 (.00094)
15	.00161 (.00064)	.00173 (.00068)	.00165 (.00065)	.00517 (.00062)	.00240 (.00095)	.00174 (.00069)	.00224 (.00088)	.00224 (.00088)
16	.00225 (.00089)	.00246 (.00097)	.00222 (.00088)	.00216 (.00085)	.00173 (.00068)	.00241 (.00095)	.00287 (.00113)	.00191 (.00075)
17	.00159 (.00063)	.00184 (.00073)	.00159 (.00063)	.00165 (.00065)	.00207 (.00082)	.00182 (.00072)	.00201 (.00079)	.00241 (.00095)
18	.00191 (.00075)	.00216 (.00080)	.00192 (.00076)	.00191 (.00075)	.00192 (.00076)	.00212 (.00084)	.00241 (.00095)	.00226 (.00089)
19	.00178 (.00070)	.00199 (.00079)	.00178 (.00070)	.00175 (.00069)	.00165 (.00065)	.00150 (.00059)	.00229 (.00090)	.00224 (.00088)
20	.00152 (.00060)	.00165 (.00070)	.00152 (.00060)	.00149 (.00059)	.00216 (.00085)	.00165 (.00065)	.00198 (.00078)	.00152 (.00060)
21	.00191 (.00075)	.00220 (.00087)	.00189 (.00075)	.00197 (.00078)	.00178 (.00070)	.00216 (.00085)	.00241 (.00095)	.00165 (.00065)
22	.00191 (.00075)	.00203 (.00080)	.00178 (.00070)	.00178 (.00070)	.00201 (.00079)	.00199 (.00079)	.00229 (.00090)	.00211 (.00083)
23	.00184 ([illegible])	.00222 (.00088)	.00183 (.00072)	.00203 (.00080)	.00152 (.00060)	.00229 (.00090)	.00229 (.00090)	.00216 (.00085)
24	.00140 (.00055)	.00191 (.00075)	.00140 (.00053)	.00165 (.00065)	.00147 (.00058)	.00187 (.00074)	.00173 (.00068)	.00206 (.00081)

CRITICAL PRE-TEST DIMENSIONS



SEALING ELEMENT NO. 2

SEALING ELEMENT NO. 3