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FINAL REPORT

DEVELOPMENT OF SPIRAL-GROOVE SELF-ACTING FACE SEALS

by

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prepared for

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16. Abstract

An experimental evaluation and a 100-hour endurance test were performed on a spiral groove geometry, self-acting face seal. The seal was tested and operated successfully at maximum conditions of 243.8 m/s (800 ft/sec) surface speed, 199.9 N/cm^2 (290 psia) air pressure, and 645.4K (702°F) air temperature. The maximum speed condition of 243.8 m/s (800 ft/sec) was obtained at a shaft speed of 72,500 rpm. Seal wear, gas leakage, and sealing element temperature were monitored during the test. Condition of the seal at the completion of the test was documented and found acceptable for further use. The spiral groove wear rate measured during the endurance test indicates a minimum potential seal life of over 2700 hours. Seal air leakage measured during the test program is within the range considered acceptable for consideration for use in a small gas turbine engine.

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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 3-19772. The period of performance was 9 February 1976 to 31 March 1977.

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. Peter Lynwander. Mr. Michael O'Brien was the principal investigator.

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SUMMARY

An experimental evaluation and a 100-hour endurance test were performed on a spiral-groove geometry film-riding face seal. The spiral-groove lift geometry was evaluated as a substitute for the Rayleigh step lift geometry used in previous test programs (References 1, 2, and 3).

The seal was tested at maximum nonconcurrent operating conditions of 243.8 m/s (800 ft/sec) surface speed, 199.9 N/cm^2 abs (290 psia) air pressure, and 645.4K (702 °F) air temperature.

The seal performed satisfactorily at all test conditions. Seal wear (lift geometry) occurred during testing but was not a serious problem in regard to completion of the test program. Internal oil coking of the seal assembly was encountered during the endurance test. Build-to-build variations in air leakage were observed and considered to be at least in part due to distortion of the primary sealing element. Seal air leakage measured during the test program is considered to be within a range usable in small gas turbine engines.

INTRODUCTION

Main shaft seals are becoming increasingly critical components in advanced gas turbine engines. High surface speeds in combination with increased air pressures and temperatures can cause excessive heat generation resulting in carbon wear, lubricant degradation and coking, and air or oil leakage.

The purpose of this program was to evaluate spiral-groove geometry self-acting face seals for use in advanced gas turbine engines. The seal is similar, with the exception of the self-acting lift geometry, to seals tested under previous programs (References 1, 2, and 3). In this design, however, the spiral-groove geometry substituted for the Rayleigh step lift pads used in test seals of these previous programs.

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 multistaged 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 surfaces 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 in an advanced gas producer turbine bearing location.

APPARATUS AND PROCEDURE

Test Vehicle

The test rig used during the performance evaluation and endurance test is illustrated in Figure 1. The test bearing and seal compartment, which is shown in detail in Figure 2, illustrates the location of the two seal assemblies, one on either side of the bearing.

The test rig prime mover is a 74.57 kw (100 hp), 30,000 rpm steam turbine. Connecting the steam turbine to the test rig is a 1:3 ratio speed increasing gearbox. The test installation is shown in Figure 3. The test rig shaft is supported by a 35 x 62 x 14 mm split inner race ball bearing in the test position and by a 35 x 55 x 10 mm split inner race ball bearing in the support position. Both bearings are hydraulically mounted with thrust loading accomplished by a combination of coil springs acting on the outer race of the support bearing and a pressure differential maintained across the hub of the shaft. A single batch of MIL-L-23699 oil was used throughout the test program. Oil flow to the test bearing package 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 package was maintained at 355 ± 6K (180° ± 10°F) during the test. Support bearing oil flow was maintained at 72.6 kg/hr (160 lb/hr) throughout the test with feed temperature at 344 ± 6 K (160° ± 10°F).

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

The volume flow rate of the air leaking through the seals was measured with rotameters as 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.

Recorded Parameters

Instrumentation incorporated in the test rig is listed in Table I. 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.

(CIRCLED NUMBERS REFER TO TABLE I)

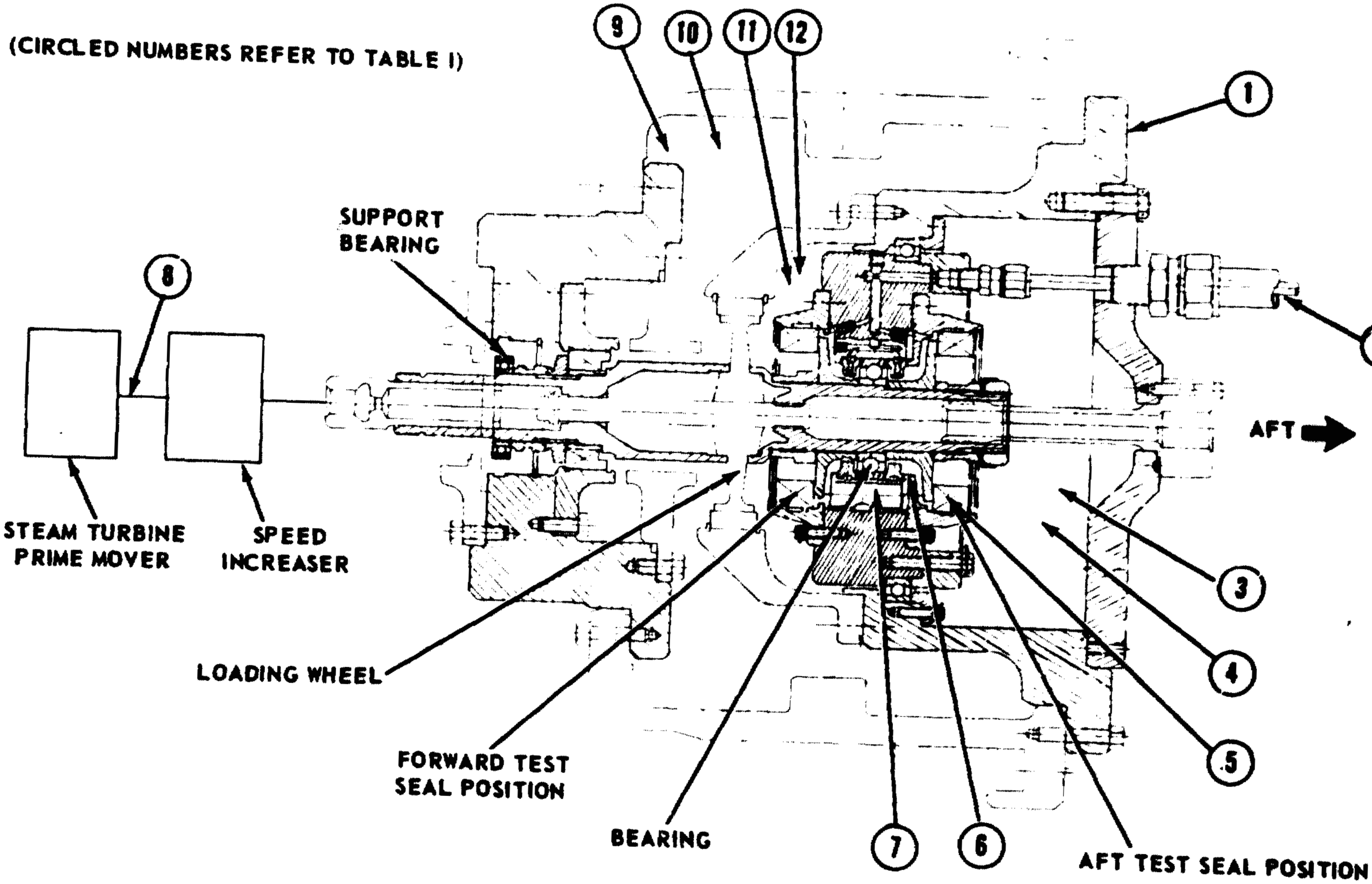

Figure 1. Test Rig and Instrumentation Plan.

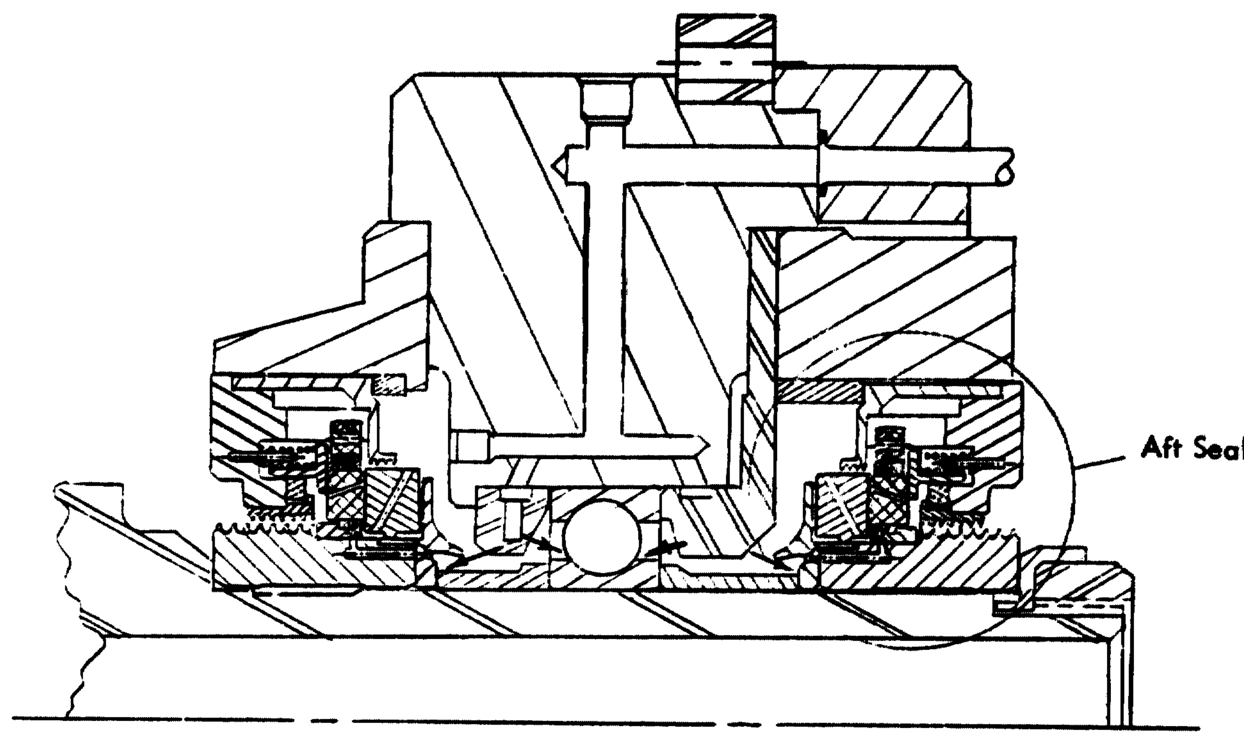

Figure 2. Test Bearing and Seal Compartment.

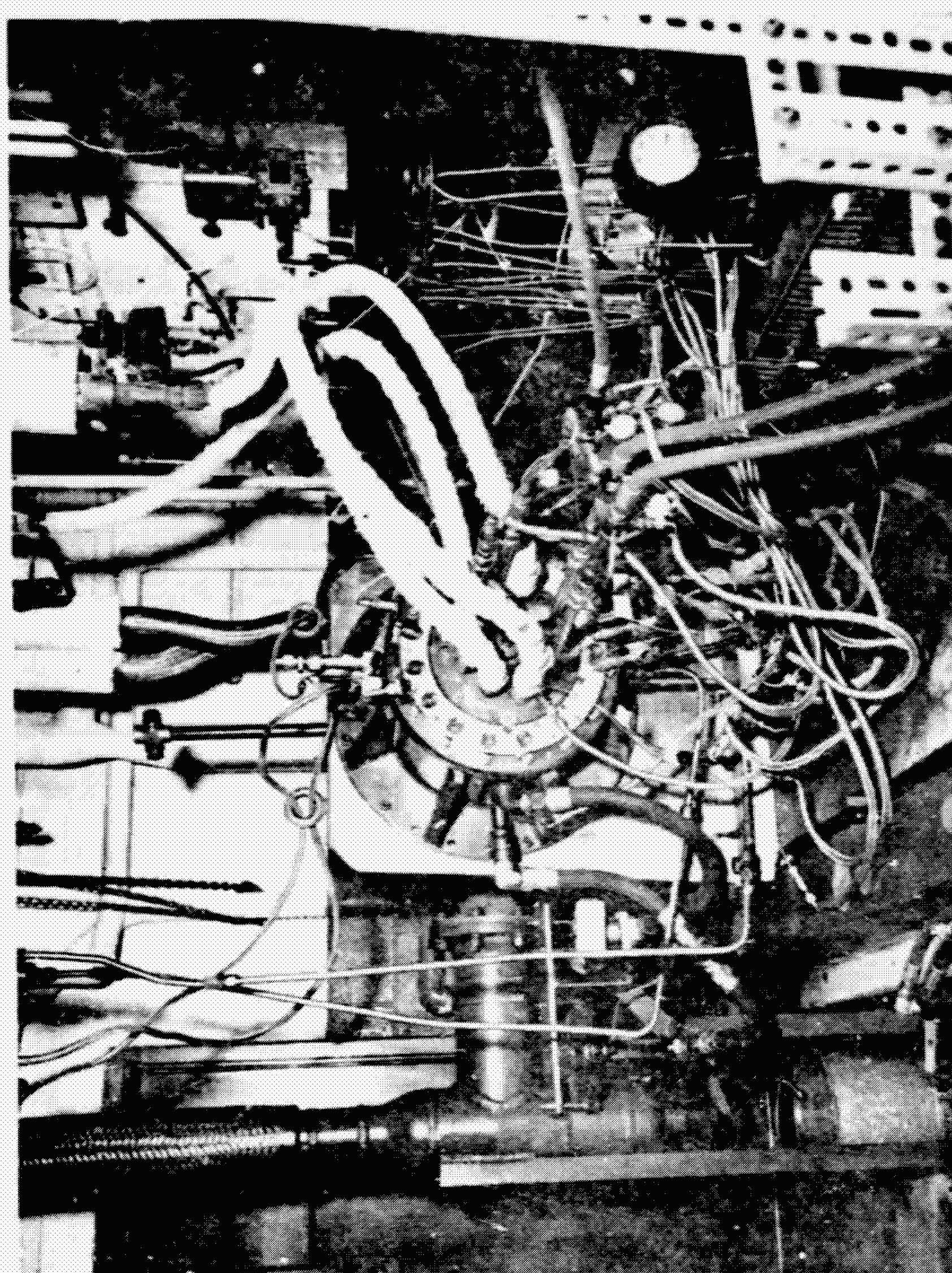

Figure 3. Test Installation.

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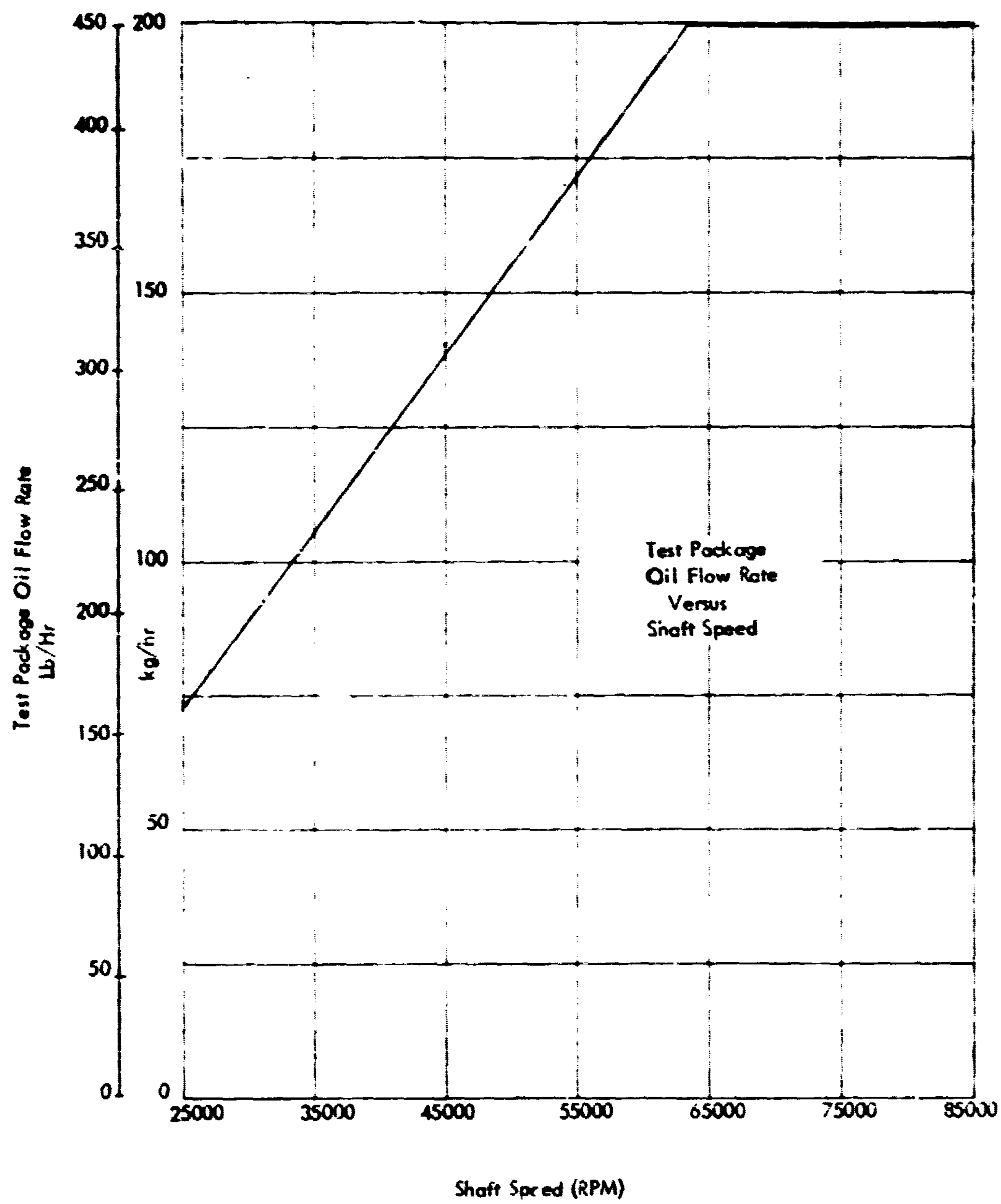

Figure 4. Oil Flow Versus Rig Speed.

TABLE I. 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	Fwd seal cavity	12
	Gage	Aft seal cavity	3
Air Temperature	Thermocouple	Fwd wheel cavity	10
	Thermocouple	Fwd seal cavity	11
	Thermocouple	Aft seal 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
Seal Temperature	Thermocouple	Seal case or carbon	5
Vibration	Velocity pickup	Test rig housing	1
Chips	Chip detector	Scavenge line	7

Spiral Groove Self-Acting Seal Design

The test seal illustrated in Figure 5 includes the following items and design features: The seal utilizes a primary sealing element of composite construction consisting of a carbon graphite ring (sealing element) retained with an interference fit at its outside diameter by a TZM alloy retaining band. Anti-rotation provisions are made through the use of three carbon blocks which are mounted in a TZM retaining band and are accommodated in slots in the seal housing. he face of the primary sealing element contains the self-acting lift geometry (spiral grooves) and the sealing dam (Figure 6). The secondary seal is a straight-cut, pressure-balanced carbon-graphite piston ring which is mounted in the seal housing. The piston ring seals against a bore provided by the piston ring carrier and against the groove wall. The carrier also serves to transmit and distribute the coil spring load to the primary sealing element. The load of the coil spring urges the primary sealing element against the seal seat. The rotating seal seat mates with the face of the primary sealing element to produce the primary sealing interface.

The seal seat is manufactured from TZM, a titanium molybdenum alloy, chosen for its low coefficient of thermal expansion and high thermal conductivity. The sealing face of the seat is flame sprayed with chrome carbide and finished to a high degree of flatness. The seat is clamped by a machined bellows spacer to reduce clamping load, thereby reducing clamping-induced distortions.

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 spring load is balanced by the force generated by the spiral grooves. The spiral groove lift force, for a given groove geometry, is a function of sliding velocity, the sealed fluid and its pressure, the viscosity (temperature) of the sealed fluid, and the separation between the sealing element and seal seat. When the seal is operating at a particular sliding velocity, sealed pressure, and temperature, the separation between the sealing element and the seat adjusts until the closing force is balanced. This establishes the leakage clearance. Ideally, this clearance should be as small as possible to minimize air leakage, but practical considerations such as assembled seat and primary sealing element flatness, along with pressure, temperature, and speed-induced distortions of these items limit achievable minimum operating clearances. In practice, this operating clearance is on the order of .0005 cm (.0002 in).

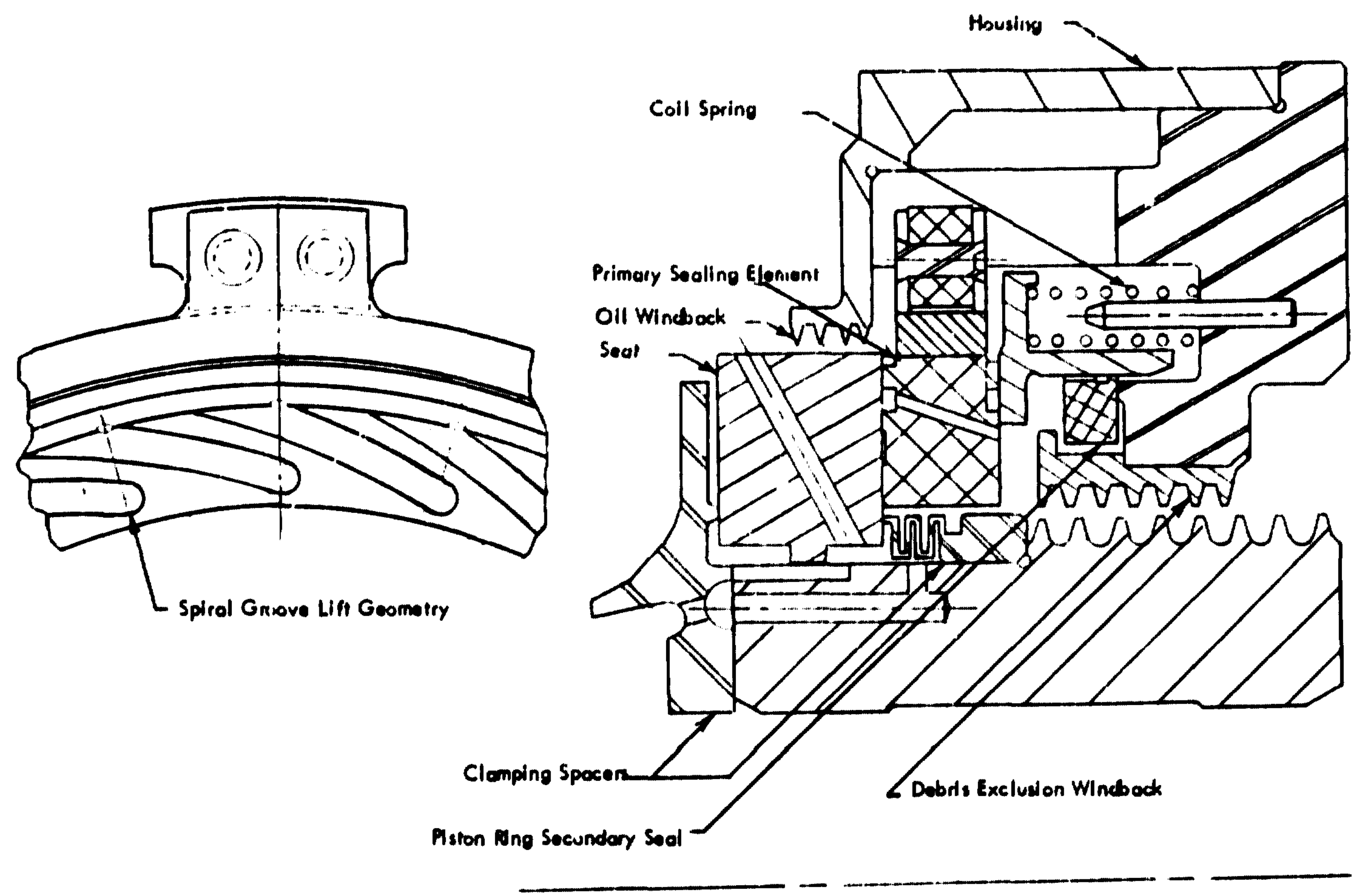

Figure 5. Test Seal.

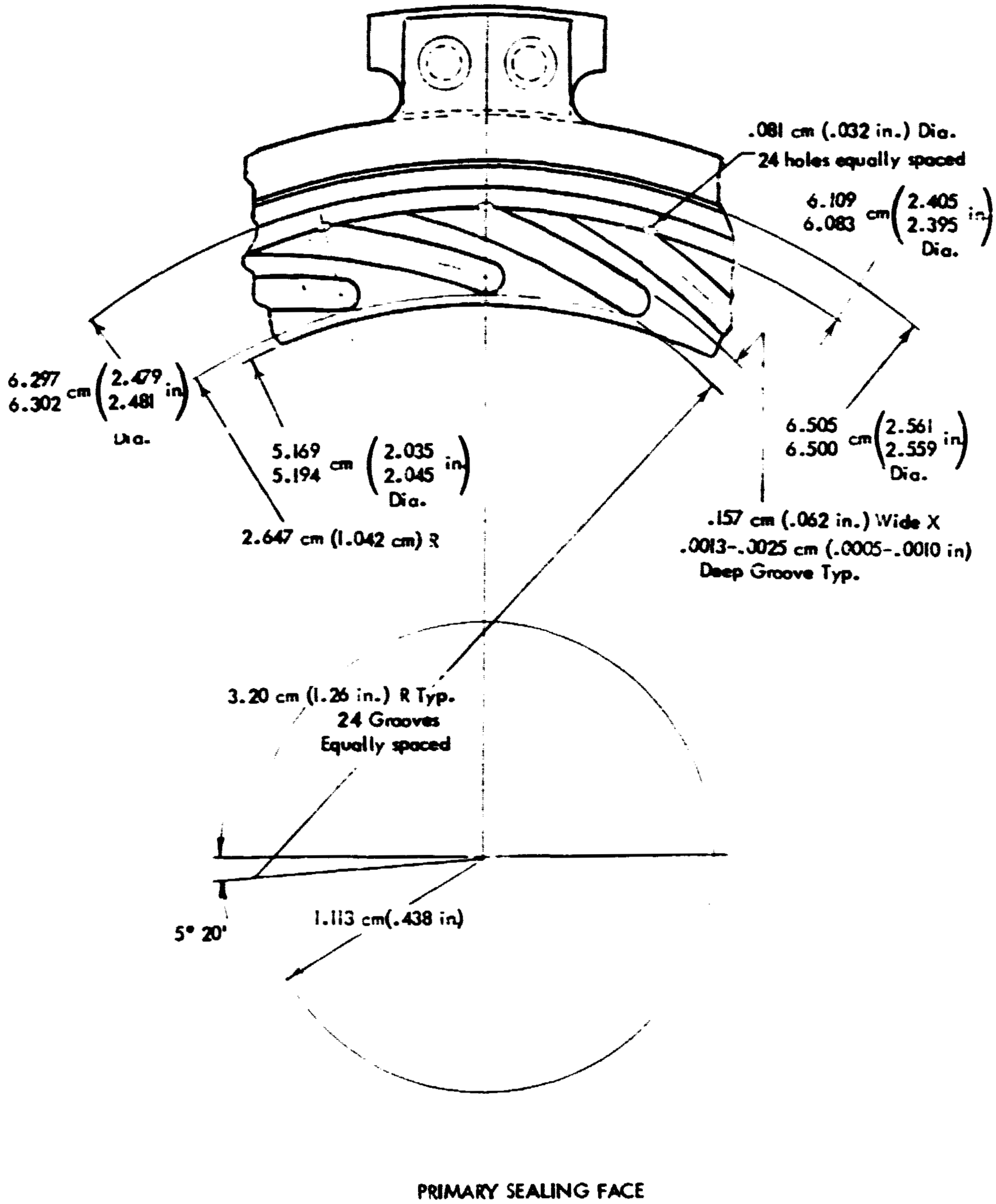

Figure 6. Primary Sealing Face.

TEST PROGRAM

The test program was divided into two parts: performance evaluation test and an endurance test. During the performance evaluation test, the test seals were subjected to various combinations of sealed pressure and surface speed for short amounts of time (15 or 30 minutes, depending upon the specific point) to reveal any potential operating problems or limits. The seals were then subjected to an endurance test, which encompassed three pressure levels and six speed ranges. The details of the test program follow.

Performance Evaluation, Build I (8.25 Hours)

Prior to the beginning of the performance evaluation, photographs were taken to document the appearance of the seals. (See Figures 7 and 8). Closeups of the seal seat and spiral-groove geometry are shown in Figures 9 through 12.

Performance data was obtained at 27 test points during Build I testing. The first six points were maintained for .5 hour each, while the remaining points were maintained for .25 hour each. Data obtained are summarized in Table II. Maximum surface speed reached was 182.9 m/s (600 ft/sec). Maximum sealed pressure was 148.2 N/cm^2 abs (215 psia).

Seal Air Leakage

Seal air leakage as a function of air side pressure for the various surface speeds run is presented in Figures 13 through 16. Air leakage increases as a function of sealed pressure as is expected. A general trend of increasing leakage with speed is seen (and expected), but because of spread in the data it is not exhibited consistently. Extraneous leakage from thermocouple passages, metal gaskets, and press fit joints undoubtedly make up a portion of the spread. The general level of seal air leakage is considered to be within a usable range for application in small gas turbine engines.

Seal Wear

At the completion of Build I testing, changes in seal face dimensions were measured, and seal wear was determined. Table III illustrates these dimensions. Wear was monitored in three locations at four equally spaced angular positons (Figure 17). These locations consisted of the sealing dam, the land area adjacent to and outboard of the spiral groove, and the surface near the ID of the sealing element. Average wear after Build I testing was as follows:

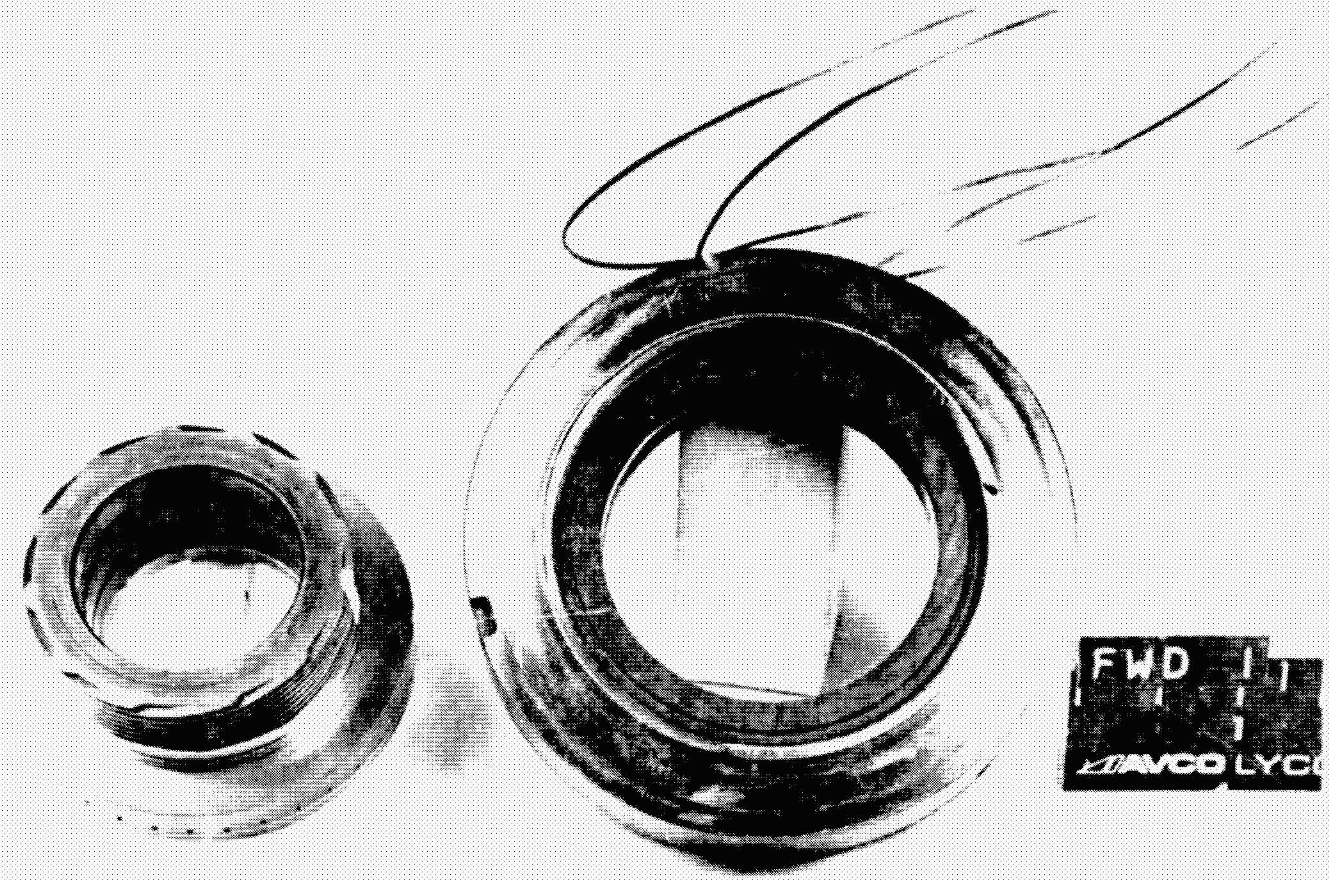

Figure 7. Forward Seal Prior to Build I.

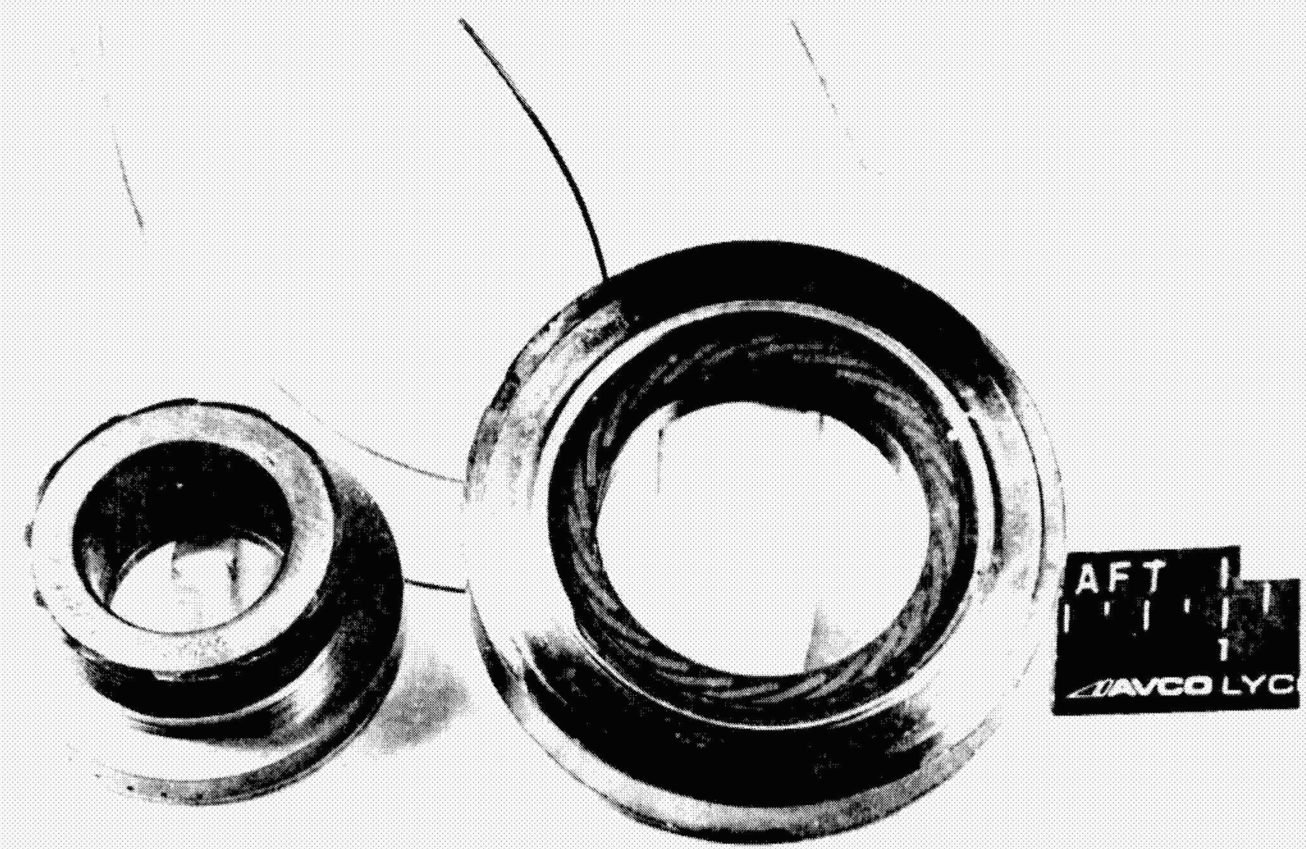

Figure 8. Aft Seal Prior to Build I.

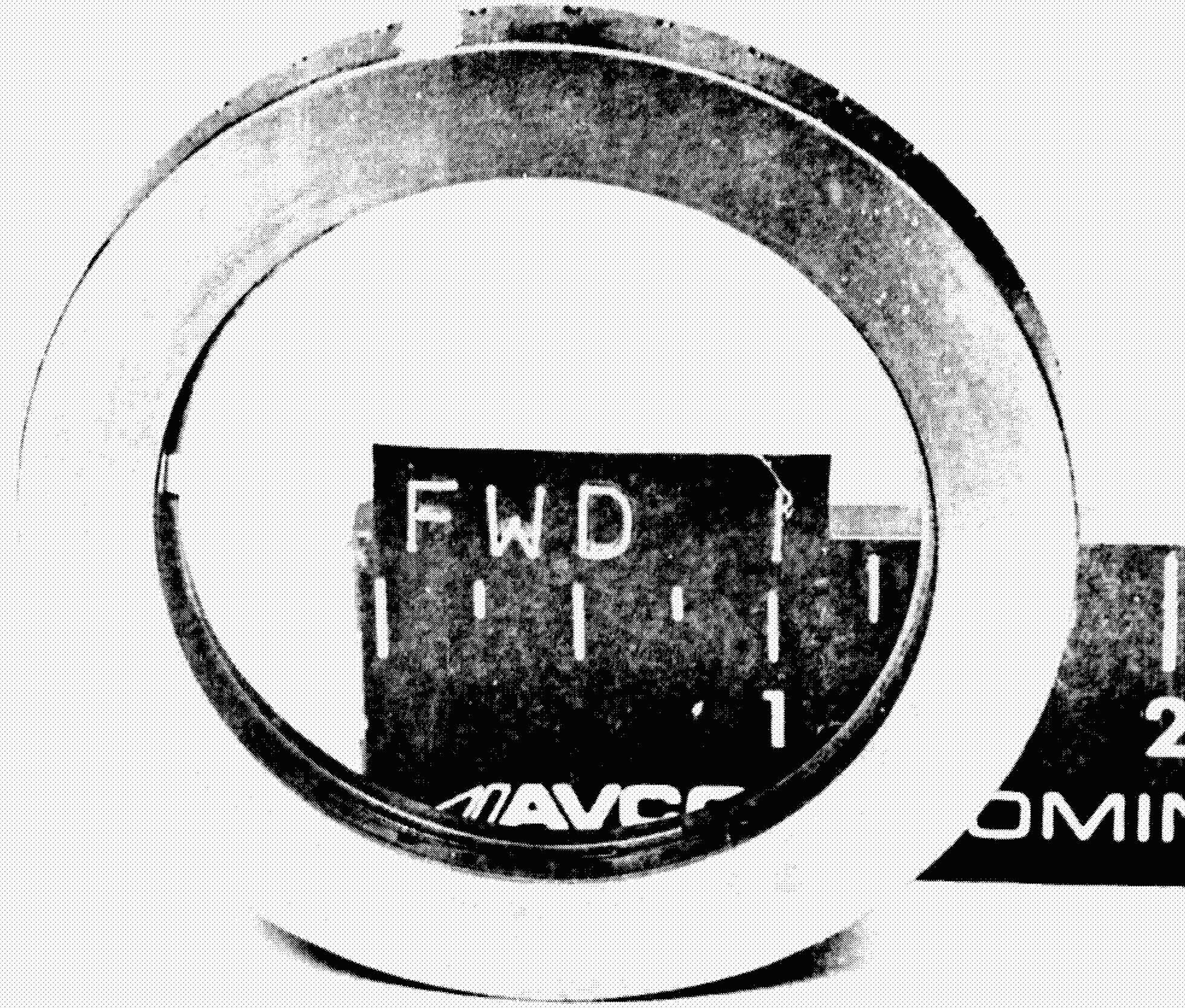

Figure 9. Close-up of Forward Seal Seat Prior to Build I.

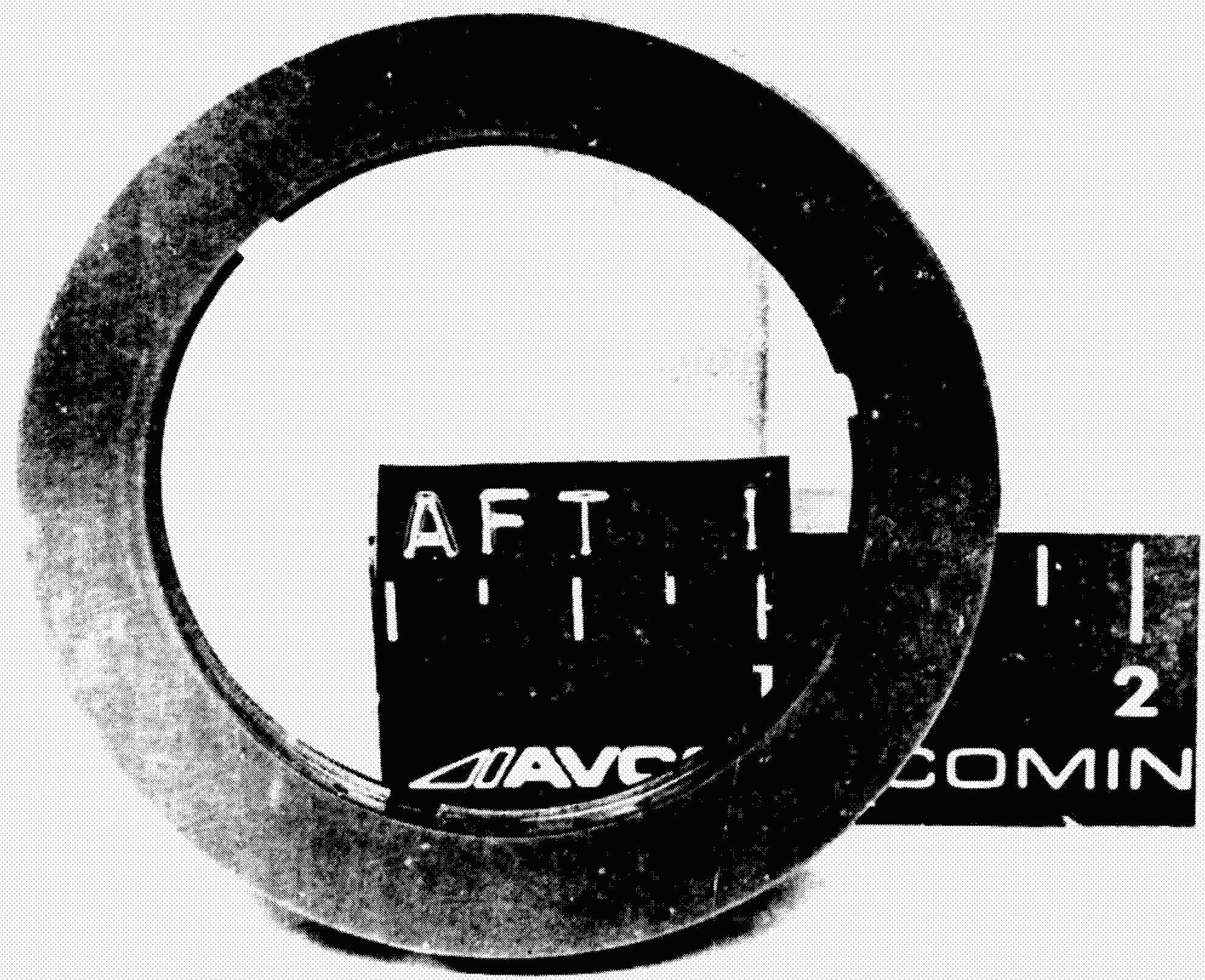

Figure 10. Close-up Aft Seal Seat Prior to Build I.

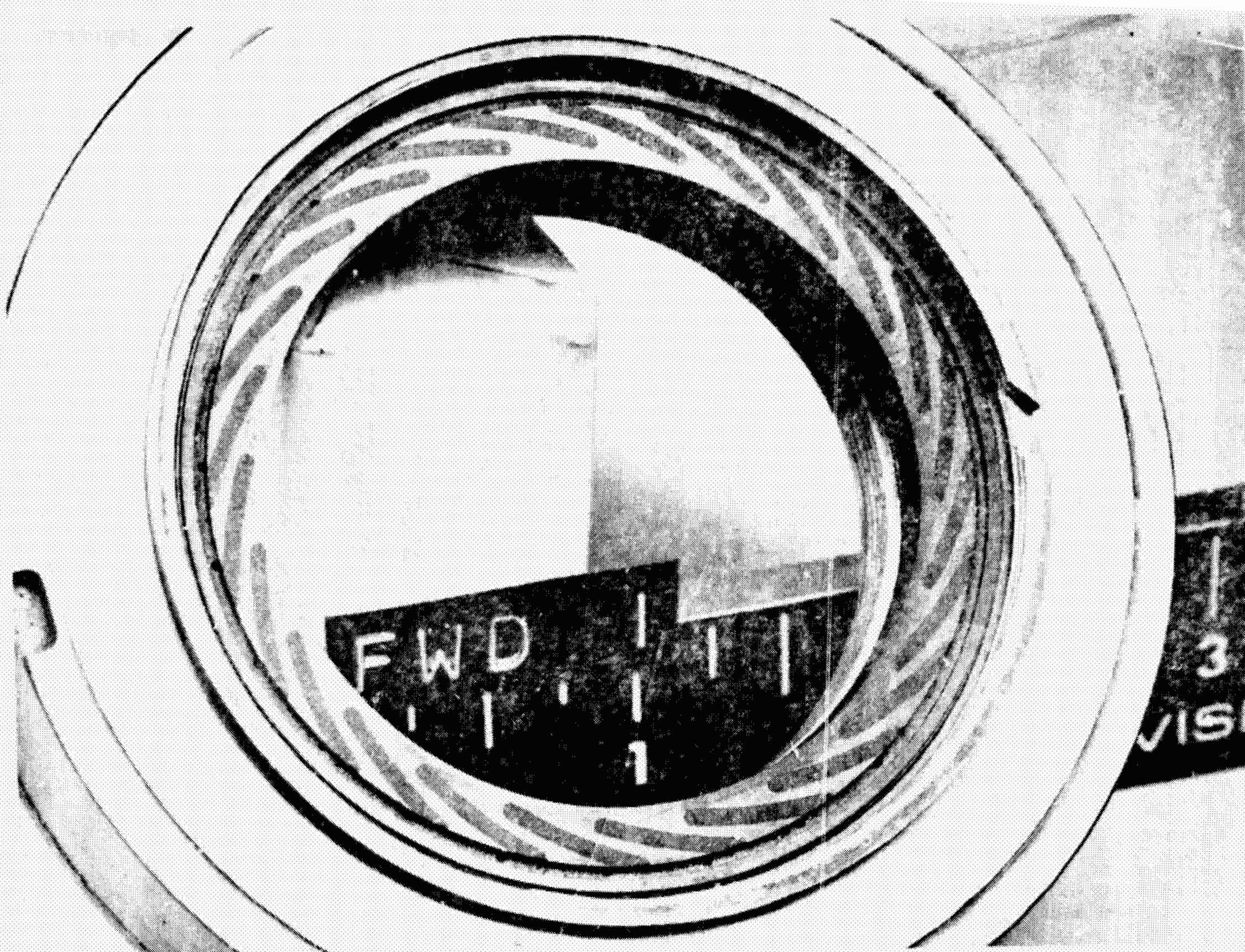

Figure 11. Close-up of Forward Seal Spiral Groove Geometry Prior to Build I.

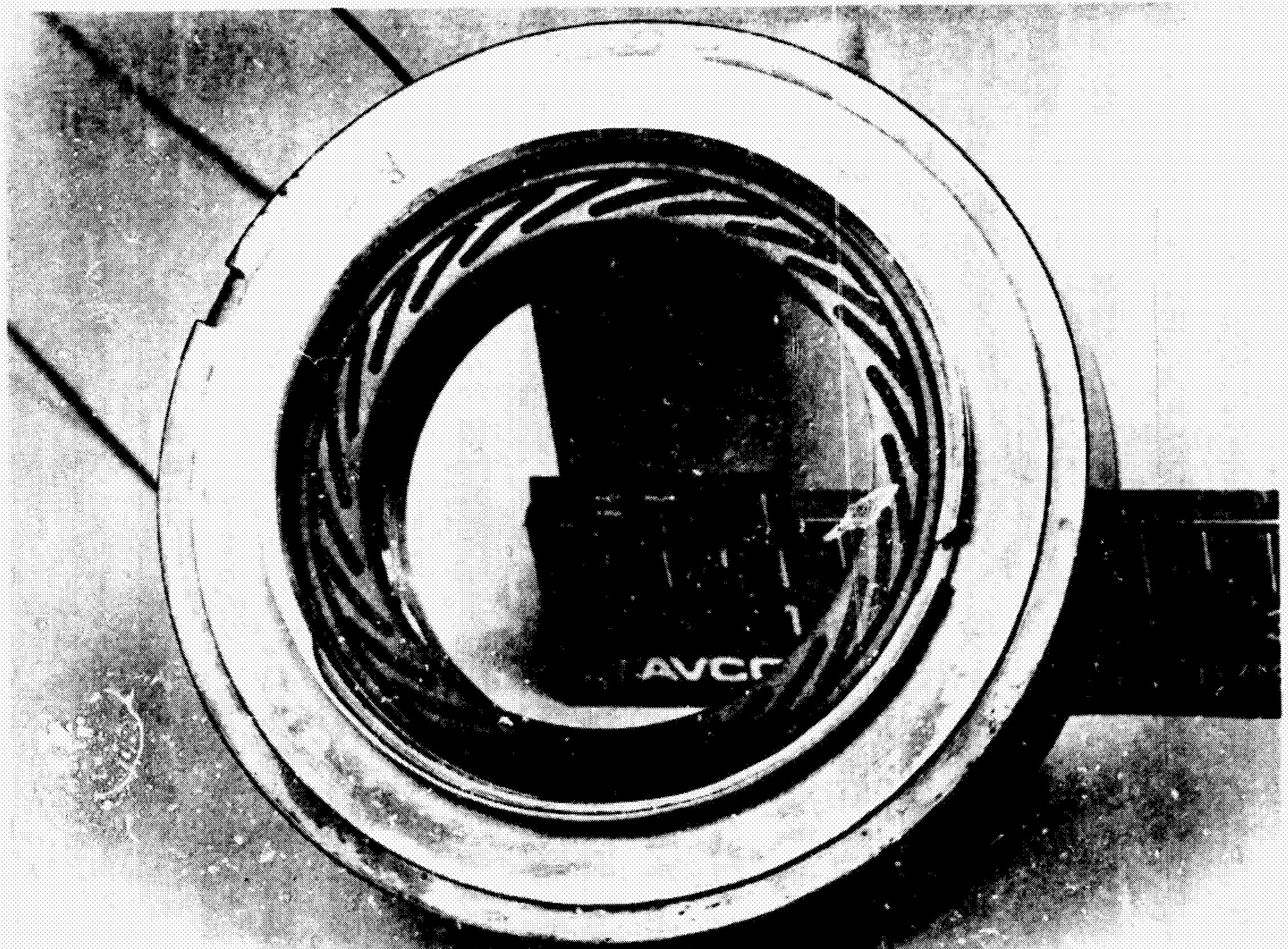

Figure 12. Close-up of Aft Seal Spiral Groove Geometry Prior to Build I.

TABLE II. BUILD I DATA SUMMARY

	SPEED			AIR PRESSURE			CAVITY PRESSURE		AIRFLOW			SEAL TEMP			
												FWD		AFT	
RUN	M/S	(FT/SEC)	(RPM)	(N/cm² abs)	(PSIA)		(N/cm² abs)	(PSIA)	(Kg/s)	(SCFM)	(lb/sec)	K	°F	K	°F
1	91.4	300	26,900	79.3	115		16.8	24.4	.0027	4.8	.0060	-	-	-	-
2	121.9	400	35,900	79.3	115		17.0	24.7	.0022	3.8	.0048	-	-	-	-
3	91.4	300	26,900	113.8	165		16.9	24.5	.0022	3.8	.0048	-	-	-	-
4	121.9	400	35,900	113.8	165		17.7	25.7	.0024	4.2	.0054	-	-	-	-
5	91.4	300	26,900	148.2	215		17.0	24.7	.0028	5.0	.0064	-	-	-	-
6	121.9	400	35,900	148.2	215		20.5	29.7	.0031	5.5	.0070	-	-	-	-
7	91.4	300	26,900	79.3	115		17.7	21.7	.0014	2.5	.0031	-	-	-	-
8	121.9	400	35,900	79.3	115		15.7	22.7	.0014	2.5	.0031	-	-	-	-
9	152.4	500	45,100	79.3	115		17.7	25.7	.0019	3.3	.0042	-	-	-	-
10	91.4	300	26,900	113.8	165		17.4	23.2	.0028	5.0	.0064	-	-	-	-
11	121.9	400	35,900	113.8	165		18.1	26.2	.0026	4.6	.0058	-	-	-	-
12	152.4	500	45,100	113.8	165		19.8	28.7	.0030	5.3	.0068	-	-	-	-
13	121.9	400	35,900	148.2	215		20.5	29.7	.0037	6.5	.0083	-	-	-	-
14	152.4	500	45,100	148.2	215		21.2	30.7	.0038	6.7	.0085	-	-	-	-
15	152.4	500	45,100	148.2	215		20.5	29.7	.0033	5.8	.0074	-	-	-	-
16	91.4	300	26,400	79.3	115		13.6	19.7	.0011	2.0	.0025	-	-	-	-
17	121.9	400	35,900	79.3	115		15.0	21.7	.0014	2.5	.0032	-	-	-	-
18	152.4	500	45,100	79.3	115		17.0	24.7	.0017	3.0	.0038	-	-	-	-
19	182.9	600	54,100	79.3	115		19.1	27.7	.0025	4.4	.0056	-	-	-	-
20	91.4	300	26,900	113.8	165		15.7	22.7	.0020	3.5	.0045	-	-	-	-
21	121.9	400	35,900	113.8	165		17.0	24.7	.0022	4.0	.0051	-	-	-	-
22	152.4	500	45,100	113.8	165		18.4	26.7	.0026	4.5	.0057	-	-	-	-
23	182.9	600	54,100	113.8	165		20.5	29.7	.0028	4.9	.0062	-	-	-	-
24	91.4	300	26,900	148.2	215		18.4	26.7	.0031	5.5	.0070	-	-	-	-
25	121.9	400	35,900	148.2	215		19.1	27.7	.0029	5.2	.0066	-	-	-	-
26	152.4	500	45,100	148.2	215		20.5	29.7	.0033	5.8	.0074	-	-	-	-
27	182.9	600	54,100	148.2	215		22.5	32.7	.0036	6.4	.0081	-	-	-	-

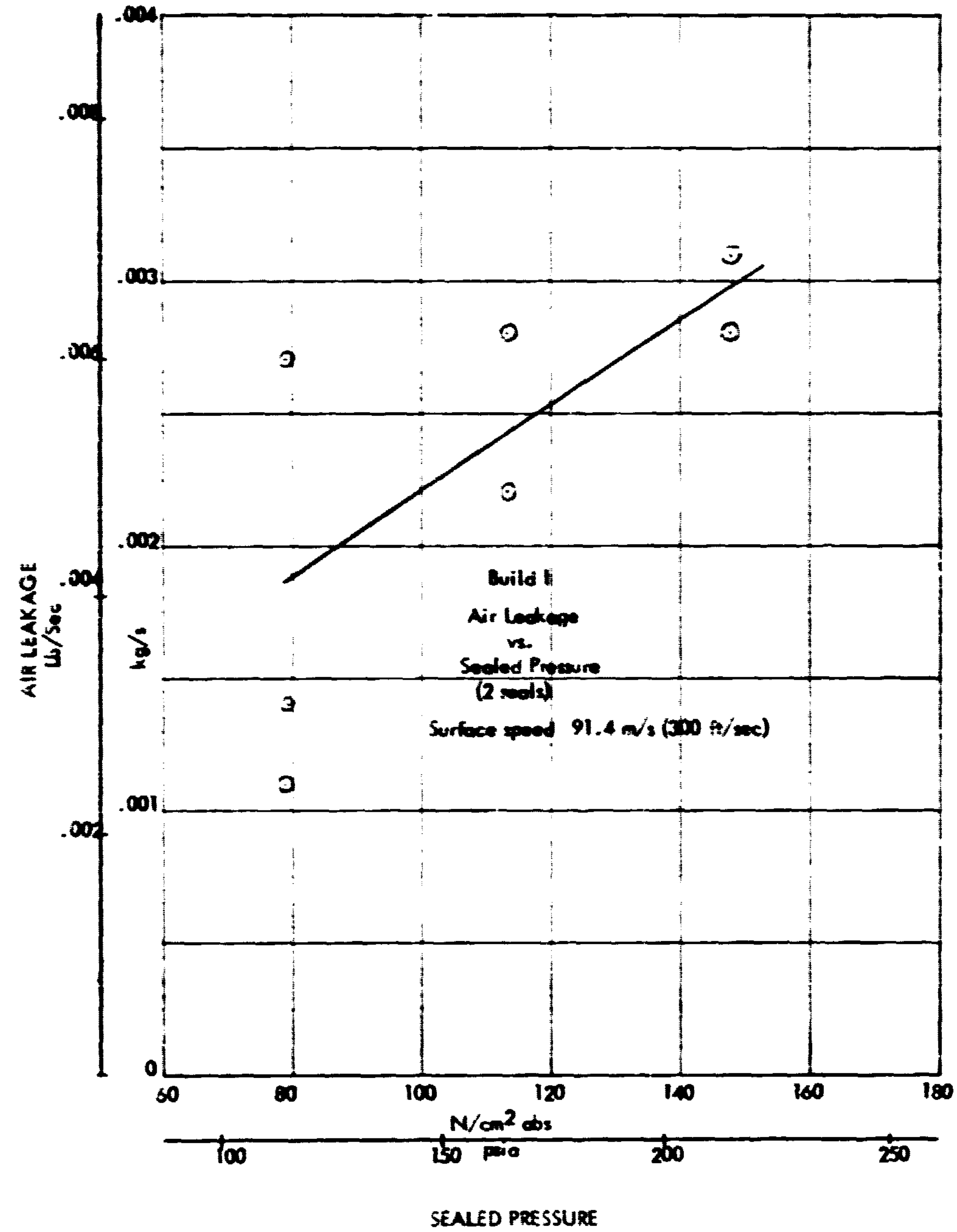

Figure 13. Seal Air Leak ge Versus Sealed Pressure, Build I - 91.3 m/s (300 ft/sec).

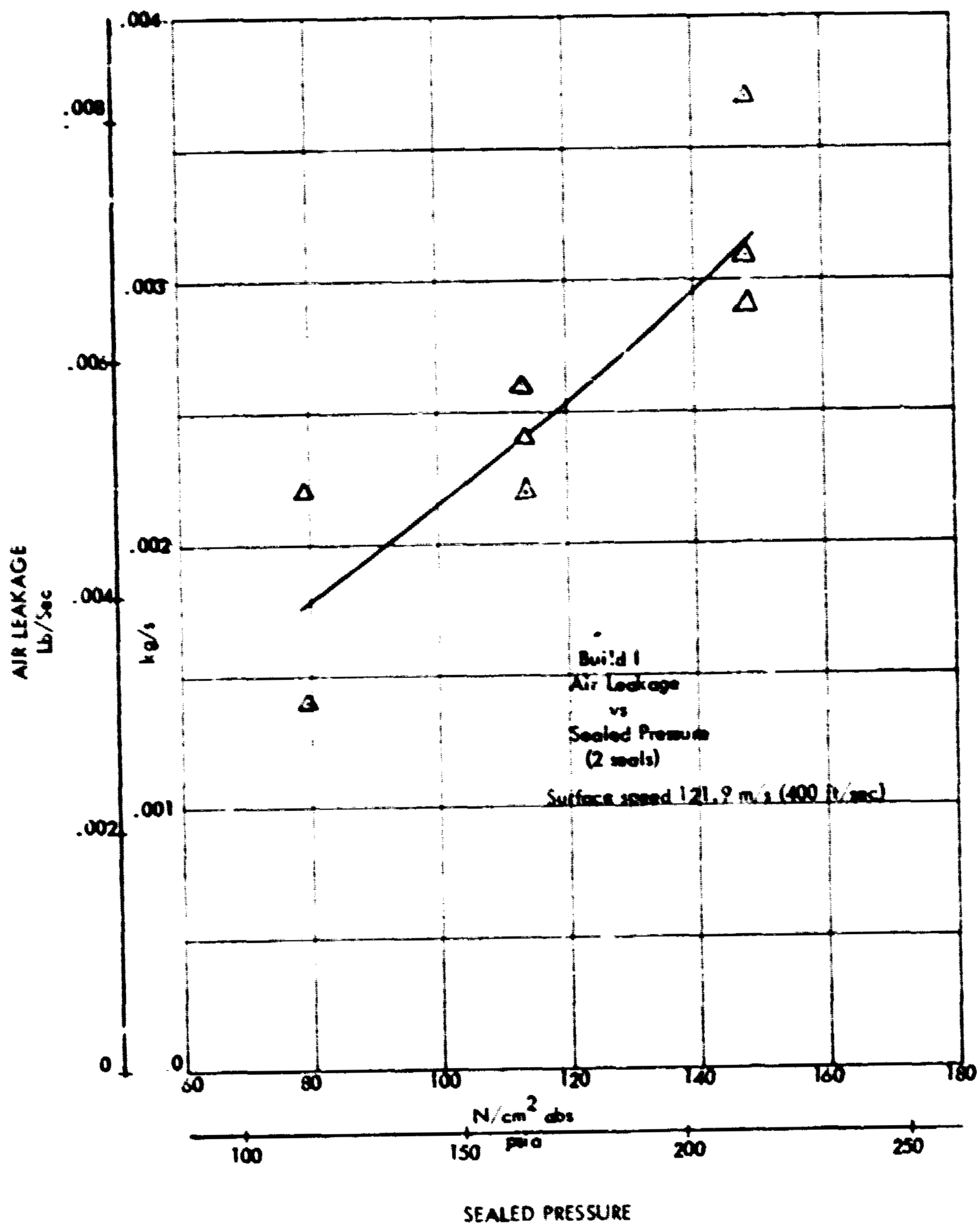

Figure 14. Seal Air Leakage Versus Sealed Pressure, Build I - 121.9 m/s (400 ft/sec).

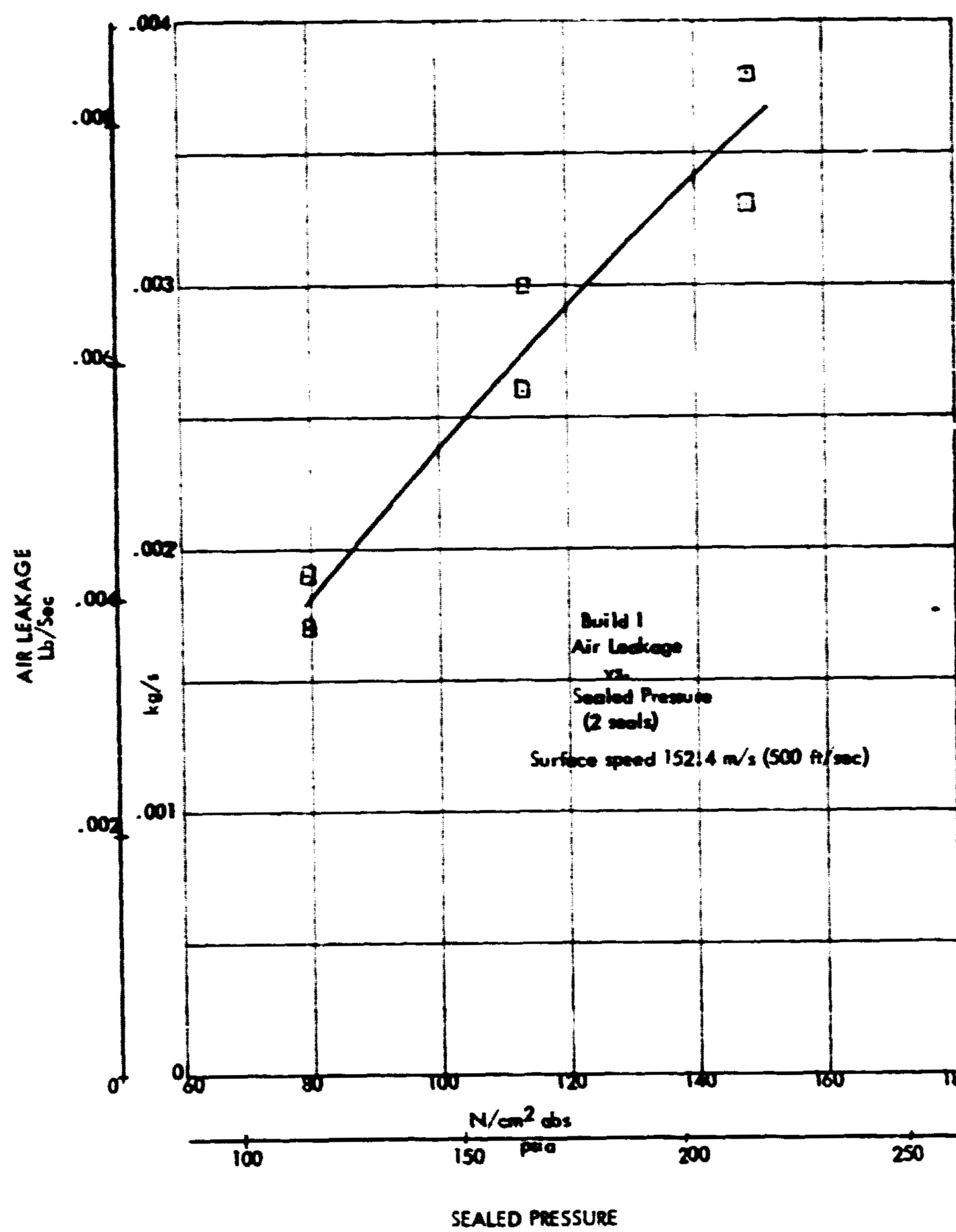

Figure 15. Seal Air Leakage Versus Sealed Pressure, Build I - 152 m/s (500 ft/sec).

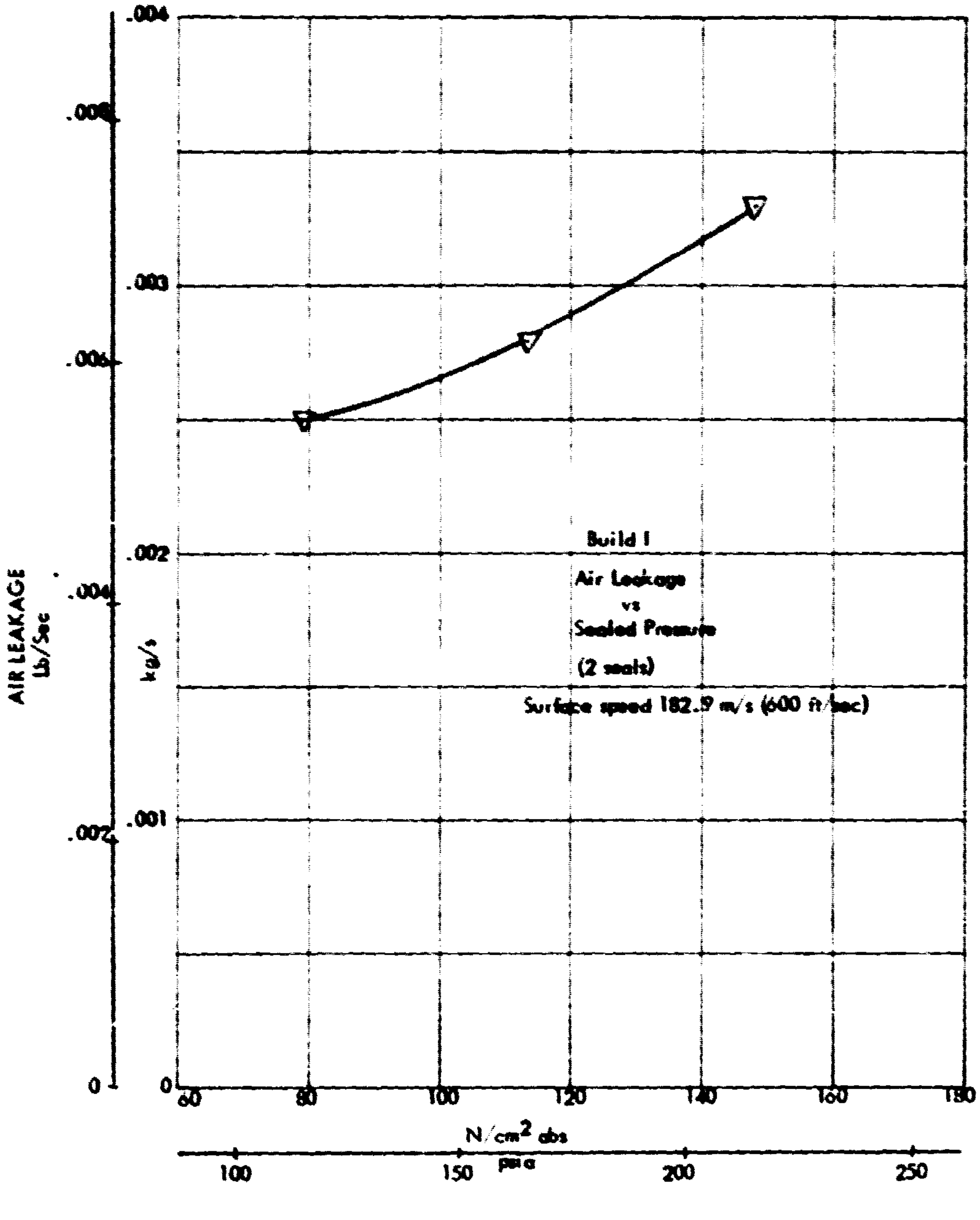

Figure 16. Seal Air Leakage Versus Sealed Pressure, Build I - 182.9 m/s (600 ft/sec).

TABLE III. CHANGES IN FACE DIMENSIONS, EVALUATION TEST, BUILD I

Forward Seal (new)			Condition Before Build I	Aft Seal		
Groove - cm (in)	Dam - cm(in)	I.D. - cm(in)	Location	Groove - cm(in)	Dam - cm(in)	I.D - cm(in)
.001460 (.000575)	.001330 (.000525)	.001397 (.000550)	1	.00305 (.001200)	.00305 (.001200)	.00305(.00120)
.001390 (.000550)	.001390 (.000550)	.00133 (.000525)	2	.00279 (.00110)	.00279 (.00110)	.00285(.001125)
.001580 (.000625)	.001520 (.000600)	.00146 (.000575)	3	.00267 (.00105)	.00267 (.00105)	.00267(.00105)
.001460 (.000575)	.001460 (.000575)	.001397 (.00055)	4	.00305 (.00120)	.00305 (.00120)	.003175(.00125)
.001470 (.000580)	.001430 (.0005631)	.00139 (.00055)	Average	.00288 (.001138)	.002889(.001138)	.00293(.001156)
Forward Seal			**Condition After Build I**	**Aft Seal**		
Groove - cm(in)	Dam - cm(in)	I.D -cm(in)	Location	Groove - cm(in)	Dam - cm(in)	I.D - cm(in)
.00152 (.00060)	.00152 (.00060)	.00152 (.00060)	1	.00305 (.00120)	.00305 (.00120)	.00305(.00120)
.00121 (.00475)	.00121 (.000475)	.00121 (.000475)	2	.002667 (.00105)	.002667 (.00105)	.002667(.00105)
.00139 (.00055)	.00139 (.00055)	.00108 (.000425)	3	.002730 (.001075)	.002667 (.00105)	.00254(.0010)
.00139 (.000590)	.00146 (.000575)	.00127 (.0005)	4	.00305 (.0012)	.00305 (.0012)	.00298(.001175)
.001349 (.000531)	.00139 (.00055)	.00127 (.0005)	Average	.00287 (.00113)	.00285 (.001125)	.00281(.001106)
			Net Average Wear (Build I)			
Groove - cm(in)	Dam - cm(in)	I.D - cm(in)		Groove - cm(in)	Dam - cm(in)	I.D - cm(in)
.000124 (.000049)	.000032 (.000013)	.000127 (.000050)		.000019 (.000008)	.000032 (.000013)	.000127(.00005)

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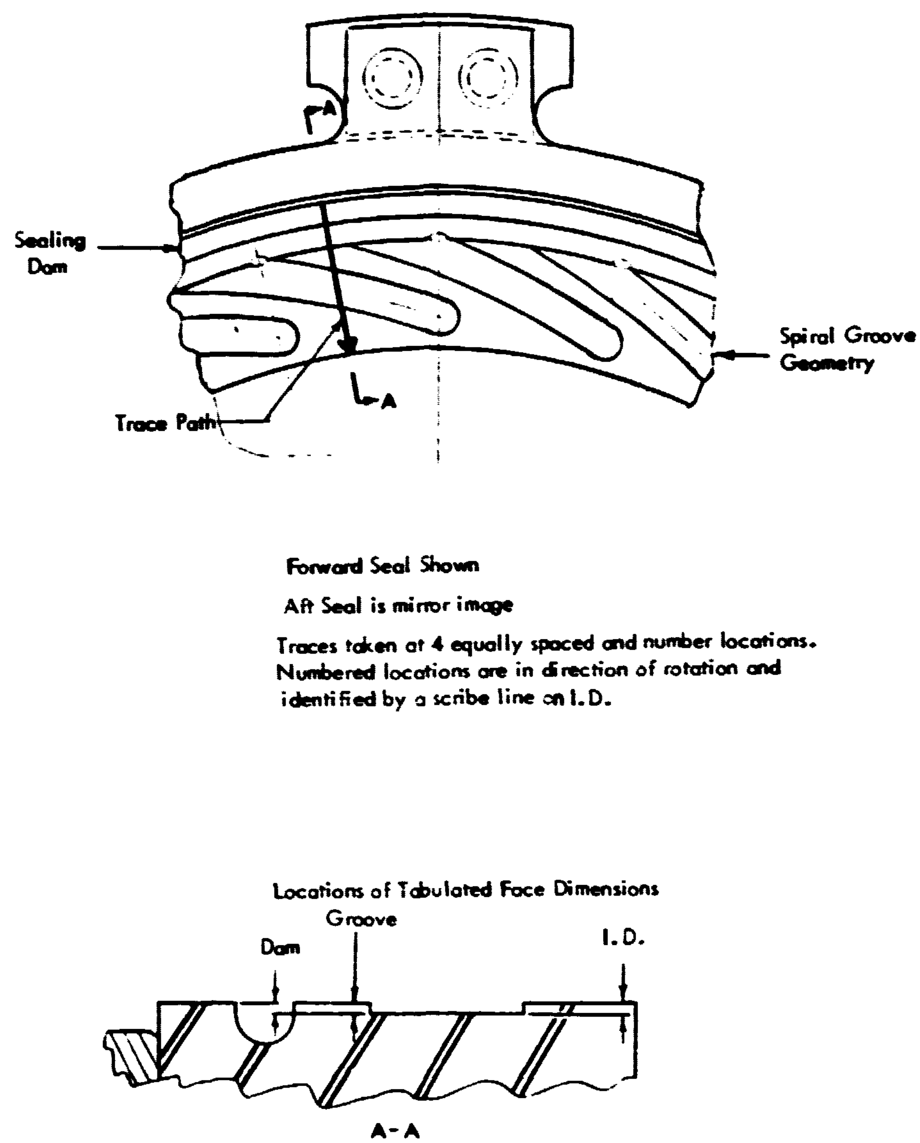

Figure 17. Locations of Wear Traces.

Forward Seal

Sealing dam	-	.000032 cm (.000013 in.)
Land adjacent groove	-	.000124 cm (.000049 in.)
Surface near ID	-	.000127 cm (.000050 in.)
Face average	-	.000094 cm (.000037 in.)
Average rate	-	.000011 cm/hr (.000004 in./hr)
Mimimum remaining groove depth	-	.000108 cm (.000425 in.)

Aft Seal

Sealing dam	-	.0000 318 cm (.000013 in.)
Land adjacent groove	-	.000019 cm (.000008 in.)
Surface near ID	-	.000127 cm (.000050 in.)
Face average	-	.000059 cm (.000023 in.)
Average rate	-	.000010 cm/hr (.000003 in./hr)
Minimum remaining groove depth	-	.002667 cm (.001050 in.)

Wear was found to be greatest and the appearance of rubbing most evident near the ID of the face. Wear of the sealing dam was uniform and very light in comparison with that experienced in previous programs (Reference 1). Figures 18 and 19 show the forward and aft seal assemblies after test. Close-up views of the spiral grooves and seats are shown in Figures 20 through 23.

The test rig was rebuilt with the same test seals to complete the performance evaluation.

Performance Evaluation, Build II (1.75 Hours)

Air Leakage

Air leakage results of Build II testing were not reported due to an anomaly in the build of the test rig. All data points were rerun during Build III testing. An out-of-position windback on the aft side of the test bearing package provided a direct air leakage path beneath the seal seat. The forward seal seat was reversed in position providing a bare TZM lapped surface to mate with the carbon sealing face.

Figure 18. Forward Seal and Seat After Build I Testing.

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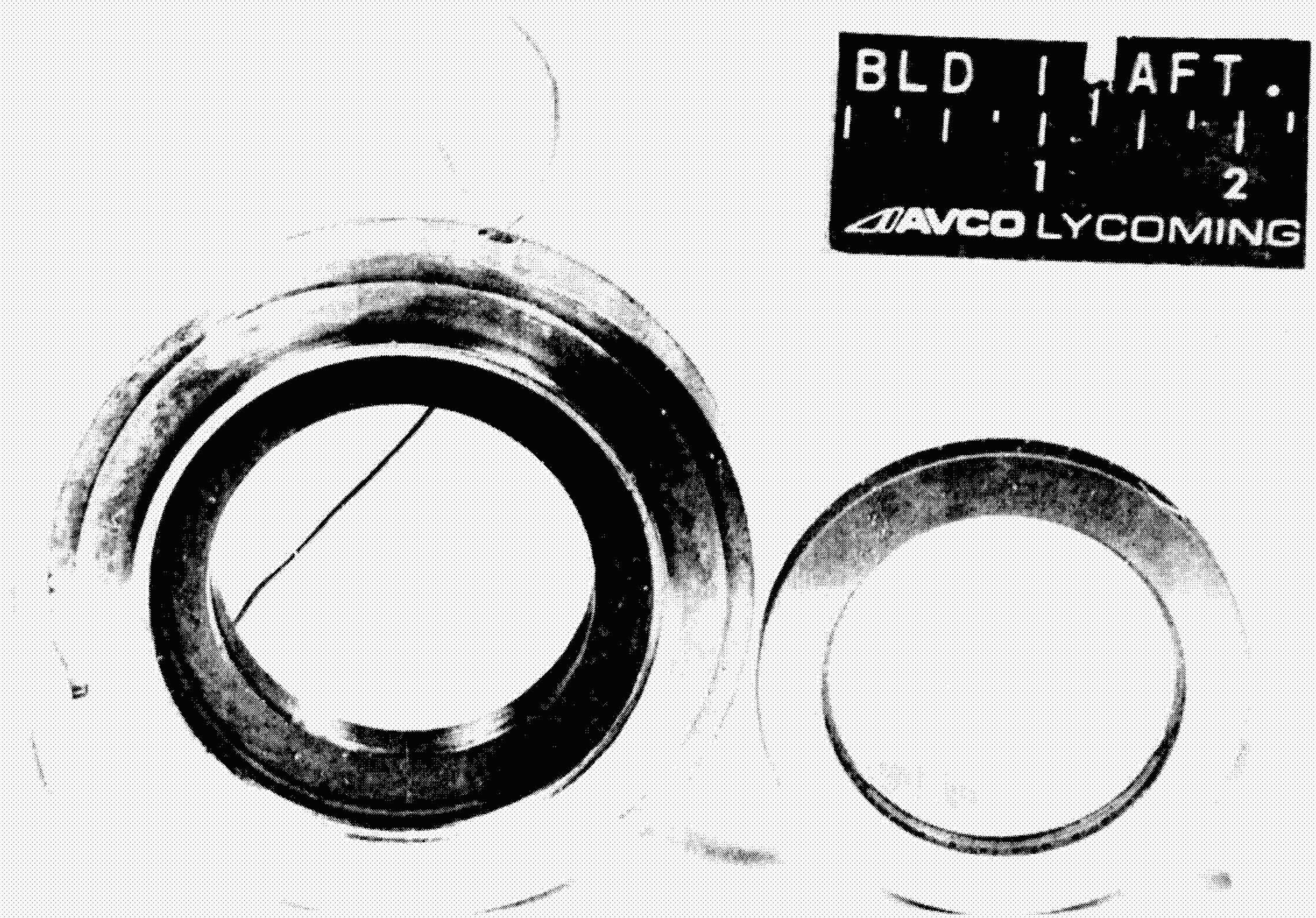

Figure 19. Aft Seal and Seat After Build I Testing.

Figure 20. Forward Seal Spiral Grooves After Build I Testing.

Figure 21. Aft Seal Spiral Grooves After Build I Testing.

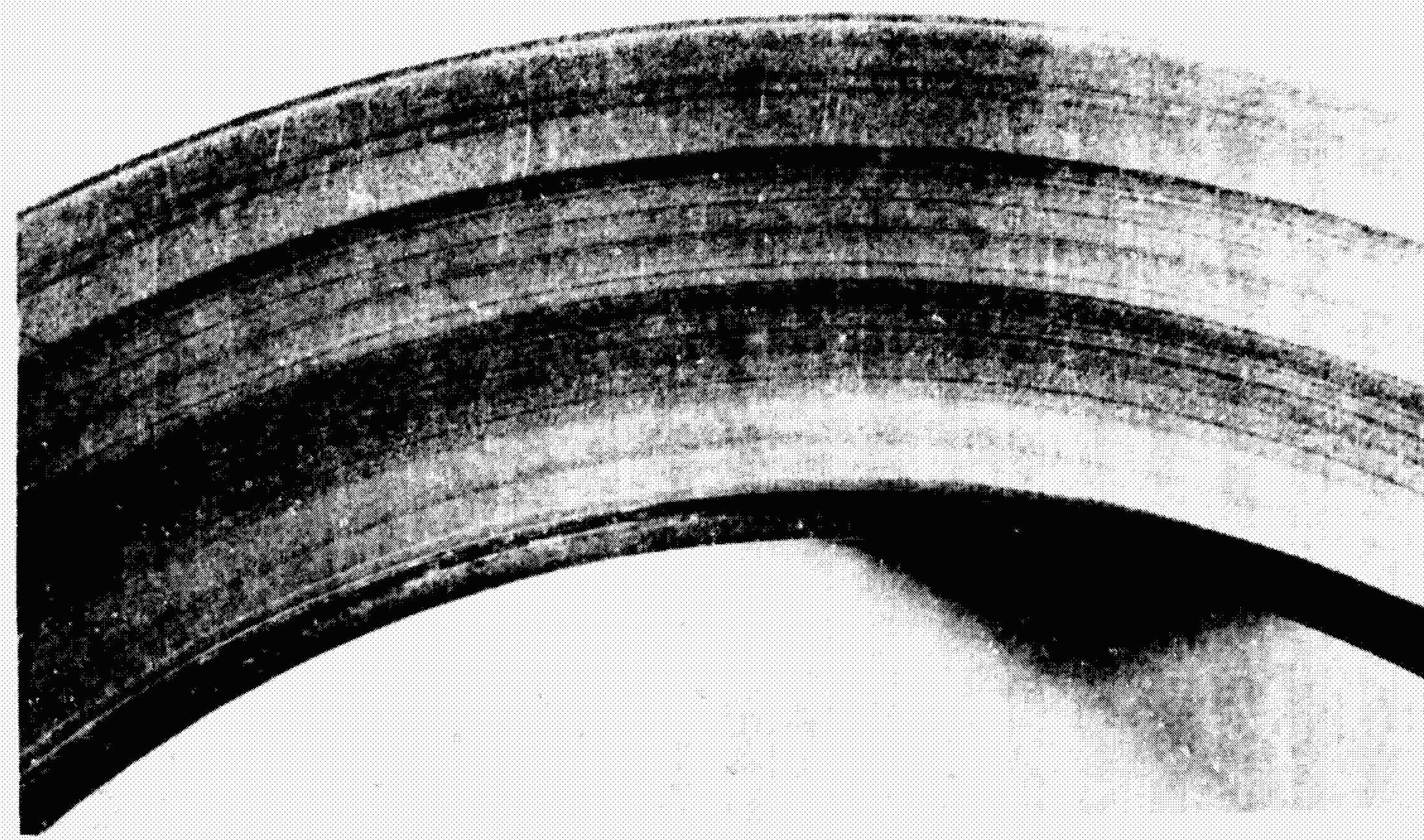

Figure 22. Forward Seal Seal After Build I Testing.

Figure 23. Aft Seal Seat After Build I Testing.

Seal Wear

The forward sealing element experienced extremely heavy wear operation under this condition. The aft seal experienced heavy wear also but appeared to be in good condition, despite operation with the loose seat. Initial spiral groove depth of the aft seal was .00287 cm (.00113 in.) compared to .001349 cm (.00055 in.) depth of the forward seal groove. Because of the initially deeper grooves, the aft seal was still usable despite the wear. Observed seal wear was as follows:

Forward Seal

Sealing dam	-	.000556 cm (.000219 in.)
Land adjacent groove	-	.000457 cm (.000180 in.)
Surface near ID	-	.000349 cm (.0001381 in.)
Face average	-	.000454 cm (.000179 in.)
Average rate	-	.000260 cm/hr (.000102 in./hr)
Mininum remaining groove depth	-	.000702 cm (.000300 in.)

Aft Seal

Sealing dam	-	.000175 cm (.000069 in.)
Land adjacent groove	-	.000188 (.000074 in.)
Surface near ID	-	.000533 cm (.000210 in.)
Face average	-	.000230 cm (.000118 in.)
Average rate	-	.000171 cm/hr (.000067 in./hr)
Minimum remaining groove depth	-	.002413 cm (.000950 in.)

Figure 24 illustrates the forward and aft sealing elements after Build II testing. Figure 25 illustrated the back (normally nonsealing side) of seal seats with the forward seat illustrating contact marks from sealing element due to it being reversed. A wear ring on the aft seat, caused by unclamped operation can be seen. Figure 26 shows the opposite side (normally the sealing side) of the seats (contact side for aft seat). The forward sealing element, exhibiting heavy wear and shallow spiral-groove geometry, was replaced with a new part of Build III testing. Table IV illustrates changes in face dimensions after Build II testing.

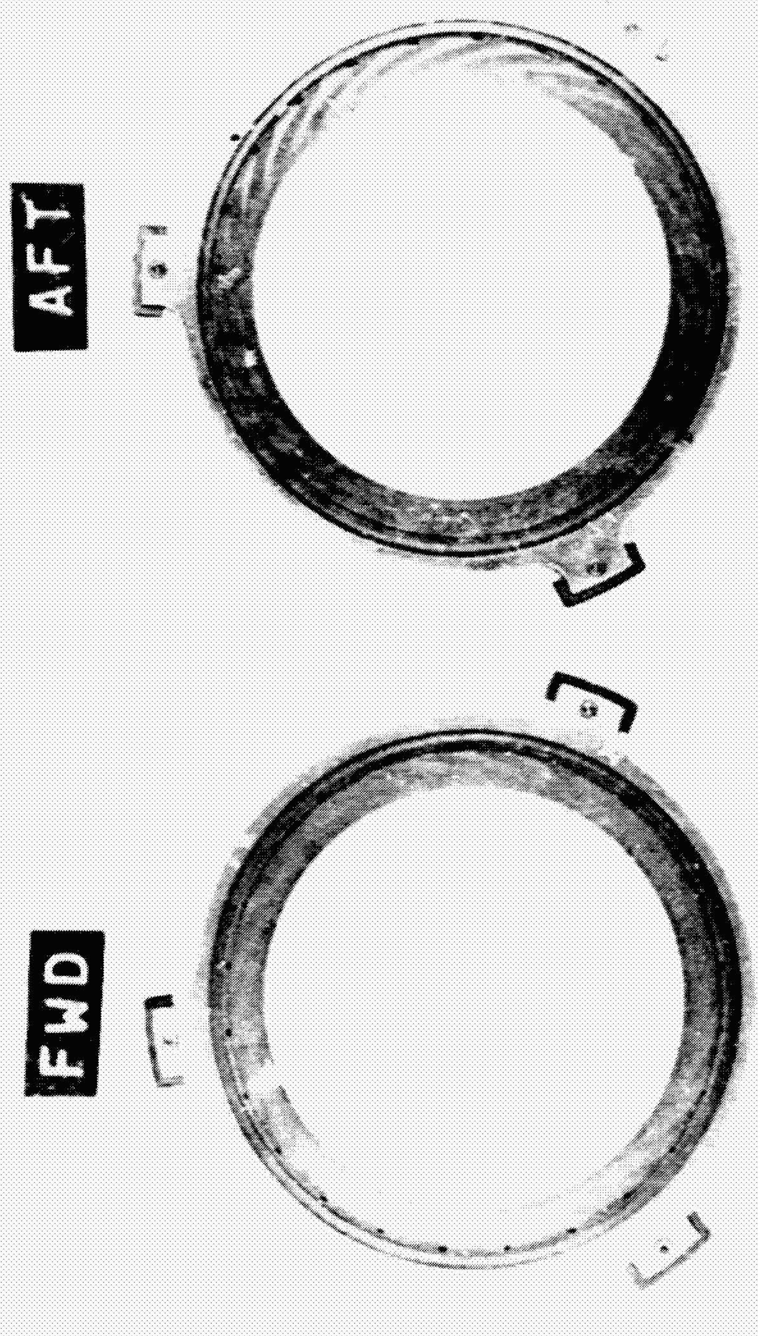

Figure 24. Forward and Aft Sealing Elements After Build II Testing.

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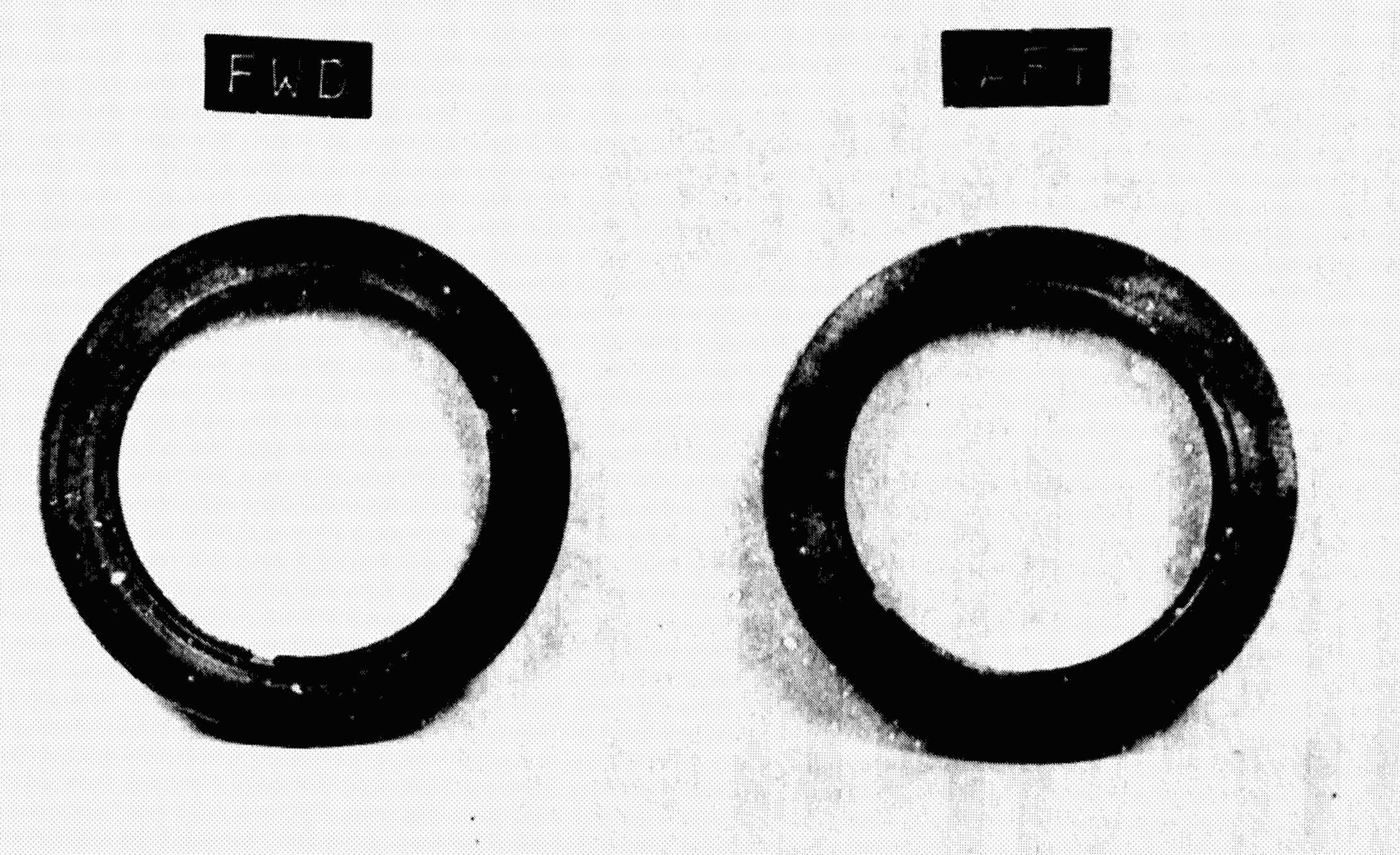

Figure 25. Back of Seal Seats After Build II Testing.

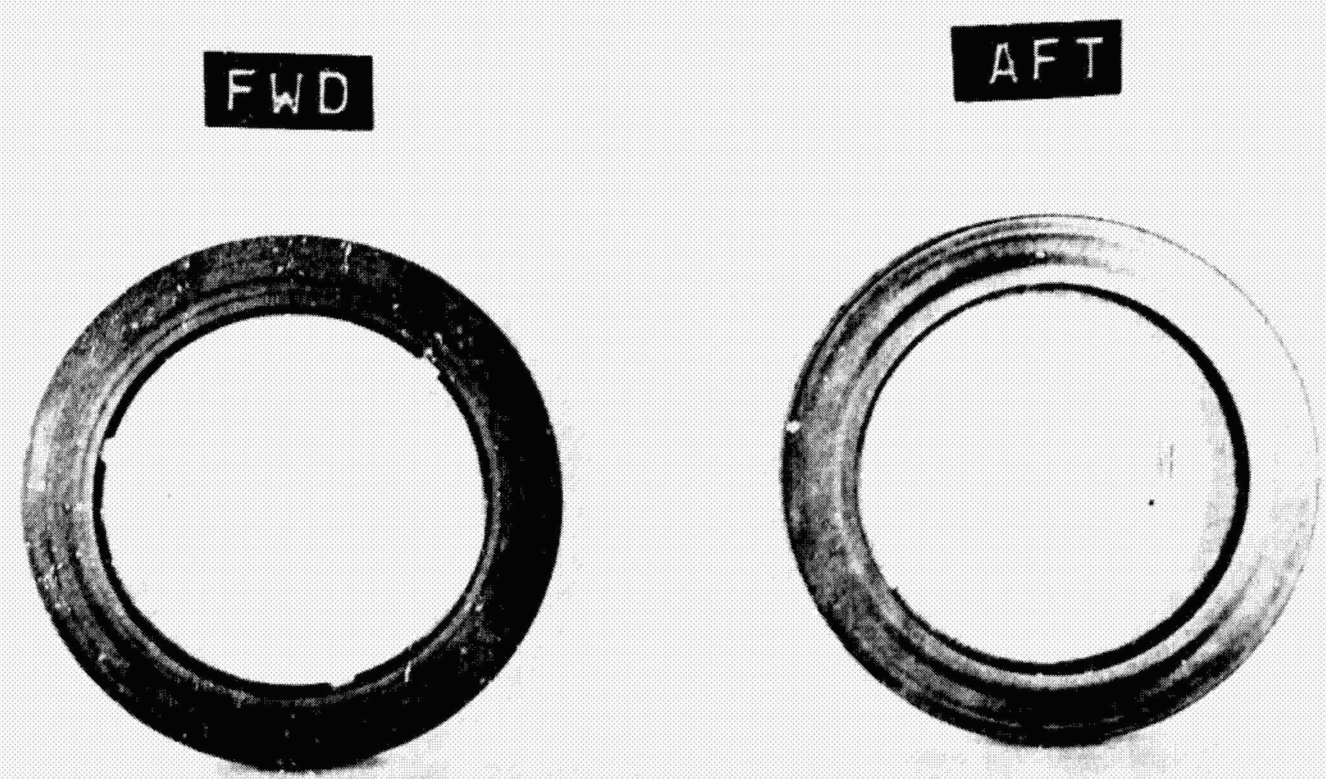

Figure 26. Front of Seal Seats After Build II Testing

TABLE IV. CHANGES IN FACE DIMENSIONS, EVALUATION TEST, BUILD II

Condition Before Build II

Forward Seal (new) Groove - cm (in)	Forward Seal (new) Dam - cm(in)	Forward Seal (new) I.D. - cm(in)	Location	Aft Seal Groove - cm(in)	Aft Seal Dam - cm(in)	Aft Seal I.D - cm(in)
.00152 (.00060)	.00152 (.00060)	.00152 (.00060)	1	.00305 (.00120)	.00305 (.00120)	.00305(.00120)
.00121 (.000425)	.00121 (.000475)	.00121 (.000425)	2	.002667 (.00105)	.002667 (.00105)	.002667(.00105)
.00139 (.00055)	.00139 (.00055)	.00108 (.000425)	3	.00273 (.001075)	.002667 (.00105)	.00254(.00100)
.00139 (.00055)	.00146 (.000575)	.00127 (.00050)	4	.00305 (.00113)	.00305 (.00120)	.00281(.001175)
.00135 (.0053)	.00140 (.00055)	.00127 (.0005)	Average	.00287 (.00113)	.00285 (.001125)	.00281(.001106)

Condition After Build II

Forward Seal Groove - cm(in)	Forward Seal Dam - cm(in)	Forward Seal I.D -cm(in)	Location	Aft Seal Groove - cm(in)	Aft Seal Dam - cm(in)	Aft Seal I.D - cm(in)
.001016 (.0004)	.001916 (.0004)	.001016 (.0004)	1	.00273 (.001075)	.00273 (.001075)	.00254(.0010)
.00082 (.000325)	.000508 (.0002)	.00082 (.000323)	2	.00254 (.0010)	.00254 (.0010)	.00238(.0009375)
.000762 (.00030)	.000762 (.0003)	.000762 (.00030)	3	.002413 (.00095)	.00241(.00095)	.00203(.0008)
.000953 (.000375)	.00108 (.000425)	.00108 (.000425)	4	.00305 (.00120)	.00268 (.001056)	.002421(.00095)
.000889 (.000350)	.000840 (.000331)	.000921(.000363)	Average	.00268 (.001056)	.00268 (.001056)	

Net Average Wear(Build II)

Forward Groove - cm(in)	Forward Dam - cm(in)	Forward I.D - cm(in)	Aft Groove - cm(in)	Aft Dam - cm(in)	Aft I.D - cm(in)
.000457 (.00018)	.000554 (.000219)	.000349 (.0001375)	.000188 (.000074)	.000175 (.000069)	.000533(.00021)

Performance Evaluation, Build III (6 Hours)

Data were taken at 24 test points during Build III testing. The duration of each test point was .25 hour. Maximum sealed pressure was 199.9 N/cm ^{2} abs (290 psia). A summary of test points run is presented in Table V.

Air Leakage

Air leakage data plotted as a function of airside pressure for the various surface speeds run is presented in Figures 27 through 30. As in Build I testing, air leakage increased as a function of sealed pressure and generally increased with shaft speed. The data exhibited spread as did Build I data, and a similar explanation applies. Air leakage was considerably higher than encountered during Build I testing at equivalent conditions. An investigation was made after disassembly with the following results:

	Forward Seal	Aft Seal
Dam flatness	.002230 cm (.000875 in.)*	.000508 cm (.000200 in.)*
Seat flatness	.000097 cm (.000038 in.)	.000170 cm (.000067 in.
Piston ring carrier ID	.001778 cm (.000700 in.)	.002286 cm (.000900 in.)
Piston ring carrier flatness	.000152 cm (.000060 in.)	.000508 cm (.000200 in.)

(*Suspect Items)

Considering blueprint requirements, the suspect items were identified as the sealing elements (flatness) and the aft piston ring carrier (flatness). These items were distorted significantly beyond blueprint flatness requirements (2 helium lightbands). The suspect items were changed prior to rebuilding for the endurance test. The seal seats were also changed since they were slightly over the desired flatness, and spare new hardware was available.

Seal Wear

The post-test condition of the seals was documented in Figure 31 and 32 . Changes in the seal face dimensions after Build III testing were measured with the following average wear results:

Forward Seal		
Sealing dam	-	.000175 cm (.000063 in.)
Land adjacent groove	-	.000260 cm (.000103 in.)

TABLE V. BUILD III DATA SUMMARY

RUN	SPEED M/S	SPEED (FT/SEC)	SPEED (RPM)	AIR PRESSURE (N/cm² abs)	AIR PRESSURE (PSIA)	CAVITY PRESSURE (N/cm² abs)	CAVITY PRESSURE (PSIA)	AIRFLOW (Kg/s)	AIRFLOW (SCFM)	AIRFLOW (lb/sec)	SEAL TEMP FWD K	SEAL TEMP FWD °F	SEAL TEMP AFT K	SEAL TEMP AFT °F
28	121.9	400	35,900	113.8	165	26.0	37.7	.0095	16.5	.021	362	192	429	174
29	152.4	500	45,100	113.8	165	28.1	40.7	.0050	9.0	.011	429	350	615	360
30	182.9	600	54,100	113.8	165	28.8	41.7	.0059	10.2	.013	640	385	651	396
31	121.9	400	35,900	148.2	215	25.3	36.7	.0086	15.0	.019	621	366	657	402
32	152.4	500	45,100	148.2	215	27.3	39.7	.0086	15.0	.019	629	374	681	426
33	182.9	600	54,100	148.2	215	29.4	42.7	.0104	18.0	.023	665	410	727	472
34	121.9	400	35,900	182.7	265	27.4	39.7	.0104	18.0	.023	645	390	687	432
35	152.4	500	45,100	182.7	265	30.8	44.7	.0104	18.0	.023	645	390	711	456
36	182.9	600	54,100	182.7	265	33.6	48.7	.0118	21.0	.027	667	412	725	470
37	121.9	400	35,900	199.9	290	27.3	39.7	.0100	17.5	.022	627	372	693	438
38	152.4	500	45,100	199.9	290	23.9	34.7	.0091	16.0	.020	613	358	665	410
39	182.9	600	54,100	199.9	290	28.1	40.7	.0095	17.0	.022	674	419	737	482
40	152.9	500	45,100	113.8	165	24.6	35.7	.0068	12.0	.015	625	370	655	400
41	182.4	600	54,100	113.8	165	30.1	43.7	.0091	16.0	.020	515	260	515	260
42	213.4	700	62,900	113.8	165	32.2	46.7	.0095	17.0	.022	641	386	661	406
43	152.4	500	45,100	148.2	215	23.9	34.7	.0073	13.0	.017	515	260	537	282
44	182.9	600	54,100	148.2	215	26.7	38.7	.0073	13.0	.017	675	420	727	472
45	213.4	700	62,900	148.2	215	29.4	42.7	.0086	15.0	.019	699	444	755	500
46	152.4	500	45,100	182.7	265	28.8	41.7	.0095	16.5	.021	665	410	721	466
47	182.9	600	54,100	182.7	265	31.5	45.7	.0104	18.5	.024	685	430	737	482
48	213.4	700	62,900	182.7	265	32.2	46.7	.0113	20.0	.025	711	456	769	514
49	152.4	500	45,100	199.9	290	28.1	40.7	.0091	16.0	.020	623	368	679	424
50	182.9	600	54,100	199.9	290	32.2	46.7	.0095	17.0	.022	659	404	727	472
51	213.4	700	62,900	199.9	290	36.3	52.7	.0118	21.0	.027	709	454	771	516

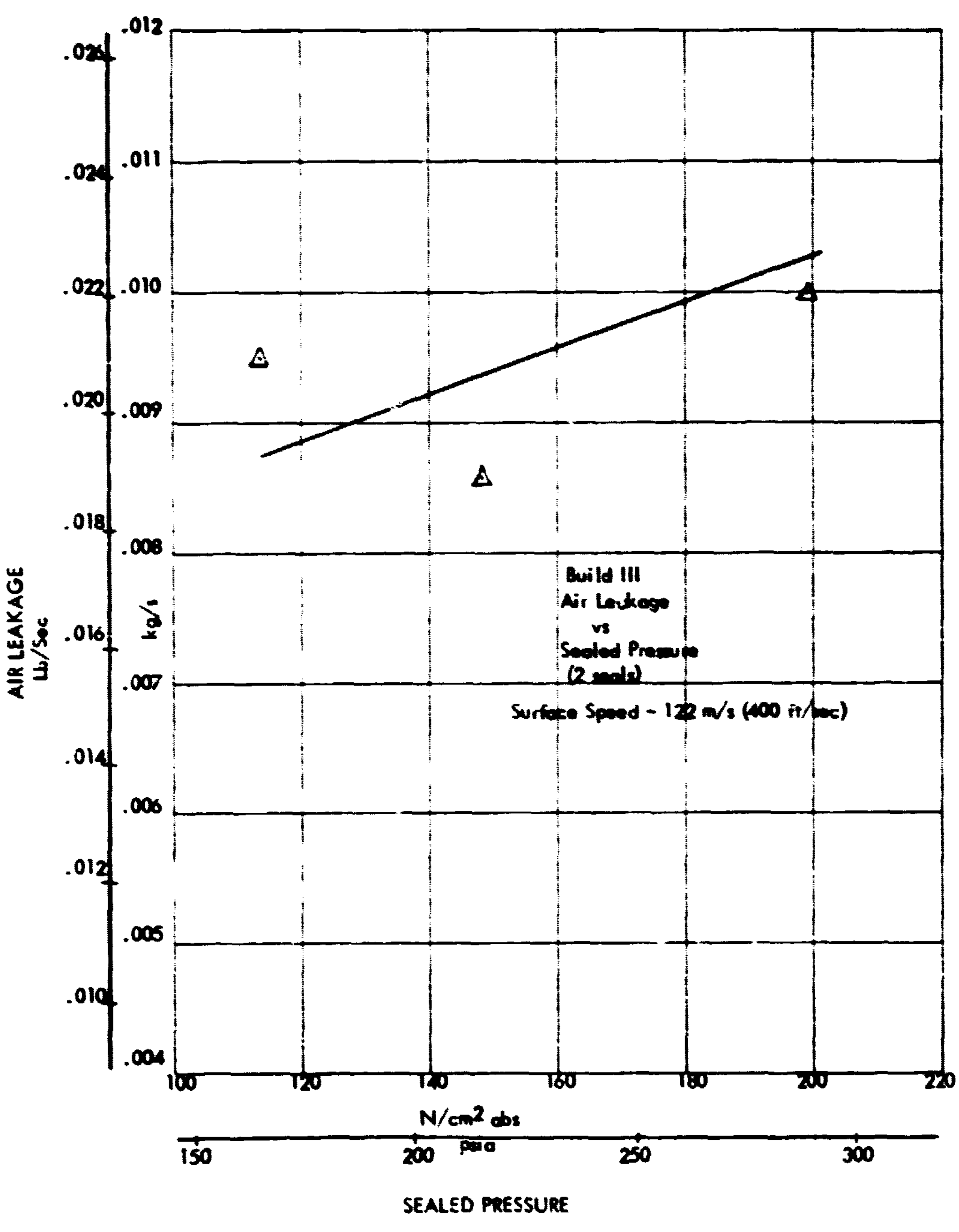

Figure 27. Seal Air Leakage Versus Sealed Pressure, Build III - 121.9 m/s (400 ft/sec).

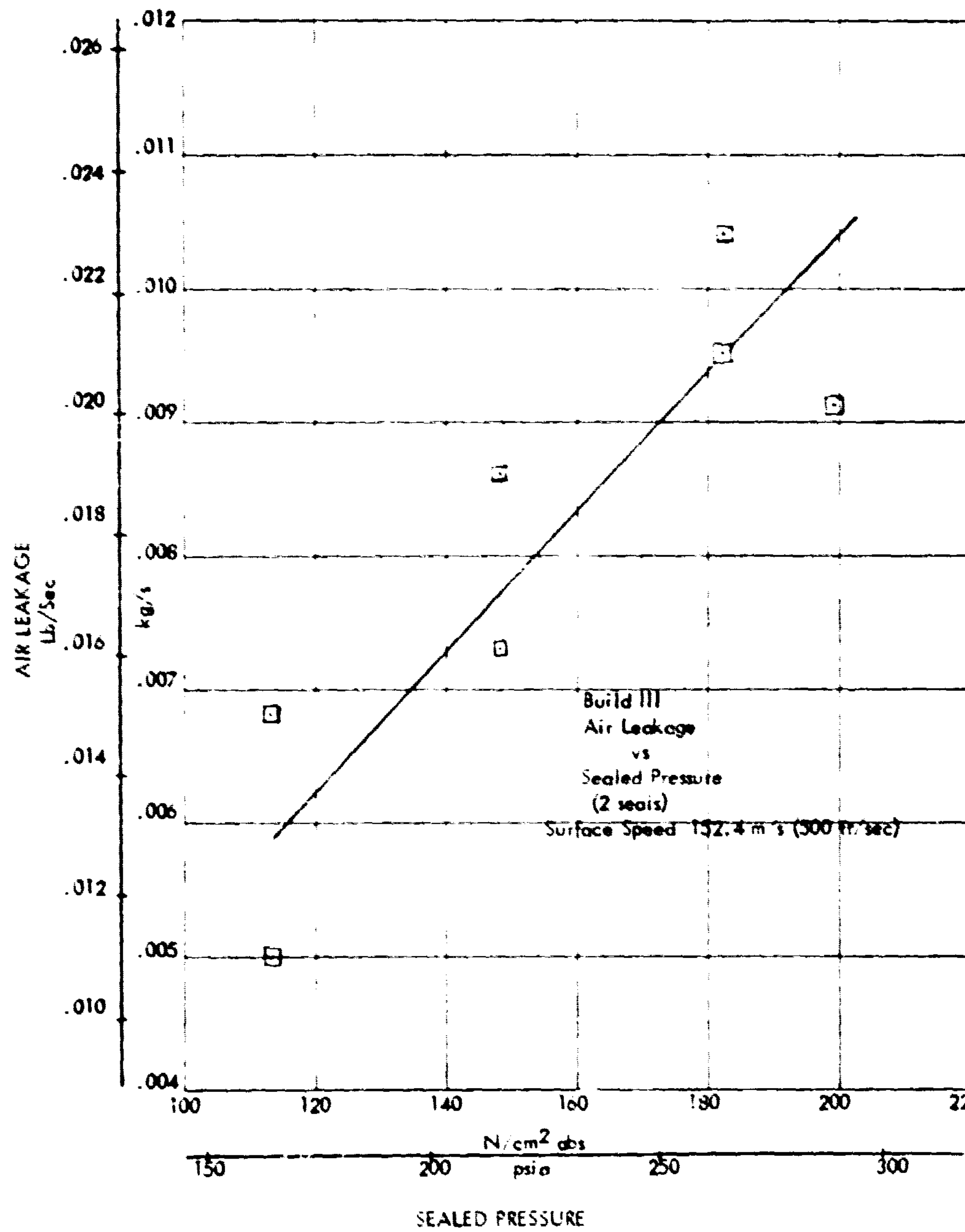

Figure 28. Seal Air Leakage Versus Sealed Pressure, Build III - 152 m/s (500 ft/sec).

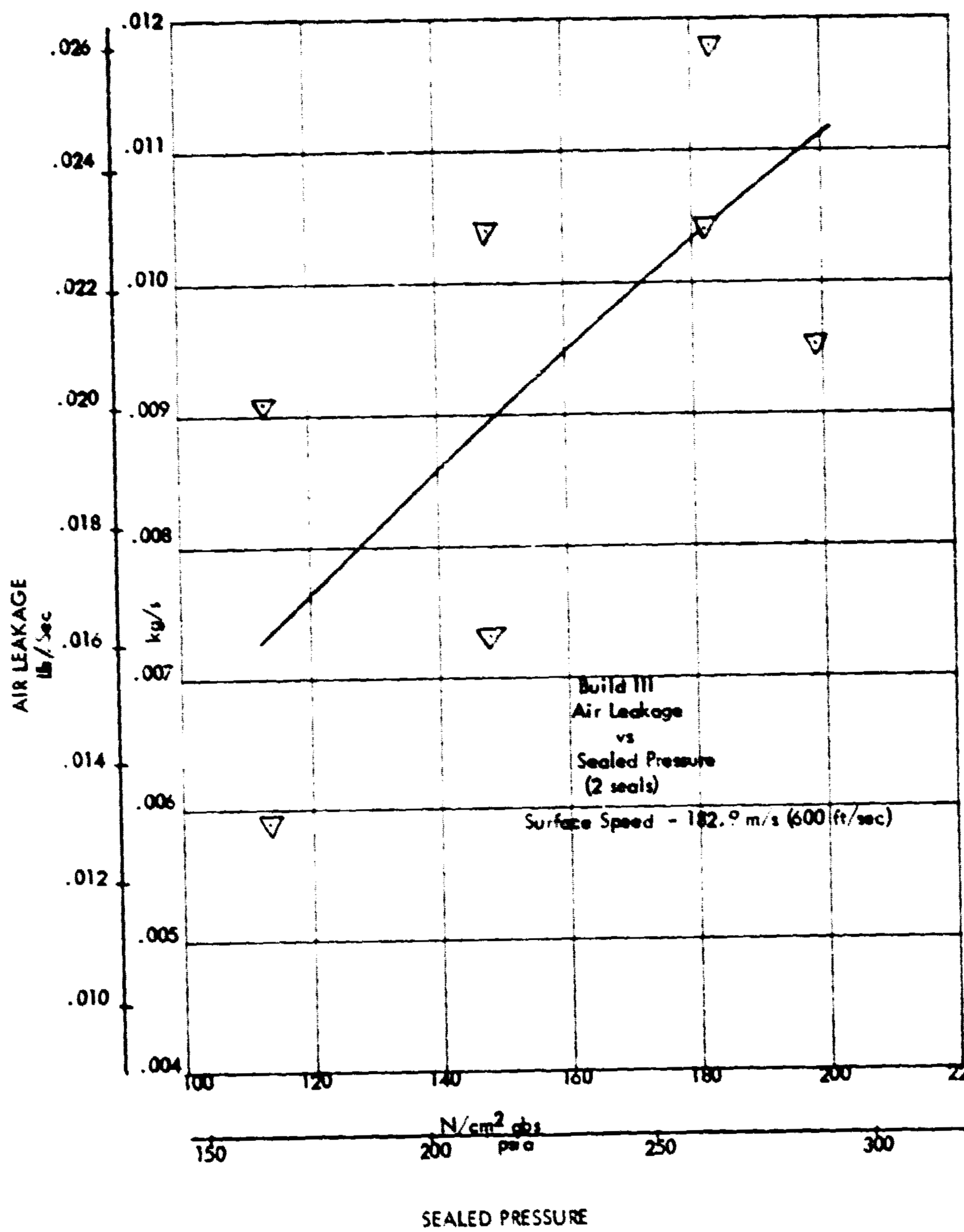

Figure 29. Seal Air Leakage Versus Sealed Pressure, Build III - 182.9 m/s (600 ft/sec).

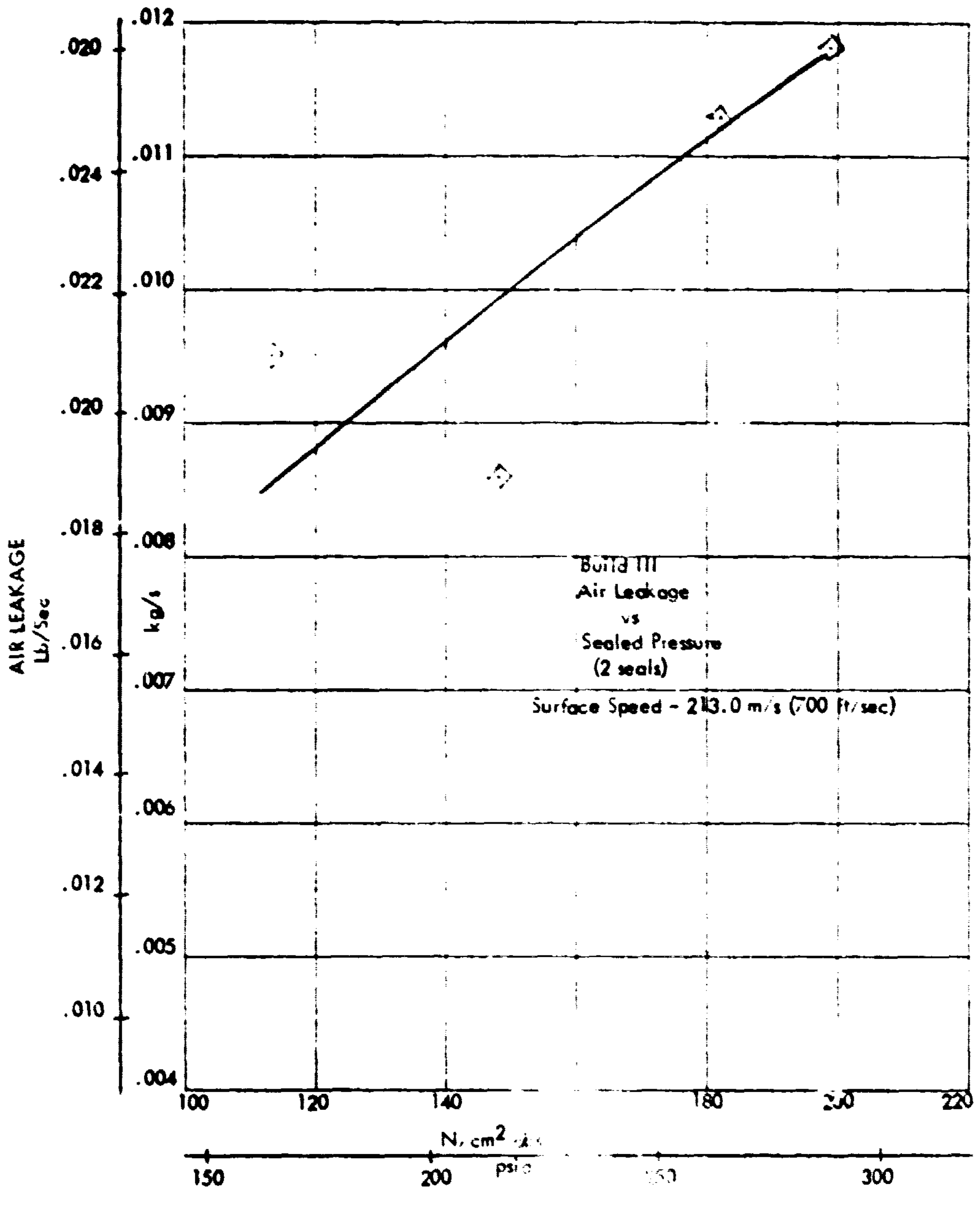

Figure 30. Seal Air Leakage Versus Sealed Pressure, Build III - 213 m/s (700 ft/sec).

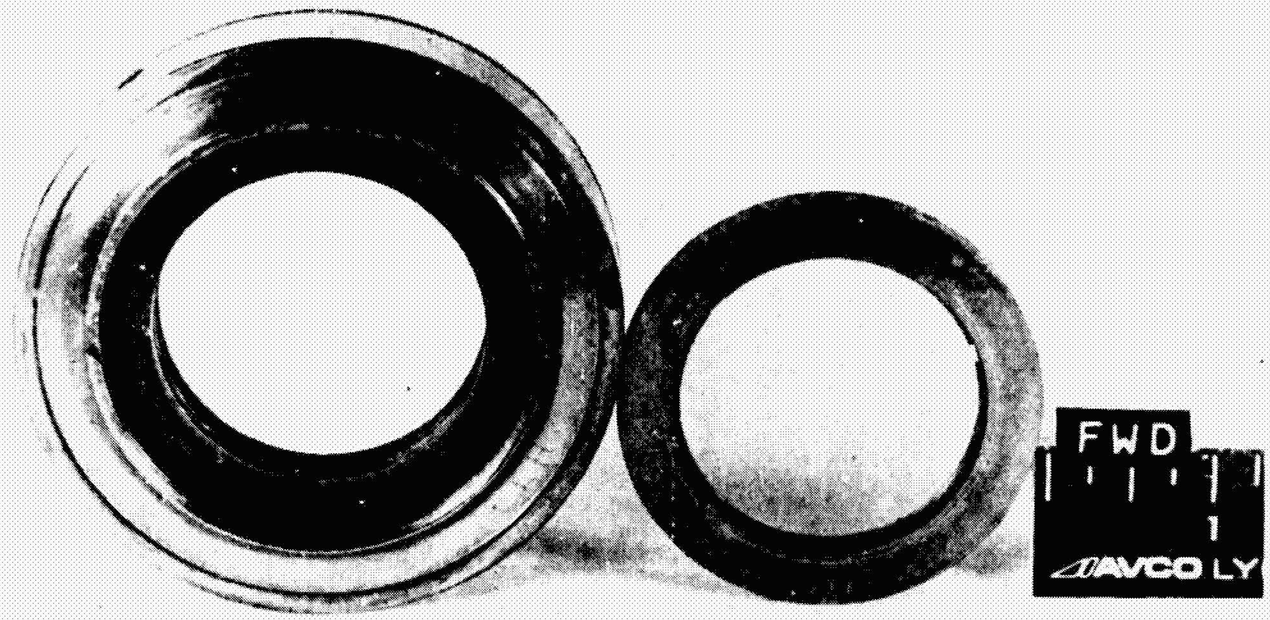

Figure 31. Forward Seal After Build III Testing.

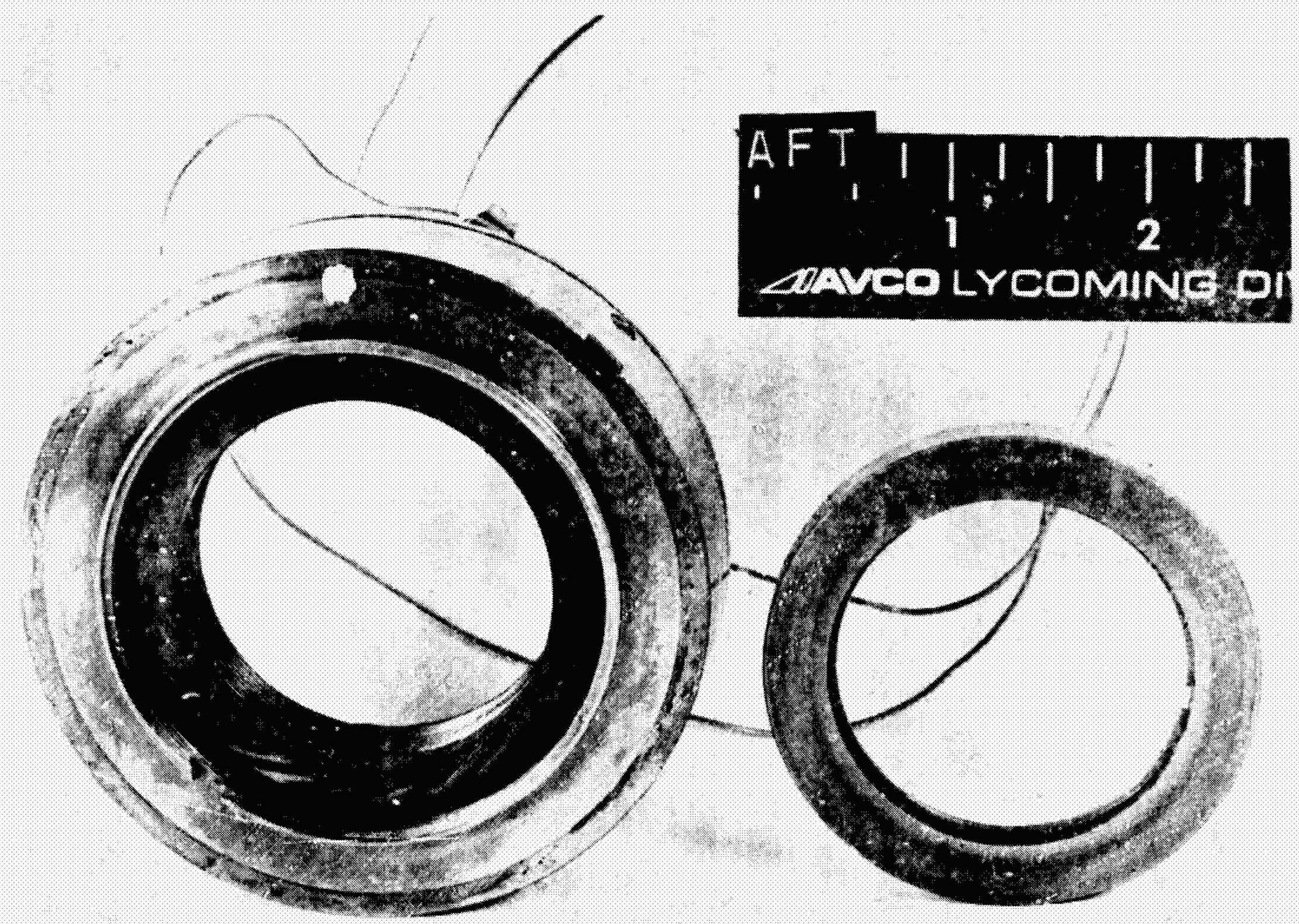

Figure 32. Aft Seal After Build III Testing.

Surface near ID	-	.000445 cm (.000175 in.)
Face average	-	.000293 cm (.000115 in.)
Average rate	-	.000048 cm/hr (.000019 in./hr)
Minimum remaining groove depth	-	.002349 cm (.000925 in.)

Aft Seal

Sealing dam	-	.000015 cm (.000006 in.)
Land adjacent groove	-	none measurable
Surface near ID	-	.000039 cm (.000015 in.)
Face average	-	.000028 cm (.000011 in.)
Average rate	-	.000005 cm/hr (.000002 in./hr)
Mininum remaining groove depth	-	.002413 cm (.000950 in.)

Maximum wear occurred at the surface near the ID of the sealing element. Average remaining groove depth (self-acting mechanism) was .002570 cm(.001010 in.) for the forward seal and .003030 cm (.001190 in.) for the aft seal. Face dimensions are summarized in Table VI.

Build III testing completed the performance evaluation.

Endurance Test, Build I (45 hours)

The endurance test encompassed 100.2 hours of operation at surface speeds to 243 m/s (800 ft/sec), sealed pressure to 148.14 N/cm^2 abs (215 psia), and sealed air temperatures of 645.4 K (702°F). A summary of the data points run is presented in Table VII. A test rig bearing problem necessitated interruption of the endurance test after 45 hours of operation. The test rig was rebuilt and seal hardware (seats, piston ring carriers, piston rings, and primary sealing elements) was changed. The damaged seal assemblies are pictured in Figures 23 through 38. During the failure, the seal seats contacted the seal housing, and the shaft rubbed the ID of the carbon sealing elements. The spiral-groove geometry remained intact except for radial cracks. Wear data was obtained but may have been influenced by the failure. These data are presented in Table VIII. Inspection of the seal housings revealed substantial oil coking within the housings and on some of the compression springs, tending to clog the coils. The interior of both seal housings and some typical coked springs are shown in Figure 38. The piston

TABLE VI. CHANGES IN FACE DIMENSIONS, EVALUATION TEST, BUILD III

Forward Seal (new)			Condition Before Build III	Aft Seal		
Groove - cm (in)	Dam - cm(in)	I.D. - cm(in)	Location	Groove - cm(in)	Dam - cm(in)	I.D - cm(in)
.003048 (.001200)	.003048 (.001200)	.003049 (.001200)	1	.002730 (.001075)	.002730 (.001075)	.002540(.001000)
.002600 (.001025)	.002600 (.001025)	.002600 (.001025)	2	.002540 (.001000)	.002540 (.001000)	.002380(.000938)
.002858 (.001125)	.002858 (.001125)	.002858 (.001125)	3	.002413 (.000950)	.002413 (.000950)	.002030(.000800)
.002794 (.001100)	.002794 (.001100)	.002794 (.001100)	4	.003050 (.001200)	.003050 (.001200)	.002730(.001075)
.002826 (.001113)	.002825 (.001113)	.002825 (.001113)	Average	.002628 (.001056)	.002680 (.001056)	.002421(.000095)

Forward Seal			Condition After Build III	Aft Seal		
Groove - cm(in)	Dam - cm(in)	I.D -cm(in)	Location	Groove - cm(in)	Dam - cm(in)	I.D - cm(in)
.002730 (.001075)	.002730 (.001075)	.002540 (.001000)	1	.002730 (.001075)	.002730 (.001075)	.002350(.000925)
.002413 (.000950)	.002540 (.001000)	.002540 (.001000)	2	.002540 (.001000)	.002476 (.000975)	.002413(.000950)
.002349 (.000925)	.002540 (.001000)	.001728 (.000700)	3	.002413 (.000950)	.002413 (.000950)	.002032(.000800)
.002790 (.001100)	.002790 (.001100)	.002667 (.001050)	4	.003048 (.001200)	.003048 (.001200)	.002794(.001100)
.002570 (.001010)	.00265[illegible] (.001044)	.002380 (.000938)	Average	.002680 (.001056)	.002667 (.001050)	.002390(.000935)

			Net Average Wear(Build III)			
Groove - cm(in)	Dam - cm(in)	I.D - cm(in)		Groove - cm(in)	Dam - cm(in)	I.D - cm(in)
.000260 (.000103)	.00175 (.000069)	.000445 (.00175)		.000000 (.000000)	.000015 (.000006)	.000034(.000015)

TABLE VII. ENDURANCE TEST DATA SUMMARY

HOURS RUN	SPEED (M/S)	SPEED (FT/SEC)	SPEED (RPM)	AIR PRESSURE (N/cm^2 abs)	AIR PRESSURE (PSIA)	CAVITY PRESSURE (N/cm^2 abs)	CAVITY PRESSURE (PSIA)	AIRFLOW (Kg/s)	AIRFLOW (SCFM)	AIRFLOW (lb/sec)	SEAL TEMP FWD K	SEAL TEMP FWD °F	SEAL TEMP AFT K	SEAL TEMP AFT °F
1	121.9	400	35,900	79.2	115	17.0	24.7	.0016	2.8	.0036	401	262	401	252
						17.0	24.7	.0015	2.6	.0033	445	342	441	334
3						17.0	24.7	.0016	2.8	.0036	439	330	439	330
4						18.4	26.7	.0022	3.8	.0048	438	328	453	356
5						18.4	26.7	.0021	3.5	.0045	426	308	451	352
6						18.1	26.7	.0019	3.3	.0042	431	316	455	360
7						18.4	26.2	.0020	3.4	.0043	433	320	459	366
8						18.4	26.7	.0023	4.0	.0051	431	316	457	364
9						18.4	26.7	.0022	3.8	.0048	433	320	456	362
10						17.0	24.7	.0020	3.4	.0043	439	330	464	376
11						17.0	24.7	.0021	3.5	.0045	435	324	454	358
12						17.0	24.7	.0021	3.5	.0045	439	330	461	370
13						17.0	24.7	.0020	3.4	.0043	443	338	463	374
14						15.6	22.7	.0012	2.1	.0027	433	320	443	339
15						15.6	22.7	.0012	2.0	.0025	437	326	442	336
16						16.3	23.7	.0014	2.4	.0031	420	296	433	320
17						16.3	23.7	.0014	2.4	.0031	433	320	442	335
18						15.6	22.7	.0012	2.0	.0025	434	321	444	340
19						15.6	22.7	.0013	2.2	.0029	430	315	439	330
20						16.3	23.7	.0016	2.7	.0034	422	300	430	315
21	182.9	600	54,100	113.7	165	21.8	31.7	.0032	5.5	.0070	492	425	475	395
22						21.2	30.7	.0030	5.2	.0066	469	385	486	415
23						20.5	29.7	.0029	5.0	.0064	483	410	504	448
24						20.5	29.7	.0030	5.1	.0065	505	450	527	490
25						21.2	30.7	.0031	5.3	.0068	513	463	536	505
26						22.2	32.2	.0034	5.8	.0074	506	452	515	468
27						22.5	32.7	.0036	6.2	.0079	506	451	514	466
28						23.9	34.7	.0041	7.0	.0089	514	465	521	478
29						25.3	36.7	.0046	7.9	.0101	510	459	514	466
30						25.3	36.7	.0046	8.0	.0102	506	452	512	462
31						23.2	33.7	.0041	7.1	.0090	511	460	519	475
32						23.2	33.7	.0039	6.7	.0085	521	478	529	493
33						23.2	33.7	.0041	7.0	.0089	519	475	525	486
34						23.2	33.7	.0042	7.3	.0093	521	478	528	492
35						23.2	33.7	.0042	7.3	.0093	521	486	529	494

TABLE VII - Continued

RUN	SPEED M/S	SPEED (FT/SEC)	SPEED (RPM)	AIR PRESSURE (N/cm² abs)	AIR PRESSURE (PSIA)		CAVITY PRESSURE (N/cm² abs)	CAVITY PRESSURE (PSIA)	AIRFLOW (Kg/s)	AIRFLOW (SCFM)	AIRFLOW (lb/sec)	SEAL TEMP FWD K	SEAL TEMP FWD °F	SEAL TEMP AFT K	SEAL TEMP AFT °F
36	182.9	600	54,100	113.	165		24.	35.7	.0044	7.6	.0097	541	513	536	505
37							23.9	34.7	.0048	7.4	.0094	539	510	537	506
33							24.	35.7	.0046	7.9	.0101	548	526	549	528
39							24.	35.7	.0045	7.8	.0099	542	515	544	520
40							23.9	34.7	.0044	7.5	.0096	549	528	549	528
41	213.0	700	62,900	148.1	215		35.5	51.7	.0116	20.0	.0255	547	525	564	555
42							36.3	52.7	.0116	20.0	.0255	547	525	567	562
43							34.9	50.7	.0116	20.0	.0255	494	430	505	450
44							37.0	53.7	.0128	22.0	.0280	555	540	572	570
45							38.	55.7	.0133	23.0	.0293	558	545	576	578
46	122.0	400	35,900				28.7	41.7	.0116	20.0	.0255	359	188	360	189
47							28.0	40.7	.0104	18.0	.0229	357	183	361	190
48							28.0	40.7	.0104	18.0	.0229	363	195	369	205
49							30.1	43.7	.0119	20.5	.0261	371	208	374	215
50							29.4	42.7	.0116	20.0	.0255	372	210	377	220
51	152.0	500	45,100				32.	46.7	.0119	20.5	.0261	377	220	386	235
52							24.	35.7	.0075	13.0	.0166	391	243	393	248
53							24.	35.7	.0073	12.5	.0159	391	245	396	253
54							25.	36.7	.0084	14.5	.0185	391	245	397	254
55							2 .	37.7	.0087	15.0	.0191	391	243	398	256
56	183.0	600	54,100				28.0	40.7	.0093	16.0	.0204	402	263	407	273
57							28.7	41.7	.0090	15.5	.0198	390	242	399	259
58							28.7	41.7	.0090	15.5	.0198	394	250	402	263
59							28.7	41.7	.0090	15.5	.0198	392	246	400	260
60							29.4	42.7	.0090	15.5	.0198	390	242	399	258
61							2 .	37.7	.00/5	13.0	.0166	416	290	425	305
62							29.4	42.7	.0073	16.0	.0264	398	256	407	272
63							28.7	41.7	.0087	15.0	.0191	409	277	419	295
64							28.0	40.7	.0084	14.5	.0185	416	290	426	308
65							30.	43.7	.0094	14.5	.0183	427	310	436	325
66	213.0	700	62,900				28.0	40.7	.0079	13.5	.0172	454	358	469	385
67							28.0	40.7	.0075	13.0	.0166	466	377	479	404
68							27.	39.7	.0075	13.0	.0166	459	360	472	390
69							27.	39.7	.00[illegible]	13.0	.0166	461	370	466	380
70							27.	39.7	.00/5	13.0	.0166	473	392	493	429

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TABLE VII - Continued

RUN	SPEED M/S	SPEED (FT/SEC)	SPEED (RPM)	AIR PRESSURE (N/cm² abs)	AIR PRESSURE (PSIA)	CAVITY PRESSURE (N/cm² abs)	CAVITY PRESSURE (PSIA)	AIRFLOW (Kg/s)	AIRFLOW (SCFM)	AIRFLOW (lb/sec)	SEAL TEMP FWD K	SEAL TEMP FWD °F	SEAL TEMP AFT K	SEAL TEMP AFT °F
71	213.0	700	62,900	148.14	215	26.7	38.7	.0070	12.0	.0153	480	405	504	448
72						30.1	43.7	.0081	14.0	.0178	472	390	494	430
73						29.4	42.7	.0073	12.5	.0159	503	447	519	475
74						29.4	42.7	.0073	12.5	.0159	511	460	533	500
75						30.1	43.7	.0081	14.0	.0178	518	474	544	520
76						30.1	43.7	.0081	14.0	.0178	530	495	558	545
77						30.1	43.7	.0081	14.0	.0178	539	510	569	565
78						29.4	42.7	.0081	14.0	.0178	511	460	512	462
79						29.4	42.7	.0078	13.5	.0172	532	498	555	540
80						30.1	43.7	.0081	14.0	.0178	542	515	567	562
81						31.5	45.7	.0087	15.0	.0191	536	505	559	547
82						32.2	46.7	.0087	15.0	.0191	536	505	560	548
83						27.4	39.7	.0081	14.0	.0178	491	424	509	456
84						27.4	39.7	.0084	14.5	.0185	517	472	545	522
85						27.4	39.7	.0087	15.0	.0191	53[illegible]	505	556	542
86						32.2	46.7	.0113	19.5	.0249	542	515	562	552
87						31.5	45.7	.0113	19.5	.0249	542	515	564	555
88						31.5	45.7	.0110	19.0	.0242	524	484	544	520
89						30.8	44.7	.0102	17.5	.0223	519	475	537	507
90						30.8	44.7	.0099	17.0	.0217	532	498	550	530
91						30.8	44.7	.0104	18.0	.0229	536	505	[illegible]55	540
92	215.5	707	63,800			32.2	46.7	.0104	18.0	.0229	527	490	544	520
93	218.7	717	64,700			30.8	44.7	.0104	18.0	.0229	540	512	555	540
94	221.8	727	65,600			32.2	46.7	.0104	18.0	.0229	522	480	542	515
95	224.6	737	66,500			32.2	46.7	.0104	18.0	.0229	534	502	561	550
96	227.7	747	67,400			32.9	47.7	.0107	18.5	.0236	543	518	569	565
97						33.6	48.7	.0116	20.0	.0255	540	512	561	550
98						33.6	48.7	.0116	20.0	.0255	539	510	561	550
98.2	215.5	707	63,800			33.6	48.7	.0110	19.0	.0242	510	458	522	480
98.5	224.6	737	66,500			34.2	49.7	.0113	19.5	.0249	523	482	536	505
98.7	224.6	737	66,500			33.6	48.7	.0113	19.5	.0249	528	492	542	516
99	227.7	747	67,400			33.6	48.7	.0113	19.5	.0249	541	514	553	536
99.2	230.7	757	68,300			34.2	49.7	.0116	20.0	.0255	541	514	555	540
99.5	230.7	757	68,300			34.2	49.7	.0116	20.0	.0255	545	522	558	544
99.7	230.7	757	68,300			34.2	49.7	.0116	20.0	.0255	547	524	559	547

TABLE VII - Continued

RUN	SPEED			AIR PRESSURE		CAVITY PRESSURE		AIRFLOW			SEAL TEMP			
	M/S	(FT/SEC)	(RPM)	(N/cm^2 abs)	(PSIA)	(N/cm^2 abs)	(PSIA)	(Kg/s)	(SCFM)	(lb/sec)	FWD K	FWD °F	AFT K	AFT °F
100	236.8	777	70,100	148.1	215	34.9	50.7	.0116	20.0	.0255	550	530	563	554
100.2	243.8	800	72,500	148.1	215	34.2	49.7	.0116	20.0	.0255	555	540	562	553

Figure 33. Forward Seal Assembly and Seat After Endurance Test, Build I.

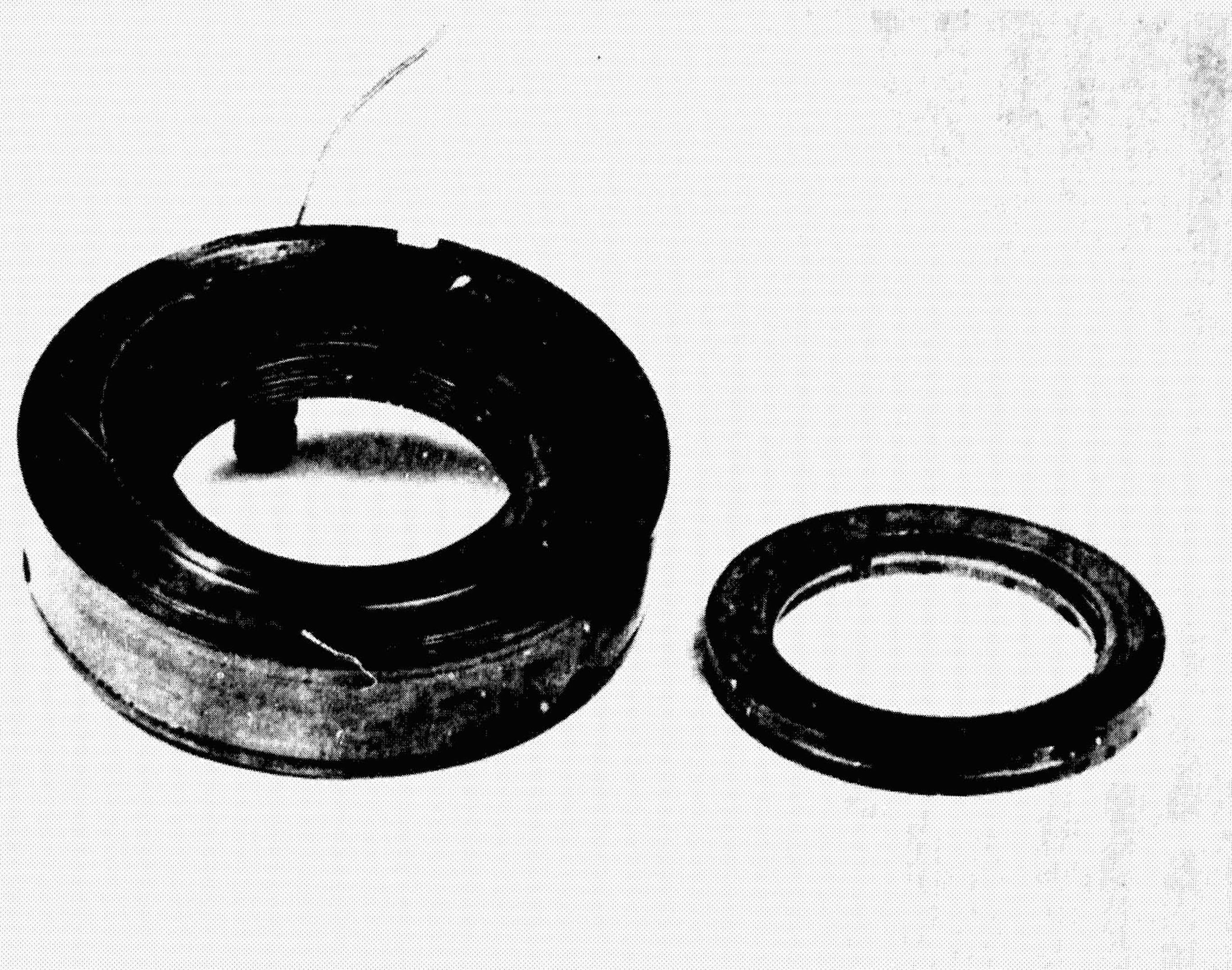

Figure 34. Aft Seal Assembly and Seat After Endurance Test, Build I.

Figure 35. Forward Seal Spiral Groove Geometry After Endurance Test, Build I.

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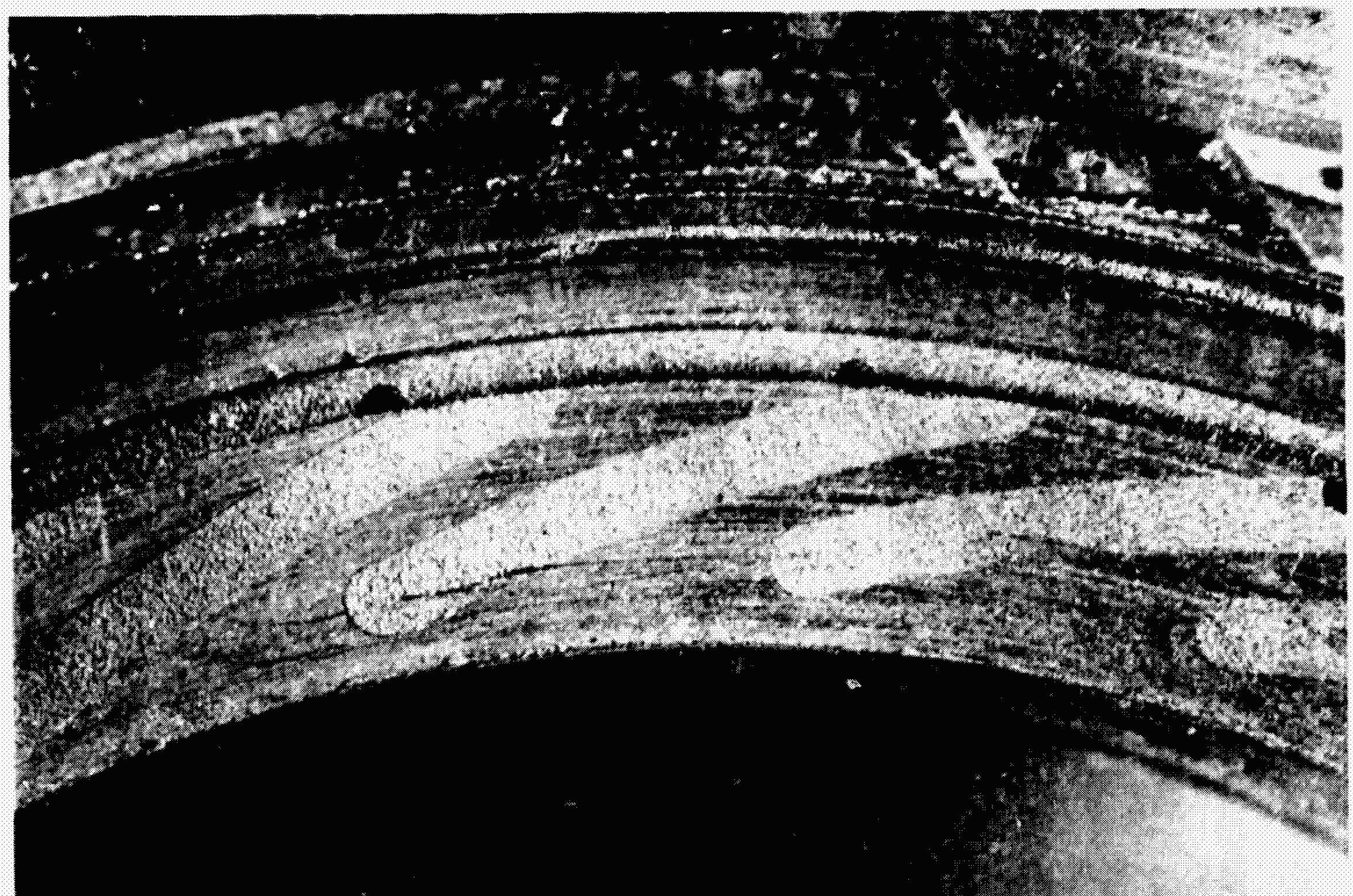

Figure 36. Aft Seal Spiral Geometry After Endurance Test Build I.

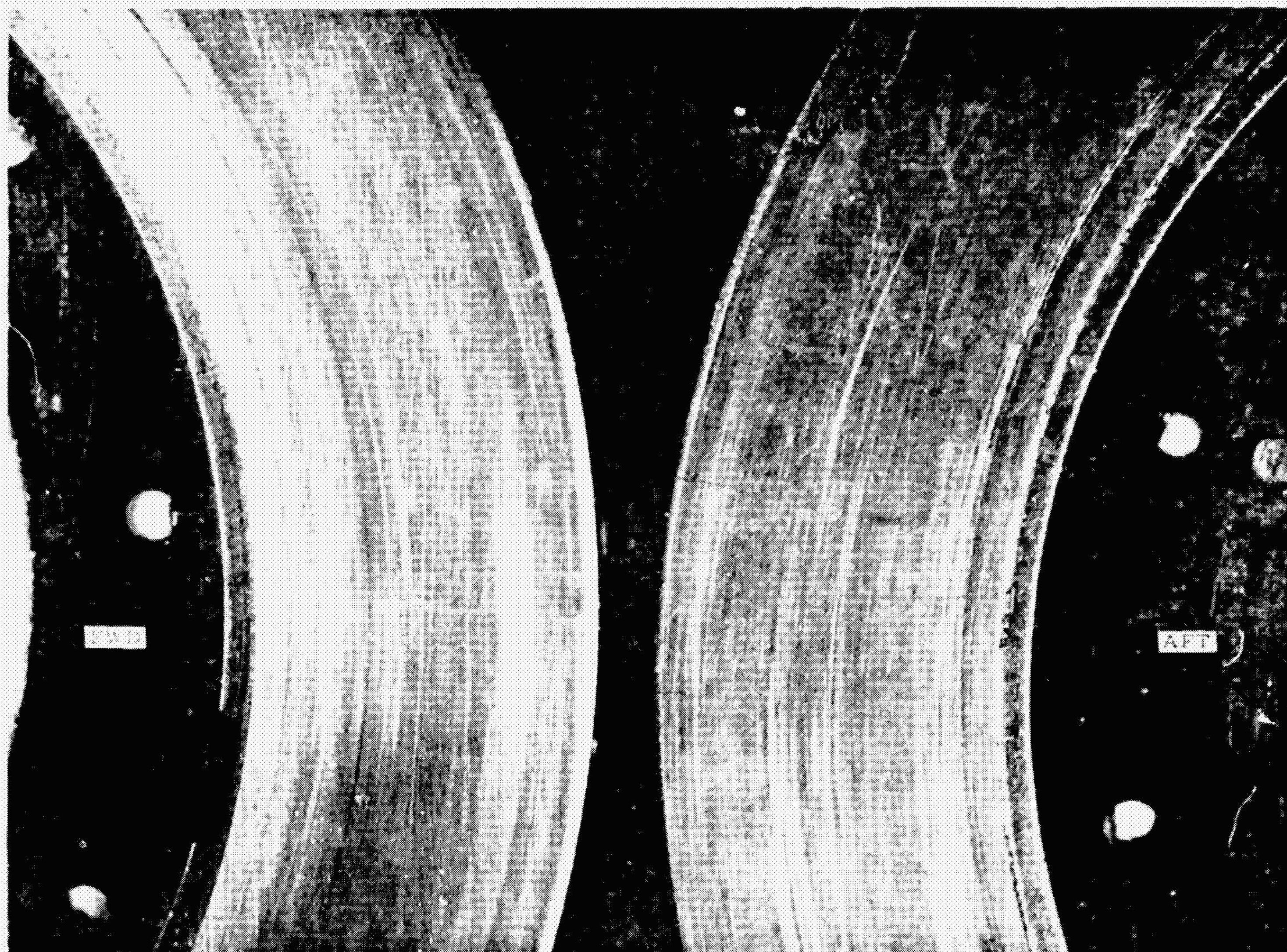

Figure 37. Forward and Aft Seal Seats After Endurance Test, Build I.

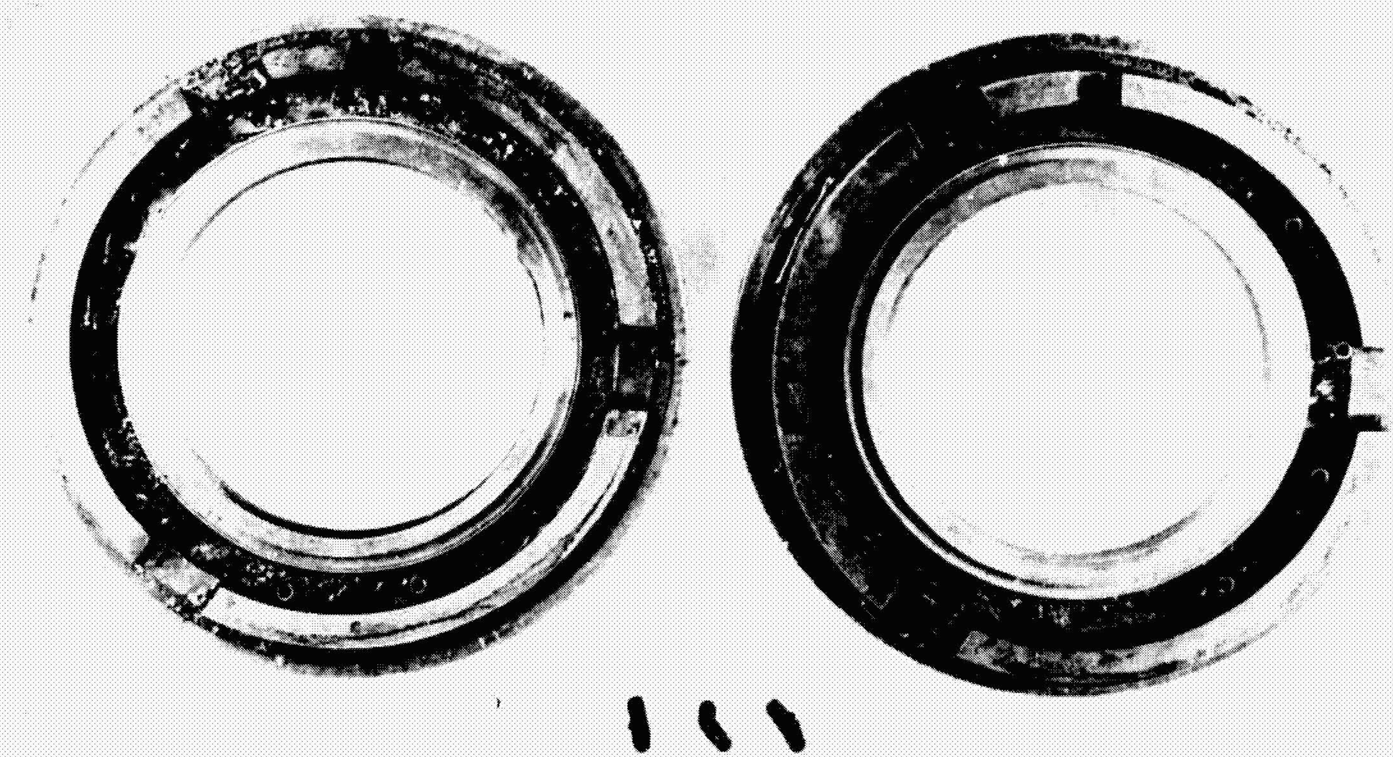

Figure 38. Coking of Housing and Springs After Endurance Test, Build I.

TABLE VIII. CHANGES IN FACE DIMENSIONS, ENDURANCE TEST, BUILD I

Forward Seal (new)			Condition Before Build I (new)	Aft Seal		
Groove - cm (in)	Dam - cm(in)	I.D. - cm(in)	Location	Groove - cm(in)	Dam - cm(in)	I.D - cm(in)
.00273 (.001075)	.00273 (.001075)	.00273 (.001075)	1	.00298 (.001175)	.00298 (.001175)	.00298(.001175)
.00286 (.001125)	.00286 (.001125)	.00286 (.001125)	2	.00349 (.001375)	.00349 (.001375)	.00349(.001375)
.00324 (.001275)	.00324 (.001275)	.00324 (.001275)	3	.00286 (.001125)	.00286 (.001125)	.00286(.001125)
.00349 (.001375)	.00349 (.001375)	.00349 (.001375)	4	.00305 (.00120)	.00305 (.00120)	.00305(.00120)
.00308 (.001213)	.00308 (.001213)	.00308 (.001213)	Average	.00309 (.001219)	.00309 (.001219)	.00309(.001219)

Forward Seal			Condition After Build I (Brg. Failure)	Aft Seal		
Groove - cm(in)	Dam - cm(in)	I.D -cm(in)	Location	Groove - cm(in)	Dam - cm(in)	I.D - cm(in)
.00254 (.00100)	.00248 (.000975)	.00178 (.00070)	1	.00248 (.000975)	.00260 (.001025)	.00222(.000875)
.00279 (.00110)	.00210 (.000825)	.00203 (.00080)	2	.00267 (.00105)	.00254 (.00100)	.00286(.001125)
.00305 (.00120)	.00260 (.001025)	.00267 (.00105)	3	.00210 (.000825)	.00184 (.000725)	.00203(.00080)
.00254 (.00100)	.00273 (.001075)	.00267 (.00105	4	.00248 (.000975)	.00222 (.000875)	.00222(.000875)
.00273 (.001075)	.00248 (.000975)	.00229 (.0009)	Average	.00243 (.00096)	.00230 (.000906)	.00233(.000919)

			Net Average Wear (Build I)			
Groove - cm(in)	Dam - cm(in)	I.D - cm(in)		Groove - cm(in)	Dam - cm(in)	I.D - cm(in)
.00035 (.000138)	.000605 (.000238)	.000795 (.000313)		.000658 (.000259)	.000795 (.000313)	.000762(.0003)

rings were free of coke and with the exception of the springs, coke did not yet appear to be seriously affecting seal operation. The seal housings were not cleaned, but coil springs were changed as required.

Endurance Test, Build II (55 Hours)

The test rig was rebuilt, and the endurance test was completed without problem. At the end of the endurance test, seal operation at 243 m/s (800 ft/sec) was accomplished. The condition of the seals at the completion of the endurance test is documented in Figures 39 through 52. Inspection revealed coking of the internal seal components had continued, and sufficient deposits had formed on the housing and piston ring carrier to prevent the seals from returning to their normal free height. Coke within the coil springs limited their action as did coke in the spring cavity (Figures 48 and 49). The effected forward seal components were less coked than the corresponding aft seal components. The piston rings of both seals were free from coke. (Figure 51)

The seal seats exhibited radial cracks in the chrome carbide surface coating originating at the seat ID. The seats were otherwise in good condition as exhibited in Figures 44 and 45.

The bellows clamping spacers acted as centrifugal separators for small particulate matter in the seat cooling oil. The deposits can be seen in Figure 47.

Seal Air Leakage

Air leakage was plotted as a function of endurance hours and is presented in Figure 52. Changes in operating parameters are indicated on the plot. What appears to be a disproportionate increase in air leakage is seen prior to the bearing problem during Build I. A 60 percent reduction in air leakage is seen at equivalent conditions after the rebuild (Build II).

Seal Wear

Changes in face dimensions for the first 45 hours (Build I) are presented in Table VIII. Changes in face dimensions for the last 55 hours of operation (Build II) are presented in Table IX.

The wear results are compared below:

Forward Seal	Build I (45 Hours)	Build II (55 Hours)
Sealing dam	.000605 cm (.000238 in.)	.001379 cm (.000543 in.)
Land adjacent groove	.000350 cm (.000138 in.)	None measurable
Surface near ID	.000795 cm (.000313 in.)	.001093 cm (.000430 in.)
Face average	.000583 cm (.000230 in.)	.000824 cm (.000324 in.)
Average wear rate	.000013 cm/hr (.000005 in./hr)	.000015 cm/hr (.000006 in./hr)

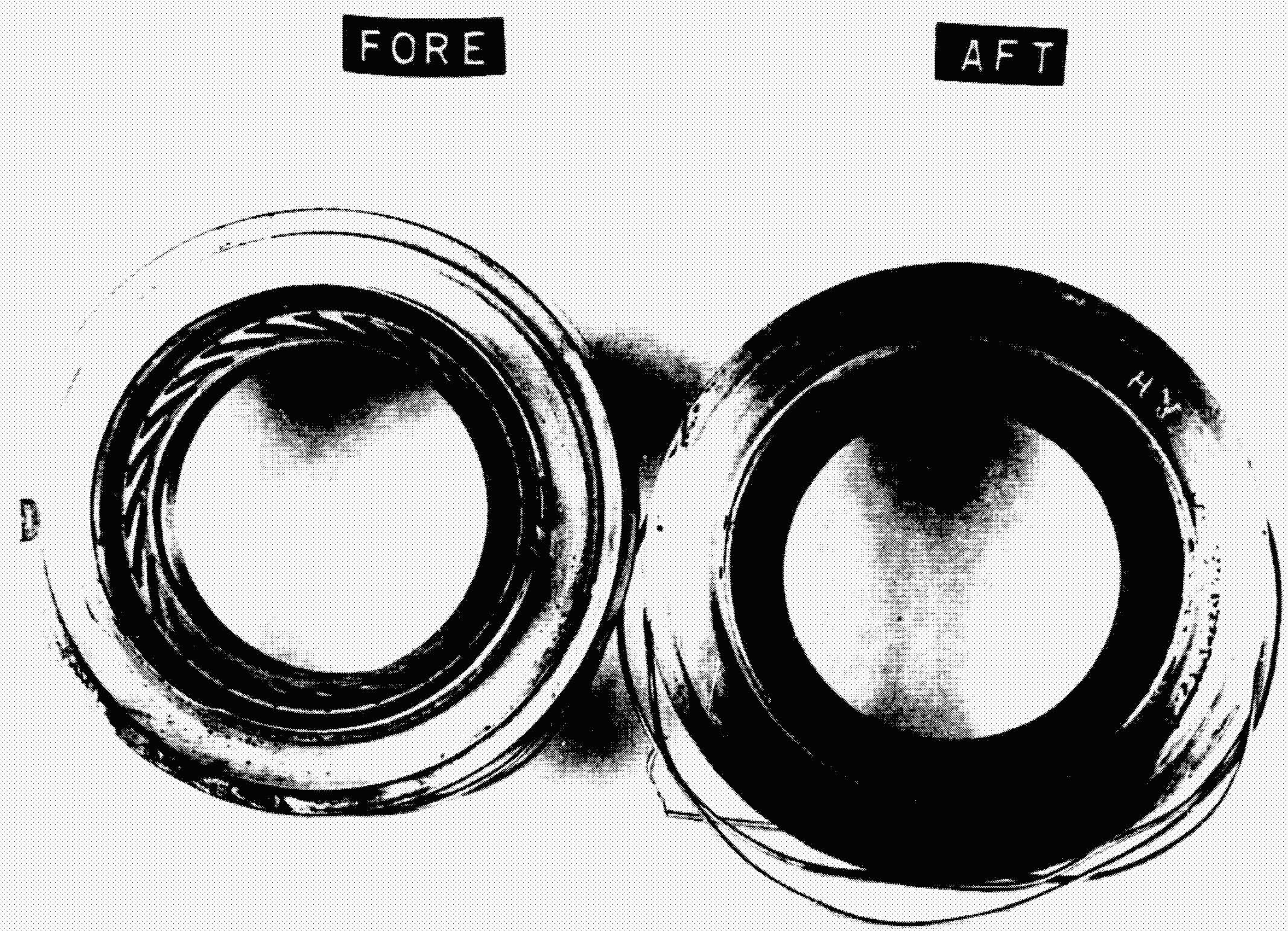

Figure 39. Forward and Aft Seal Assemblies After Endurance Test, Build II.

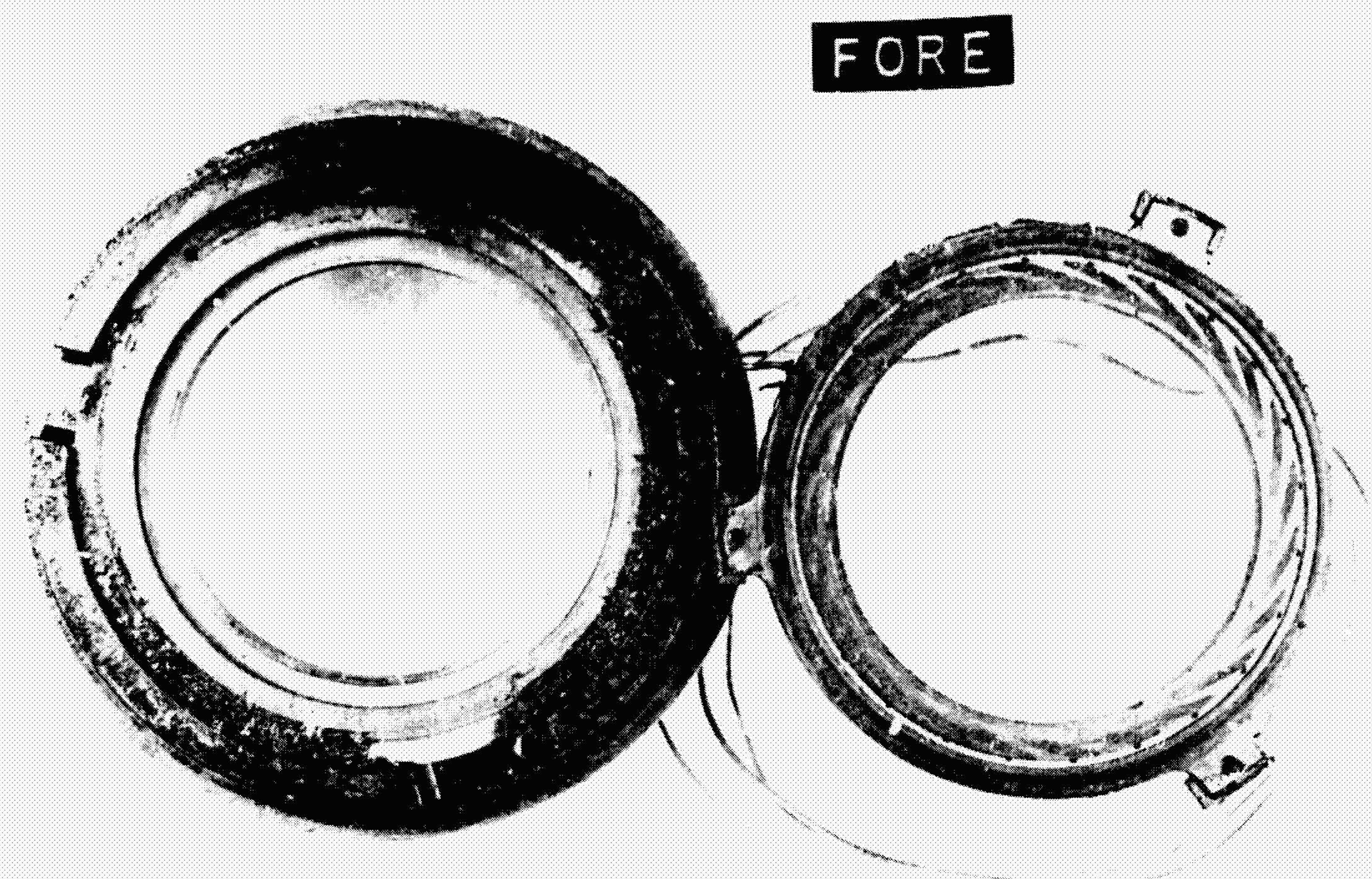

Figure 40. Internal Coking of Forward Seal After Endurance Test, Build II.

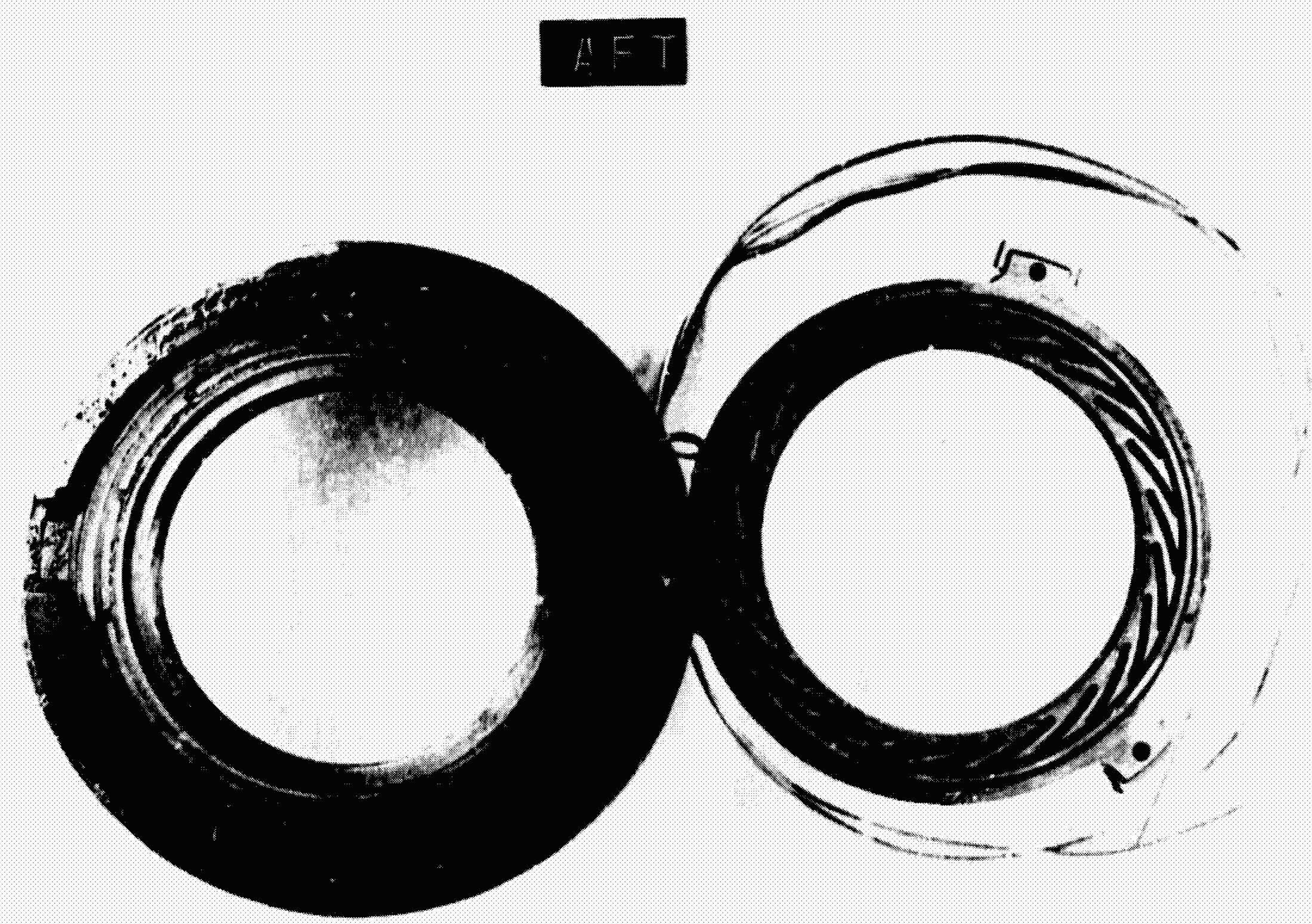

Figure 41. Internal Coking of Aft Seal After Endurance Test, Build II.

Figure 42. Forward Sealing Element After Endurance Test, Build II.

Figure 43. Aft Sealing Element After Endurance Test, Build II.

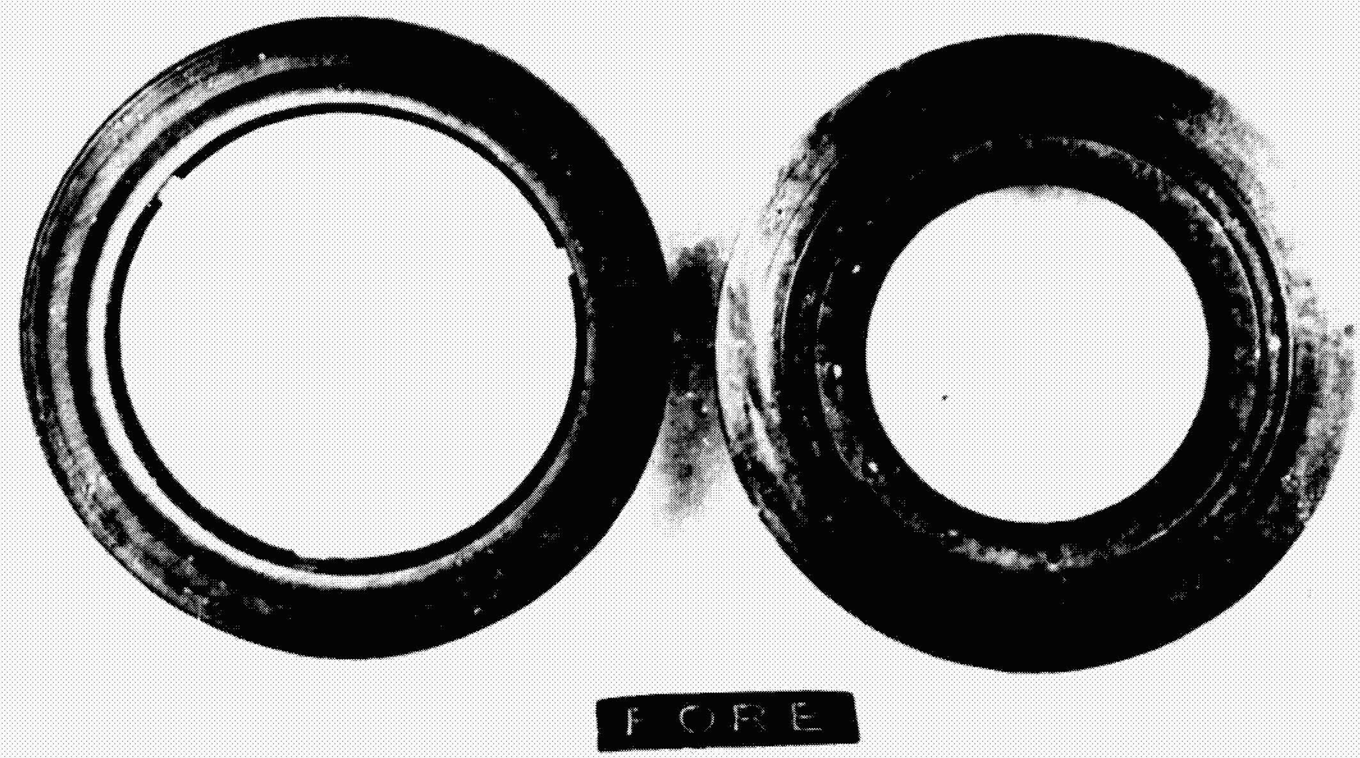

Figure 44. Forward Seal Seat and Dam After Endurance Test, Build II.

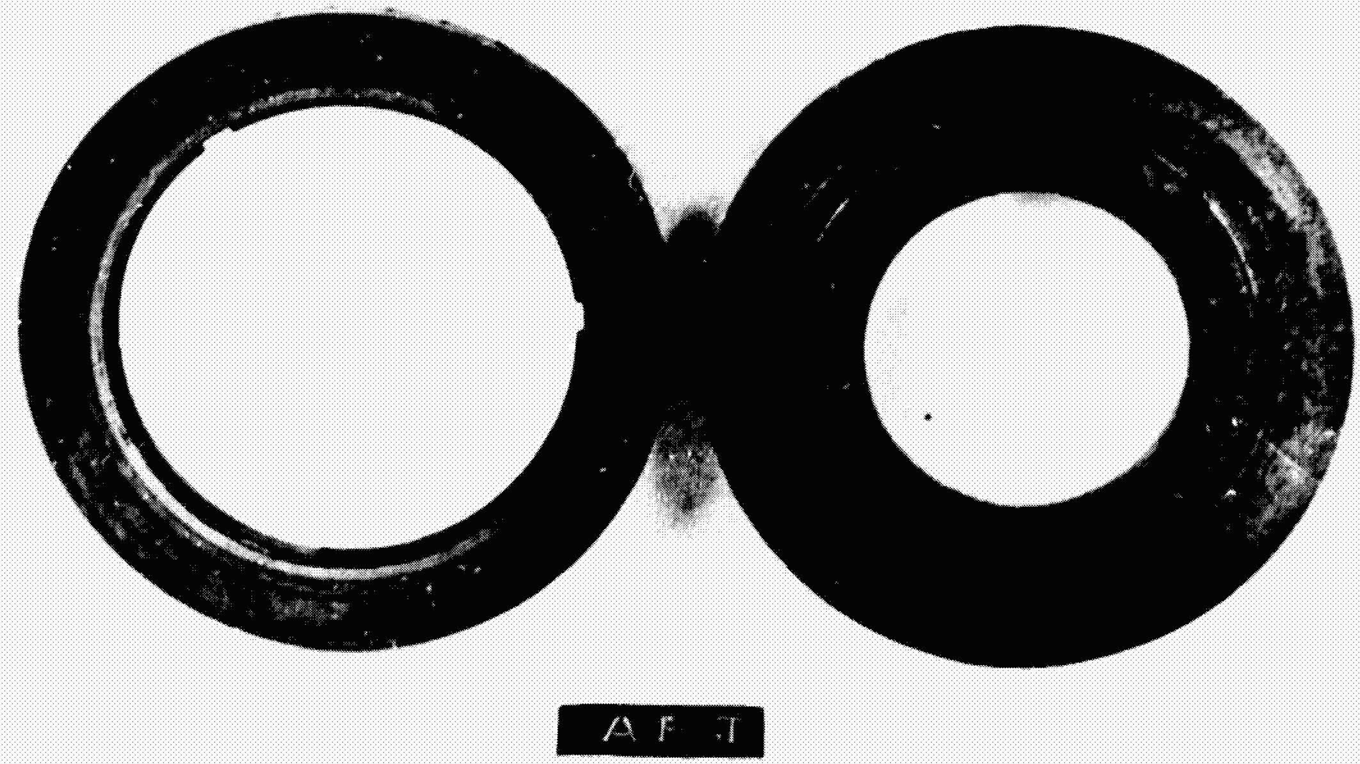

Figure 45. Aft Seal Seat and Dam After Endurance Test, Build II.

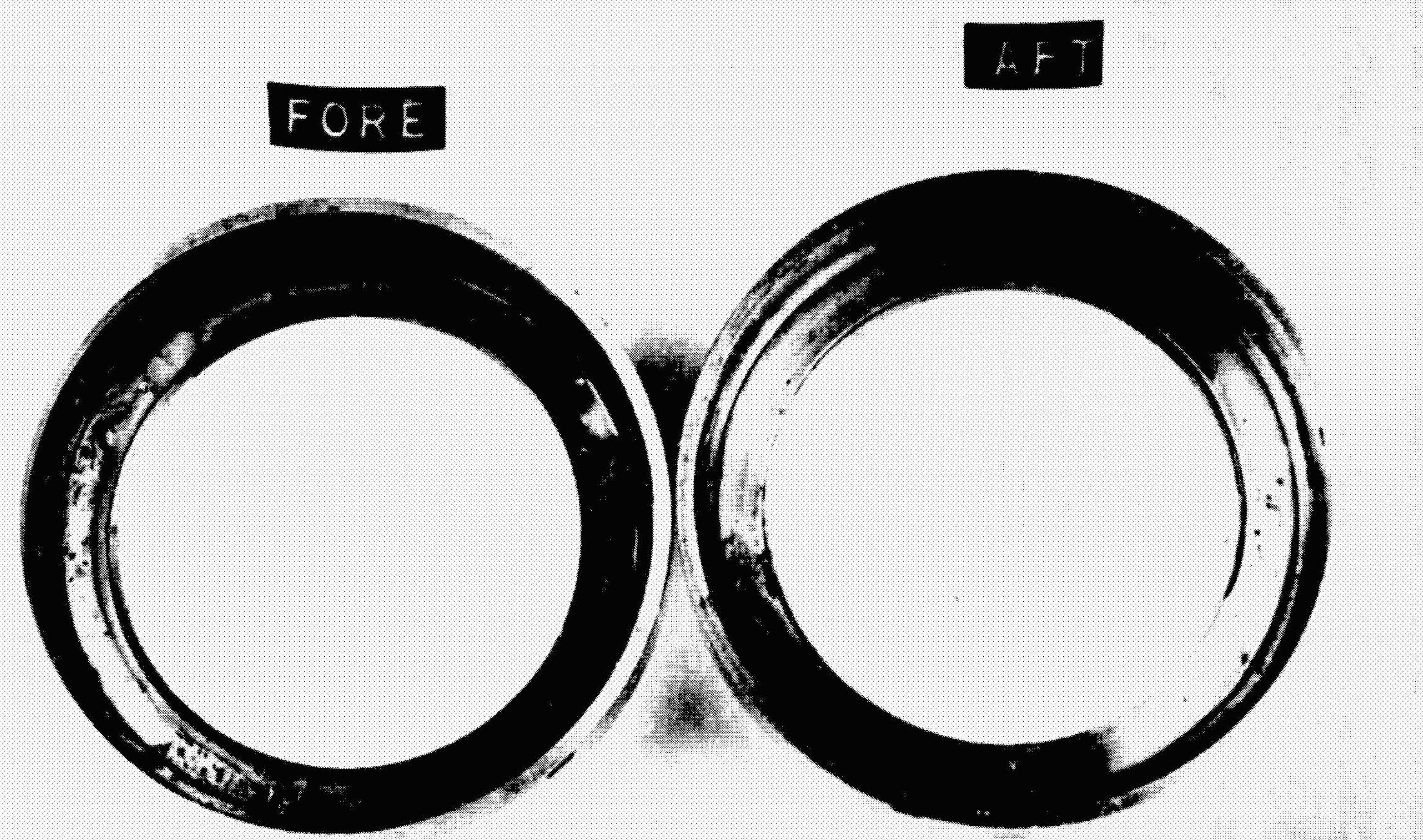

Figure 46. Interior of Housing Covers, Forward and Aft, After Endurance Test, Build II.

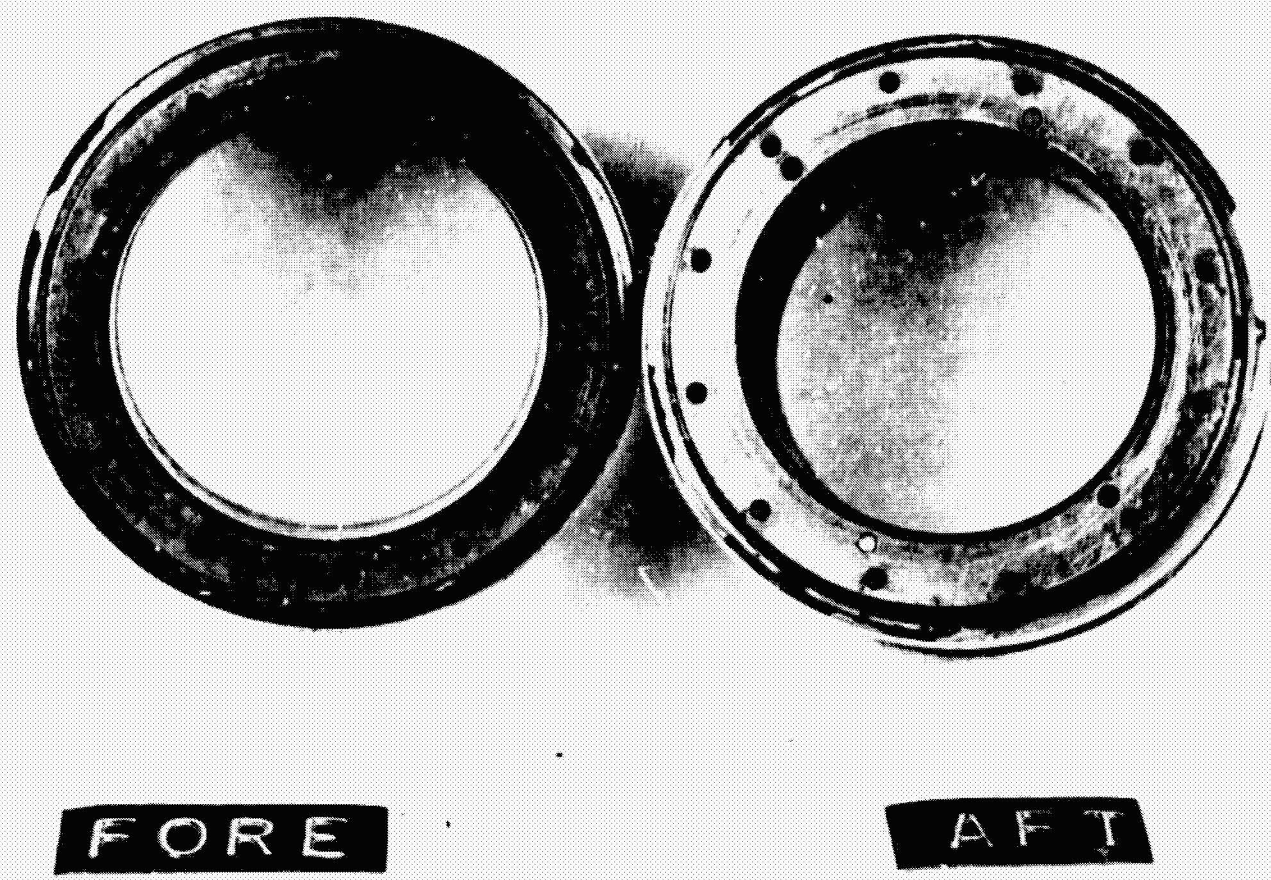

Figure 47. Forward and Aft Windbacks With Bellows Spacers After Endurance Test, Build II.

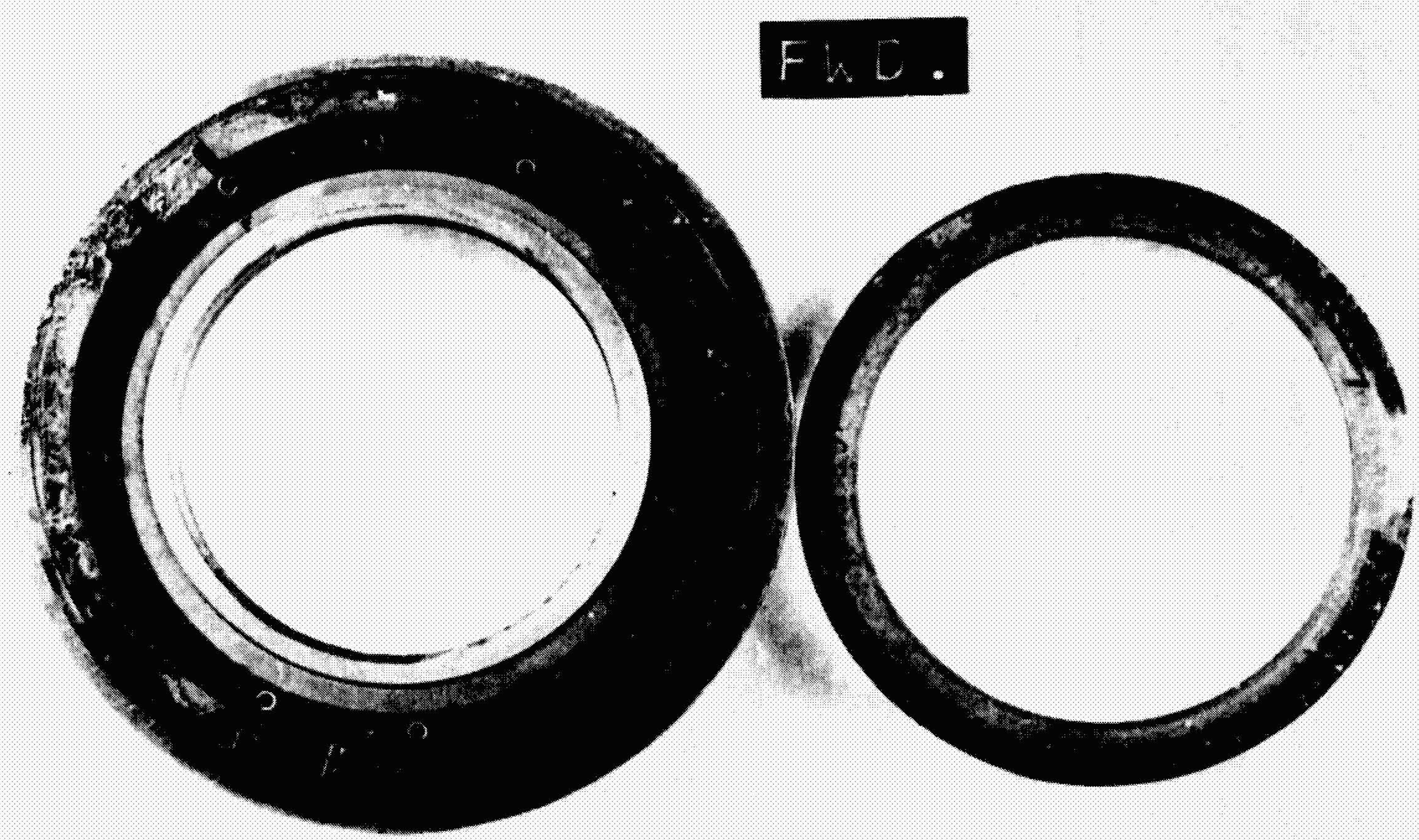

Figure 48. Forward Seal Housing and Piston Ring Carrier After Endurance Test, Build II.

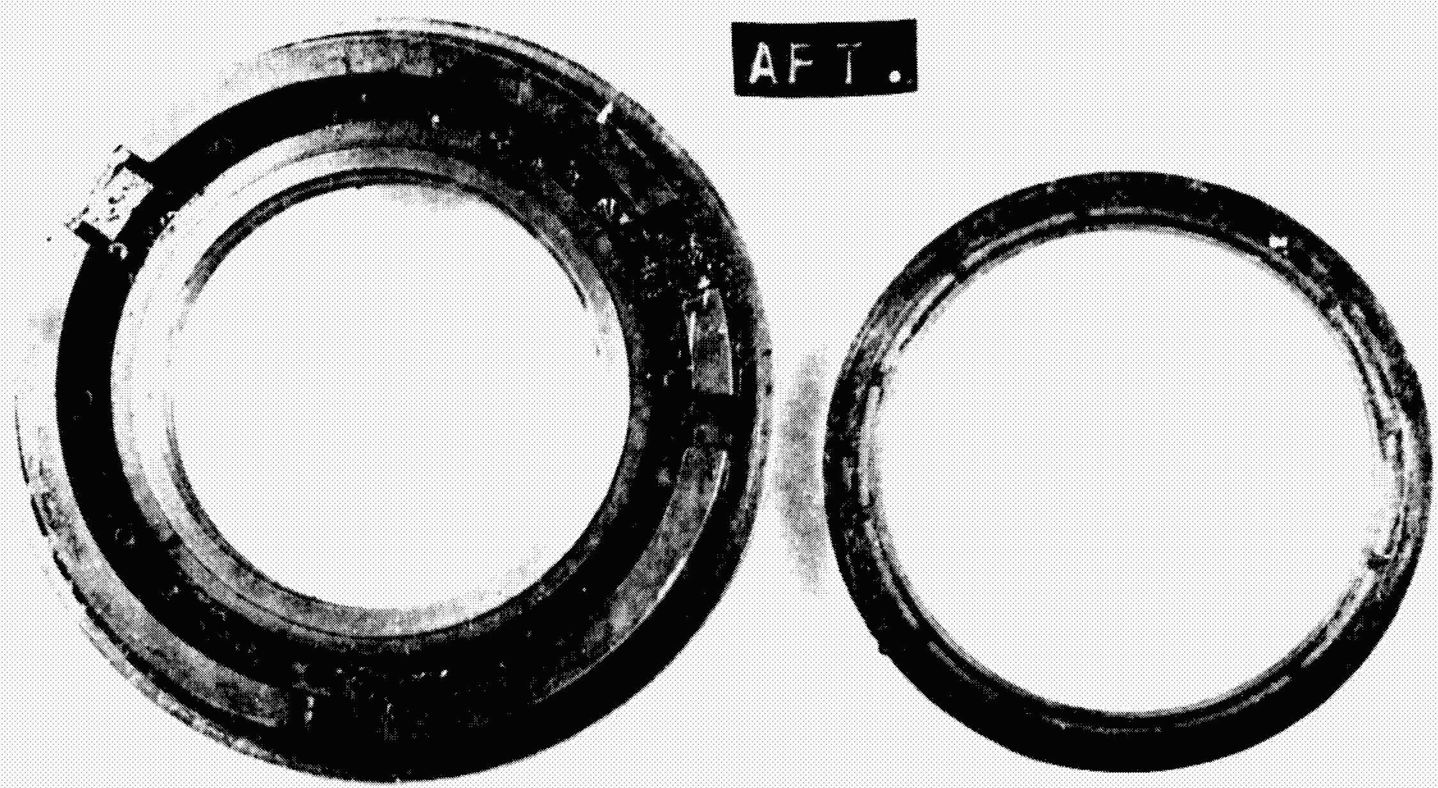

Figure 49. Aft Seal Housing and Piston Ring Carrier After Endurance Test, Build II.

Figure 50. O. D. View of Forward and Aft Piston Ring Carriers After Endurance Test, Build II.

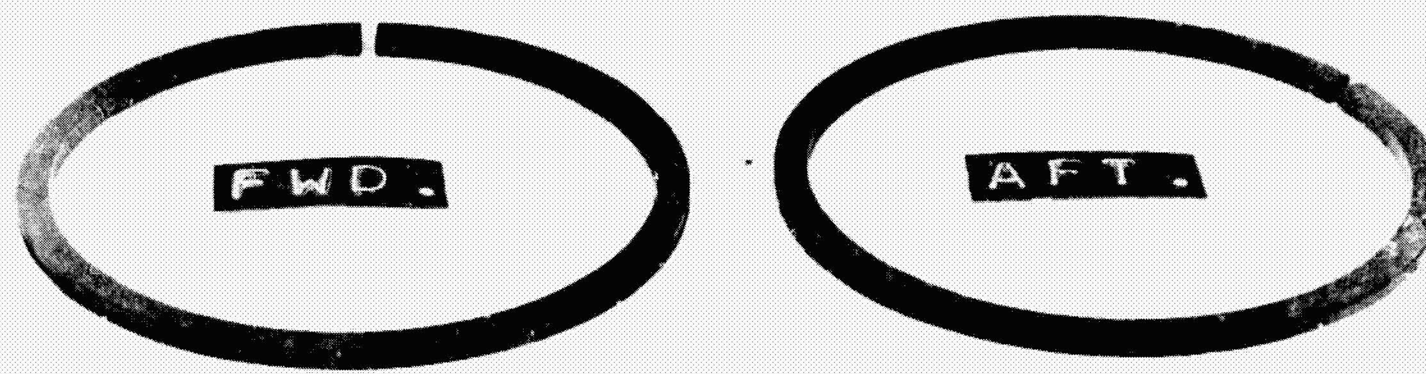

Figure 51. Forward and Aft Piston Rings After Endurance Test, Build II.

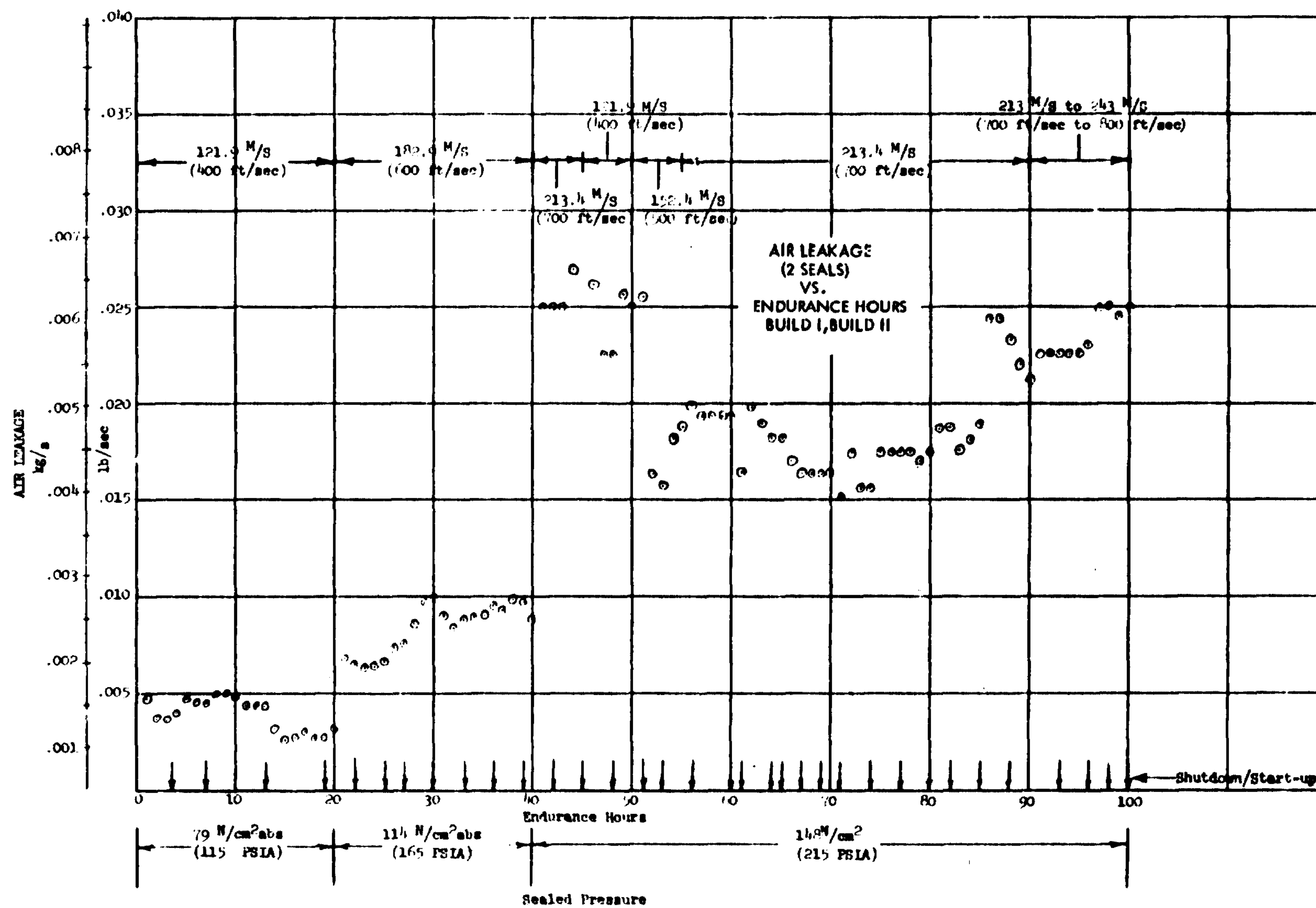

Figure 52. Air Leakage Versus Endurance Hours, Build I, Build II.

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TABLE IX. CHANGES IN FACE DIMENSIONS, ENDURANCE TEST, BUILD II

Forward Seal (new)		Condition Before Build II		Aft Seal		
Groove - cm (in)	Dam - cm(in)	I.D. - cm(in)	Location	Groove - cm(in)	Dam - cm(in)	I.D - cm(in)
.00254 (.00100)	.00254 (.00100)	.00254 (.00100)	1	.00286 (.001125)	.00286 (.001125)	.00286(.001125)
.00273 (.001075)	.00273 (.001075)	.00273 (.001075)	2	.00305 (.00120)	.00305 (.001200)	.00305(.001200)
.00305 (.001200)	.00305 (.001200)	.00305 (.001200)	3	.00241 (.00095)	.00241 (.00095)	.00241(.00095)
.00381 (.001500)	.00381 (.001500)	.00381 (.001500)	4	.00229 (.00090)	.00229 (.00090)	.00229(.00090)
.00303 (.001194)	.00303 (.001194)	.00303(.001194)	Average	.00265 (.001044)	.00265 (.001044)	.00265(.001044)

Forward Seal		Condition After Build II (55 hr)		Aft Seal		
Groove - cm(in)	Dam - cm(in)	I.D -cm(in)	Location	Groove - cm(in)	Dam - cm(in)	I.D - cm(in)
.00254 (.00100)	.00102 (.00040)	.00152 (.00060)	1	.00286 (.001125)	.00241 (.00095)	.00248(.000975)
.00273 (.001075)	.00108 (.000425)	.00178 (.00070)	2	.00305 (.00120)	.00305 (.00120)	.00273(.001075)
.00305 (.00120)	.00178 (.00070)	.00210 (.000825)	3	.00241 (.00095)	.00241 (.00095)	.00178(.00070)
.00381 (.00150)	.00273 (.001075	.00325 (.000925)	4	.00229 (.00090)	.00229 (.00090)	.00165(.00065)
.003032 (.001194)	.001451(.00065)	.001936(.000763)	Average	.00265 (.00104)	.00254 (.0010)	.00216(.00085)

			Net Average Wear (Build II)			
Groove - cm(in)	Dam - cm(in)	I.D - cm(in)		Groove - cm(in)	Dam - cm(in)	I.D - cm(in)
.000000 (.000000)	.001379 (.000543)	.001095 (.000430)		.000009 (.000004)	.00011 (.000044)	.000497(.000196)

Forward Seal	Build I (45 Hours)	Build II (55 Hours)
Mininum remaining groove depth	.002540 cm (.001000 [illegible]	[illegible] 002540 cm (.001000 in.)

Aft Seal	Build I (45 Hours)	Build II (55 Hours)
Sealing dam	.000795 cm (.000313 in.)	.0[illegible]1 cm (.000044 in.)
Land adjacent groove	.000658 cm (.000295 in.)	.000009 cm (.000040 in.)
Surface near ID	.000762 cm (.000300 in.)	.000497 cm (.000196 in.)
Face average	.000768 cm (.000303 in.)	.000207 cm (.000081 in.)
Average wear rate	.000017 cm/hr (.000007 in./hr)	.000004 cm/hr (.000001 in./hr)
Minimum remaining groove depth	.002096 cm (.000825 in.)	.002286 cm (.000900 in.)

Seal life was calculated using spiral groove wear data from Build II of the endurance test. Build I data were discounted because of the bearing failure which interrupted testing. Wea[illegible] of the [illegible]ther seal features (i.e. sealing dam and seal face near I.[illegible].) was not considered in the wear rate calculation Wear of these features may affect seal leakage rates but should not affect seal life.

Forward seal wear rate - non-measurable

Aft seal wear rate - $1.8 \times 10 \frac{cm}{hr}$ $(7.3 \times 10^{8} \frac{in.}{hr})$

The above wear rate for the aft seal infers a potential life between 2700 hours (min. initial groove depth) and 9500 [illegible]urs (maximum initial groove depth). This assumes a minimum rema[illegible]ning groove depth of 0.00076 cm (.000030 in.) which is sufficient to sustain seal operation. Wear rates experienced during the experimental evaluation phase were somewhat higher, as were wear rates observed during previous programs (Reference 1). A concise explanation of the variations in wear rates is not available and suggests additional investigation of parameters influencing wear would be valuable. Wear characteristics may be stabilized with a seal redesign placing the spiral grooves in the hard surface of the seal seat.

CONCLUSION AND RECOMMENDATIONS

- The spiral-groove self-acting seal was tested and found capable of operation at surface speeds to 243 m/s (800 ft/sec), sealed pressures of 199.9 N/cm^2 abs (290 psia), and air temperatures of 645.4 K (702°F) (nonconcurrent conditions). The maximum speed condition of 243 m/s (800 ft/sec) is a rotative speed of 72,500 rpm.

- Seal life calculated from Build II endurance test wear data indicates a minimum potential life of 2700 hours. Variations in wear rates in this and previous programs (Ref. 1) indicate additional investigation of parameters influencing wear would be valuable. A redesign that transfers the spiral grooves into the hard seal seal from the carbon element may contribute to increased life.

- Seal air leakage measured during the test program is considered to be within a range usable in small gas turbine engines.

- Oil coke deposits on internal seal components were significant by the end of the endurance test. Future seal designs should incorporate cooling or insulating mechanism to reduce oil coke deposits.

- Distortion of the carbon sealing face was found to occur during testing. It is believed that the TZM retaining band may be influencing sealing face flatness. Eliminating composite construction of the sealing elements would minimize this possibility.

- The spiral - groove film - riding face seal has exhibited the capability to operate at advanced gas turbine engine conditions. Additional development effort is required in the areas of distortion control, wear mechanisms, and control of oil degradation (coking).

REFERENCES

1. O'Brien, M., DEVELOPMENT OF A SHORT-LENGTH SELF-ACTING SEAL, Avco Lycoming Report LYC 76-71, NASA CR-135159, 1976.

2. Lynwander, P., DEVELOPMENT OF SELF-ACTING SEALS FOR HELICOPTER ENGINES, Avco Lycoming Report LYC 74-55, NASA CR-134739, 1974.

3. Lynwander, P., SELF-ACTING SEALS FOR HELICOPTER ENGINES, Avco Lycoming Report LYC 75-78, NASA CR-134940, 1975.

APPENDIX

This appendix is divided into the following sections, presenting the actual proficorder traces of the carbon faces and seal seats:

Section 1. Explanation of Proficorder Trace

Section 2. Evaluation Test
Carbon face traces from Build I through Build III
Seal seat traces from Build I through Build III

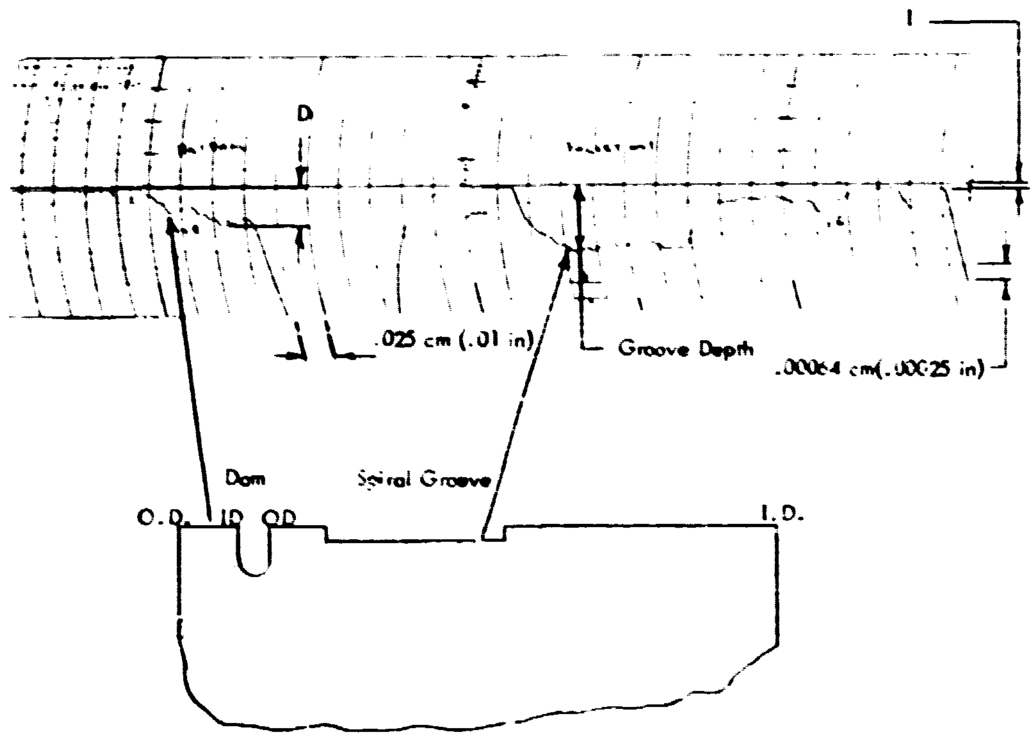
Section 3. Endurance Test
Carbon face traces from Build I and Build II
Seal seat traces from Build I and Build II

SECTION 1

Seal Face Traces

Seal face traces were taken at four equally spaced locations proceeding from the O.D. towards the I.D.

TYPICAL TRACE



Dam Wear = D + change in groove depth since previous build.
I.D. Wear = I + change in groove depth since previous build.

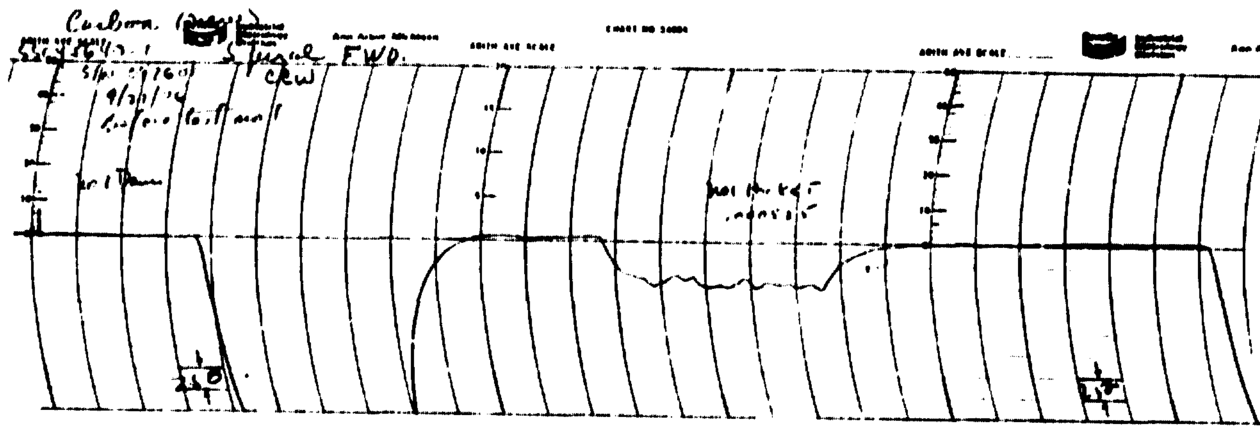
Seal Seat Traces

Seal Seat traces illustrate both waviness and surface finish. Initial and final traces are presented except for the case where hardware was damaged during the malfunction of the test rig bearing.

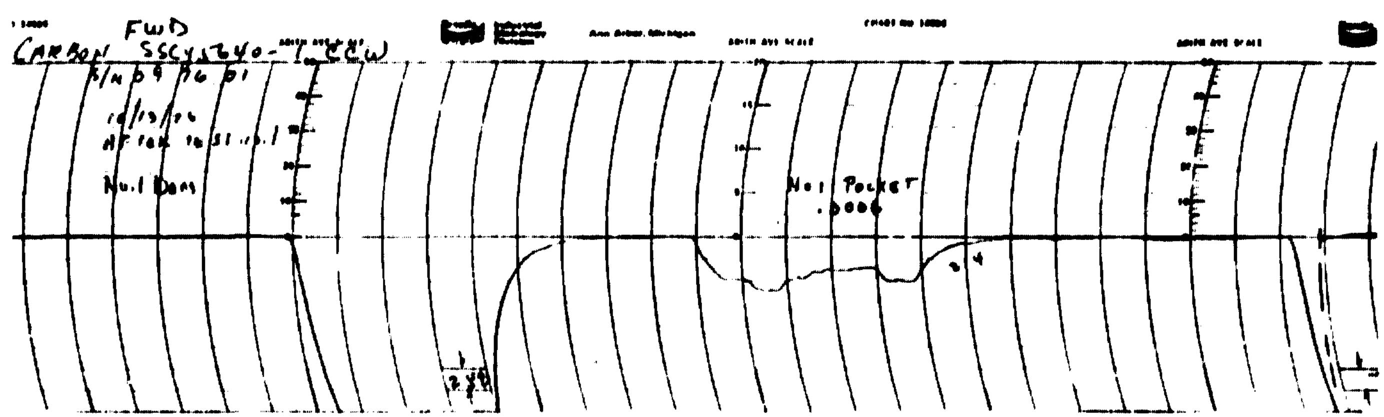
Traces are presented in series illustrating relative changes from build to build.

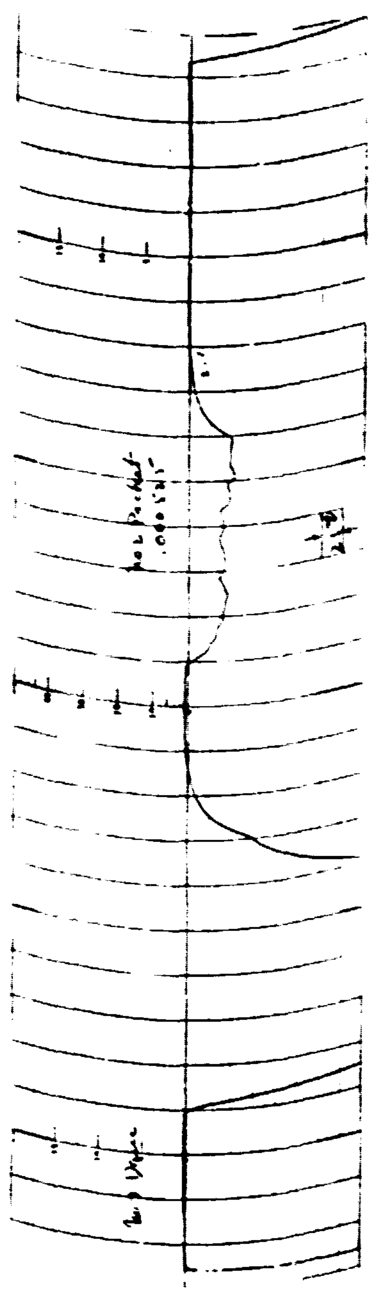
SECTION 2

Evaluation Test
Location 1
Fwd Seal New

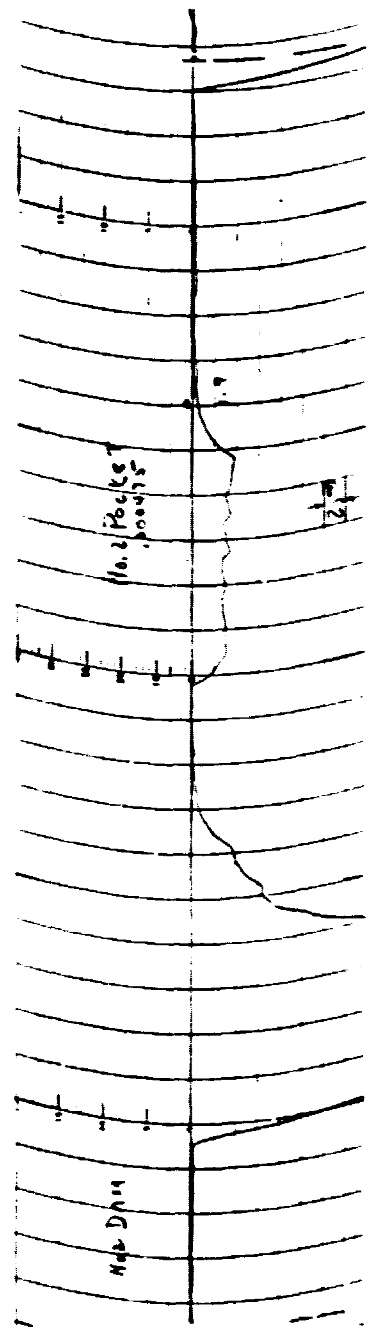


Fwd Seal After Build I



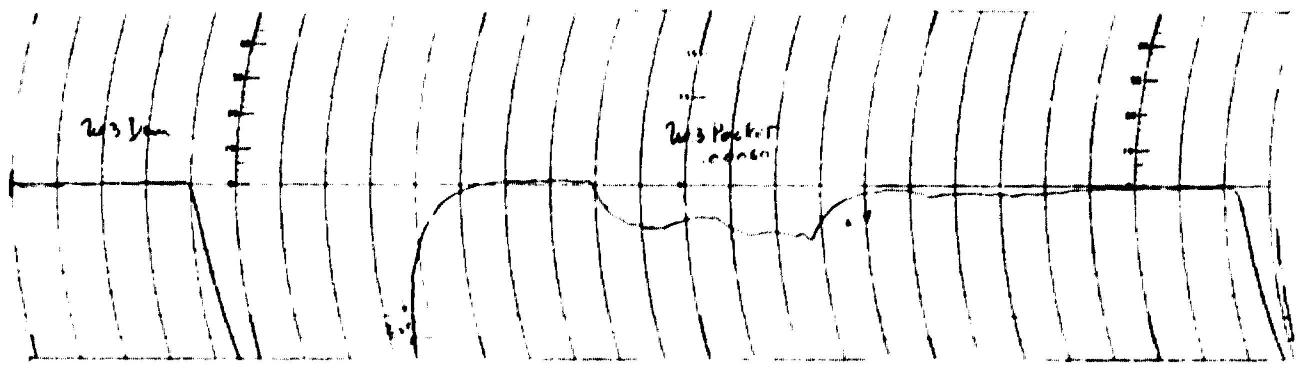


Evaluation Test
Location 2
Fwd Seal New

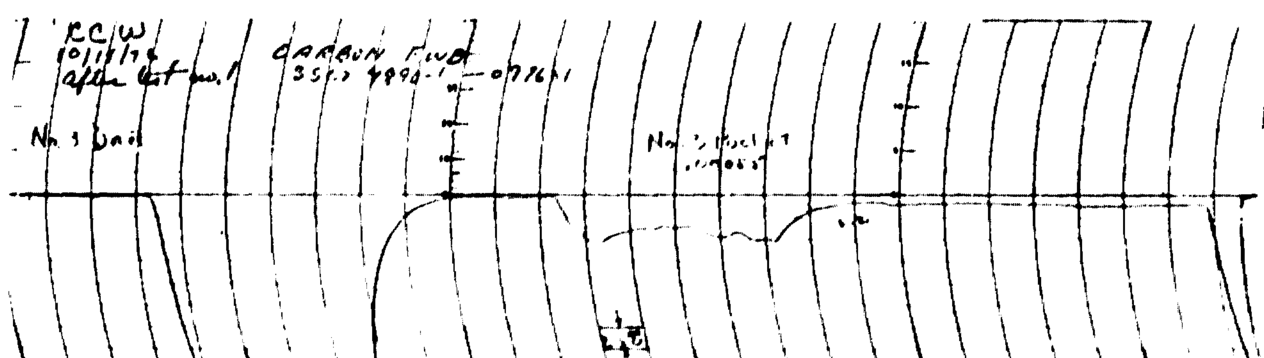


Fwd Seal After Build I

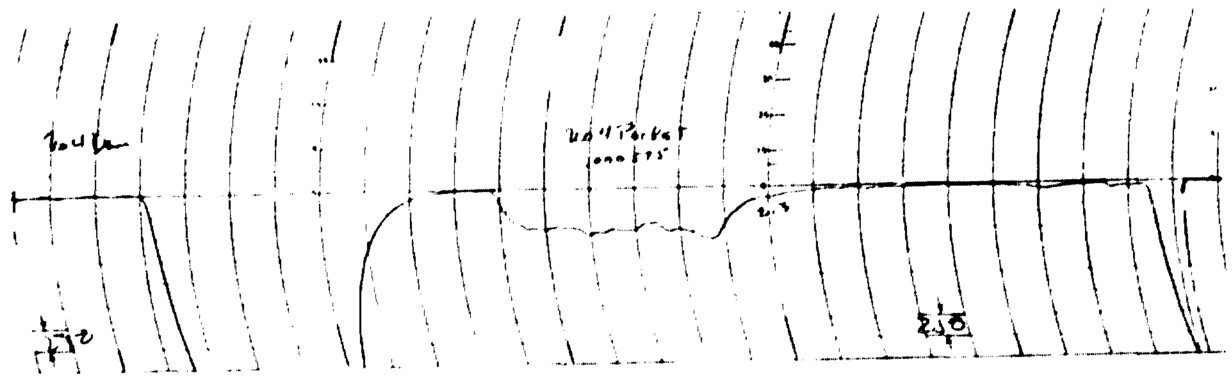
Evaluation Test
Location 3
Fwd Seal New



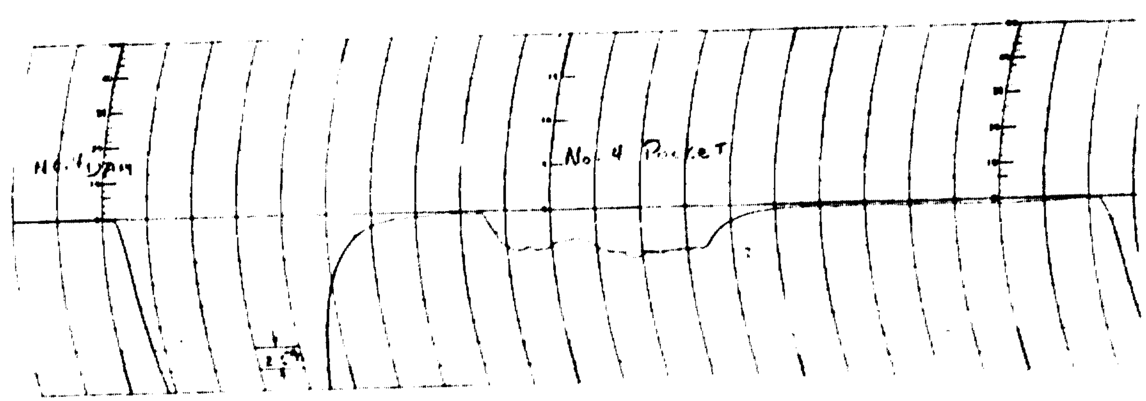
Fwd Seal After Build I

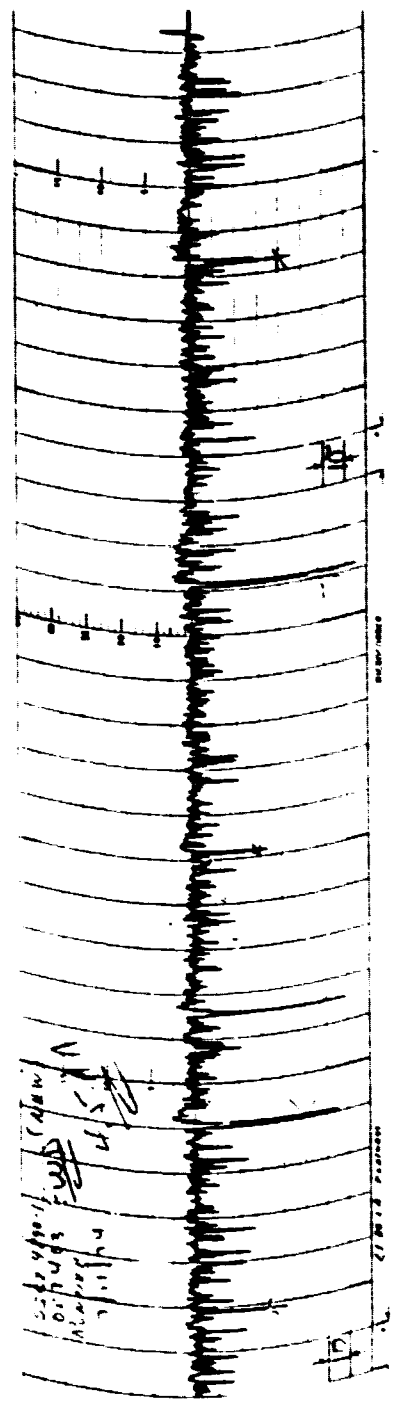


Evaluation Test
Location 4
Fwd Seal New

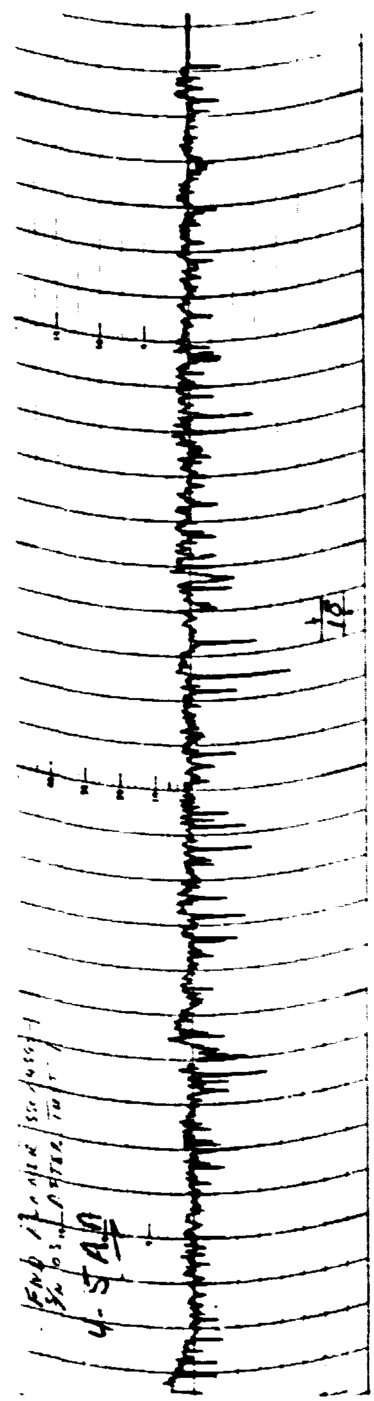


Fwd Seal After Build I



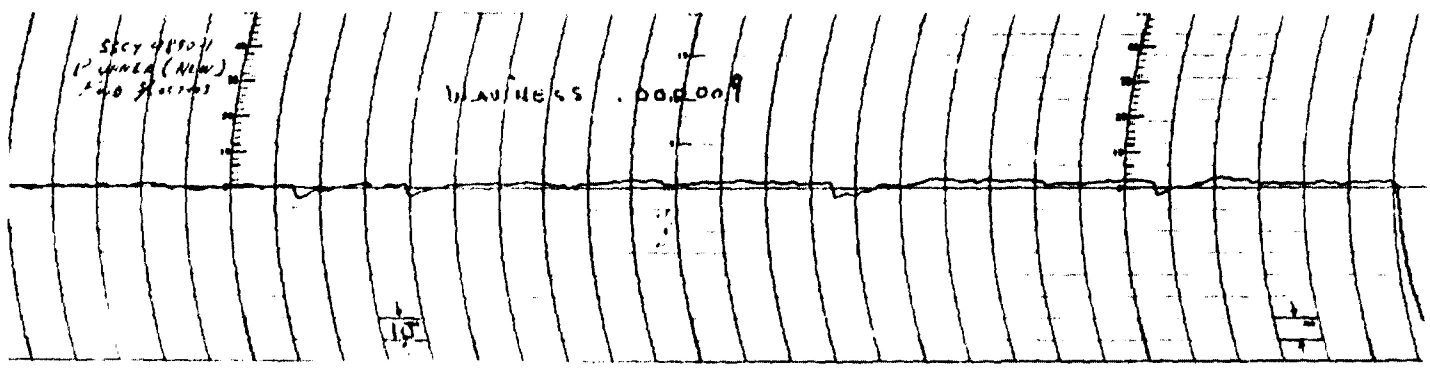


Forward Seal Seat Finish Before Evaluation Testing

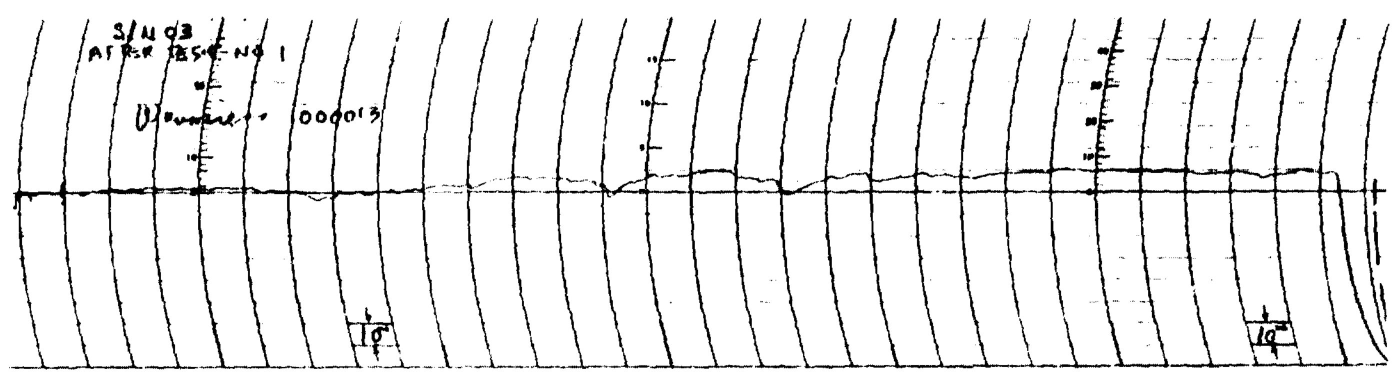


Forward Seal Seat Finish After Build I

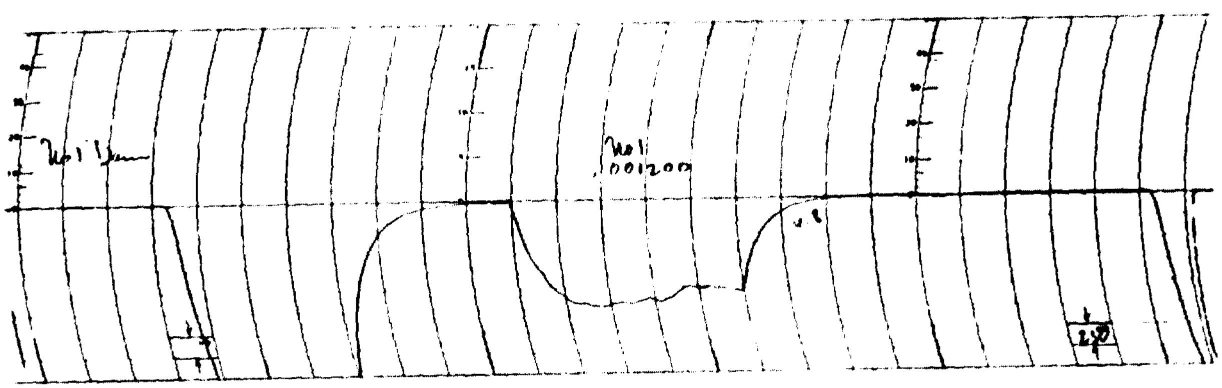
Fwd Seal Seat Waviness Before Evaluation Testing



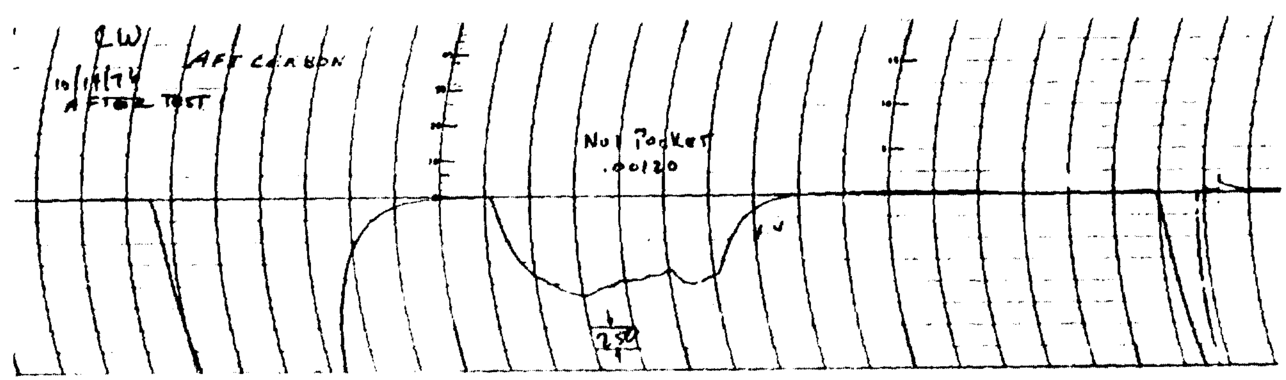
Fwd Seal Seat Waviness After Build I



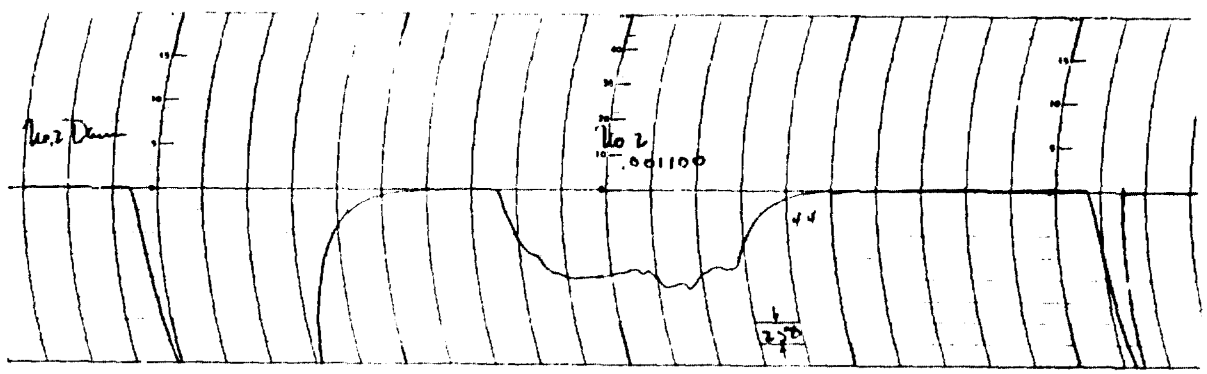
Evaluation Test
Location 1
Aft Seal New



Aft Seal After Build I



Evaluation Test
Location 2
Aft Seal New



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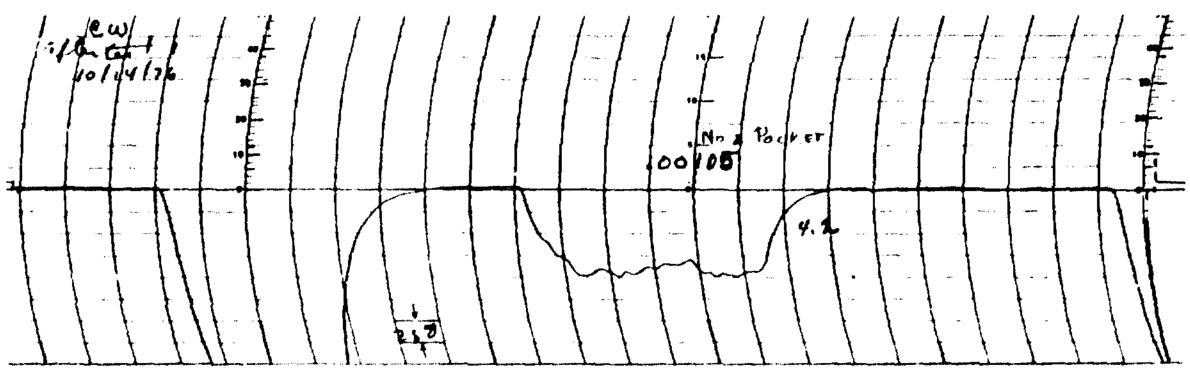
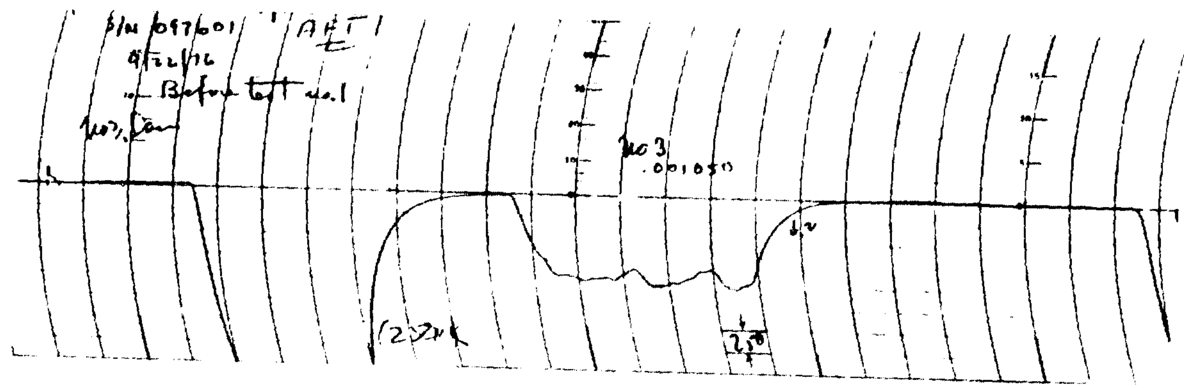
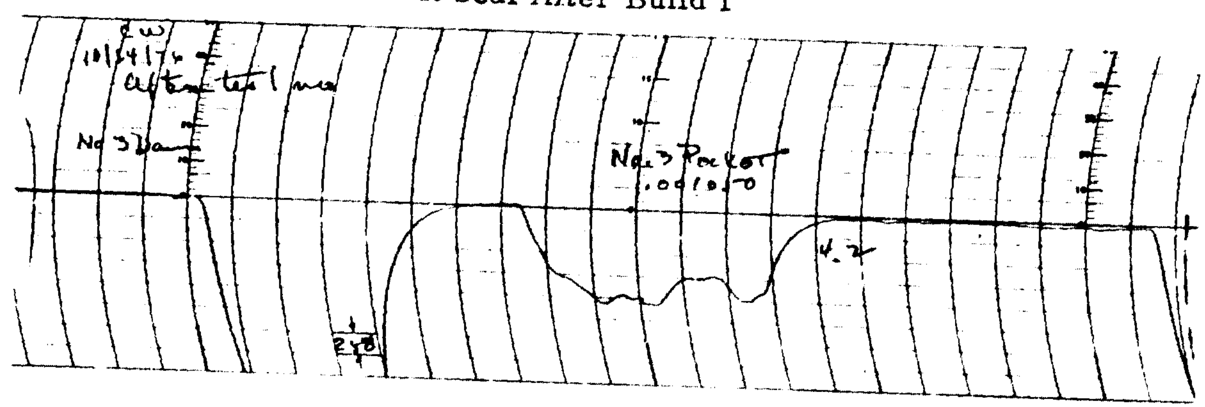


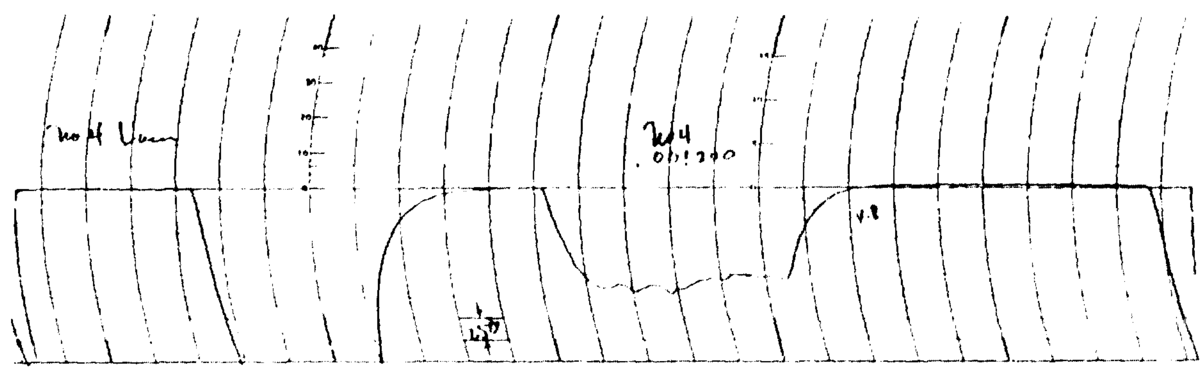
Evaluation Test
Location 3
Aft Seal New



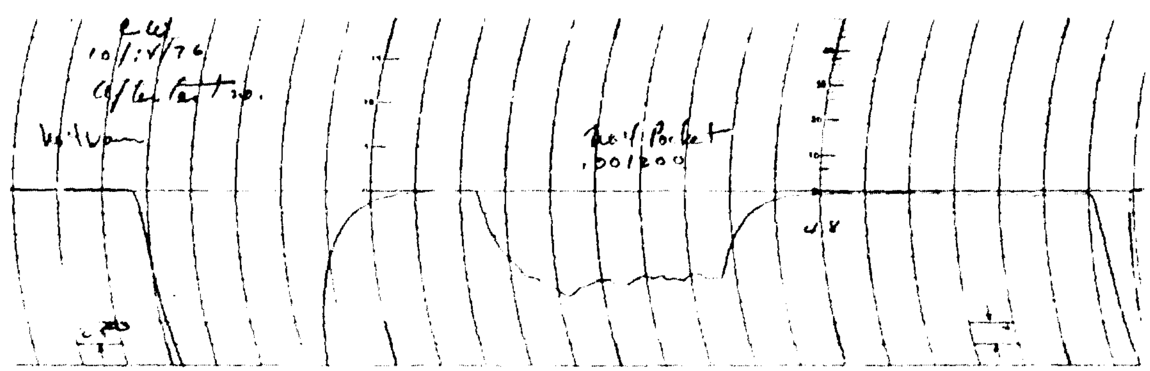
Aft Seal After Build I



Evaluation Test
Location 4
Aft Seal New



Aft Se 1 After Build I



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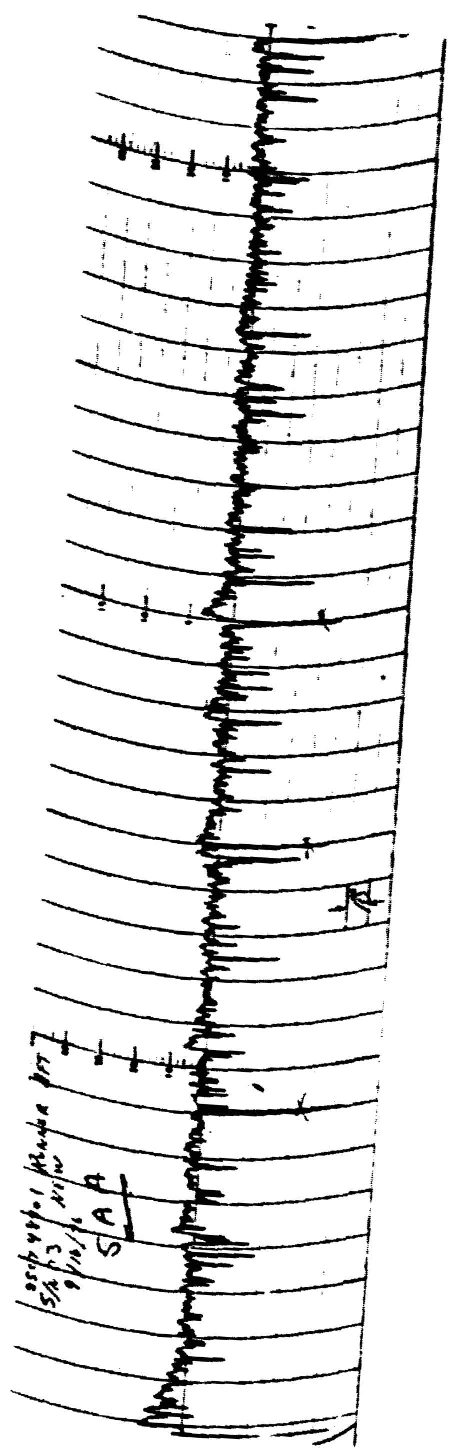
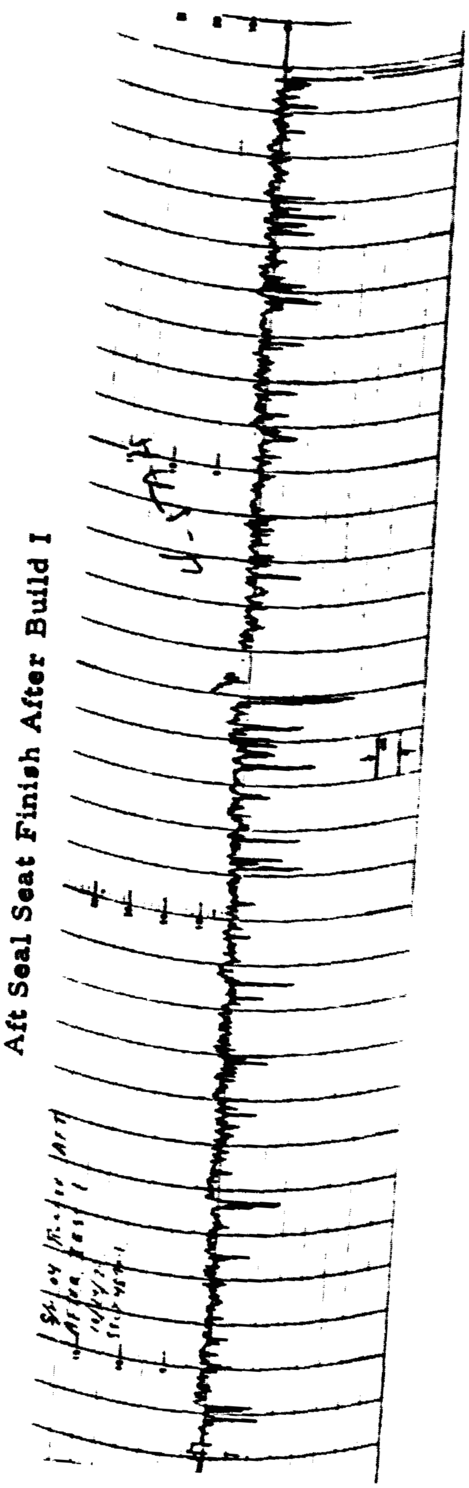


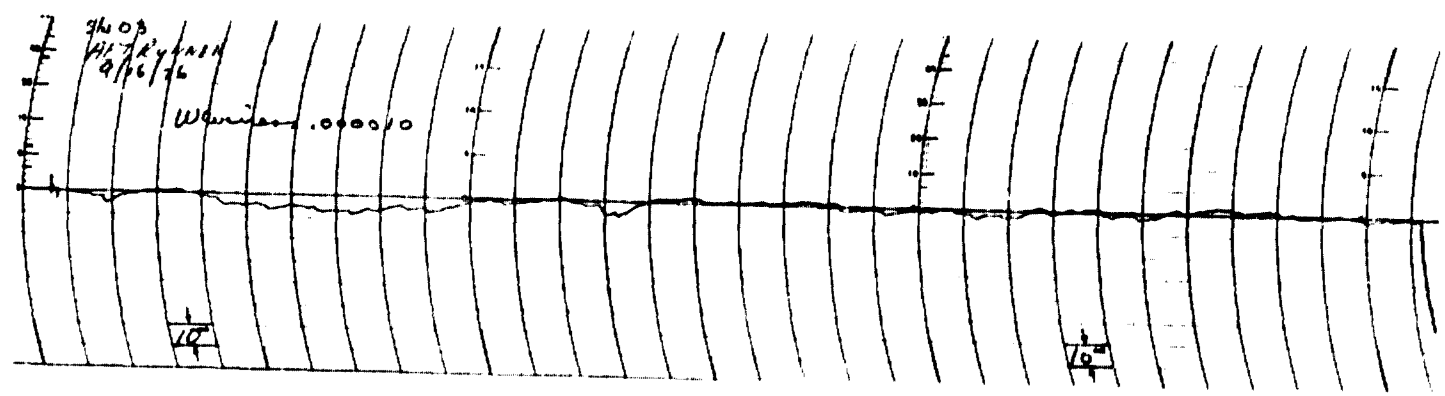
Aft Seal Seat Finish Before Evaluation Testing



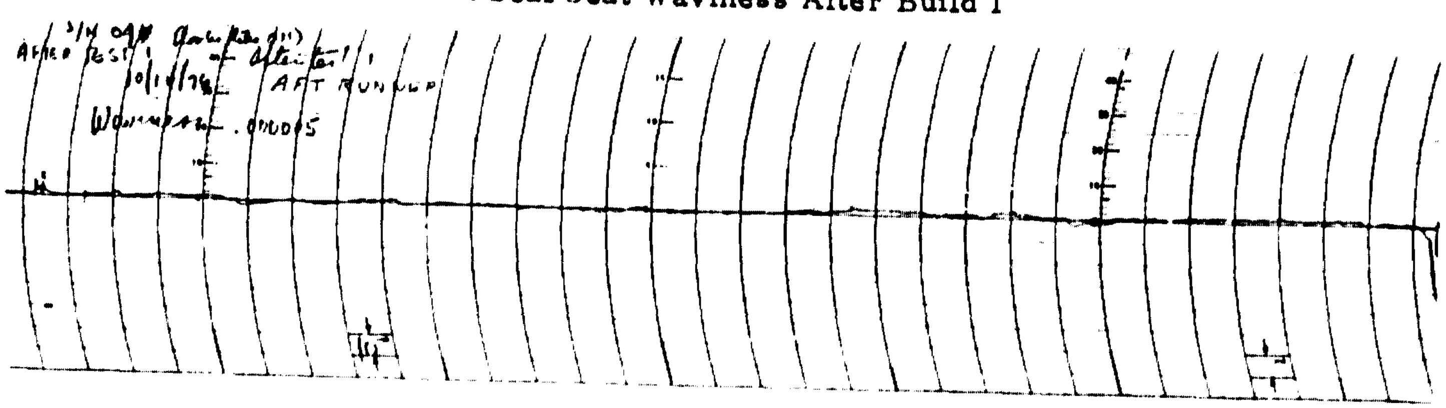
Aft Seal Seat Finish After Build I

C-2

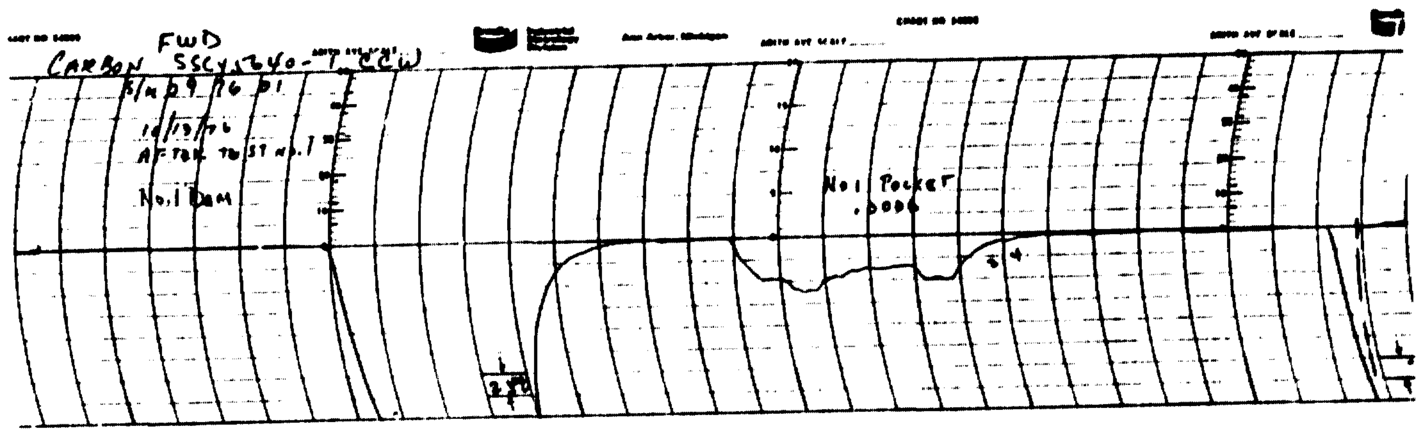
Aft Seal Seat Waviness Before Evaluation Testing



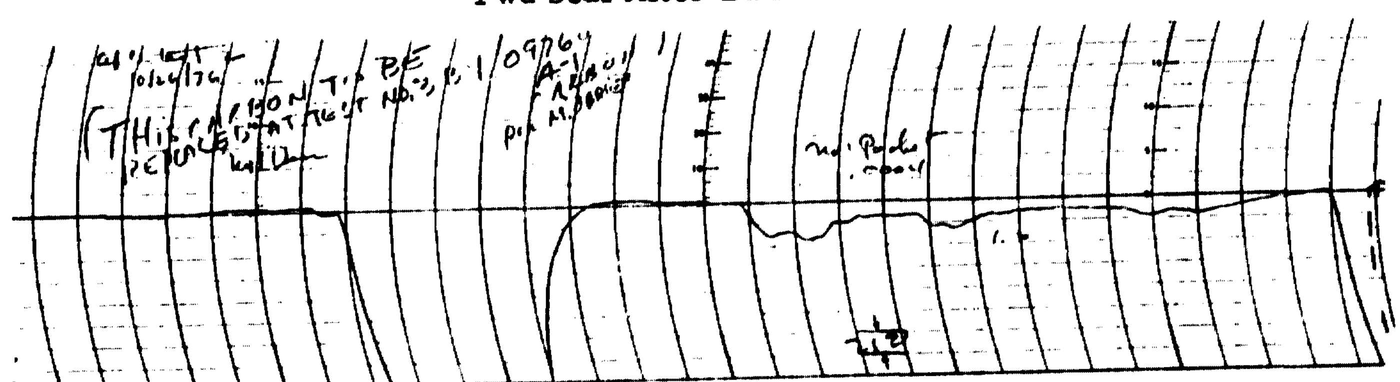
Aft Seal Seat Waviness After Build I



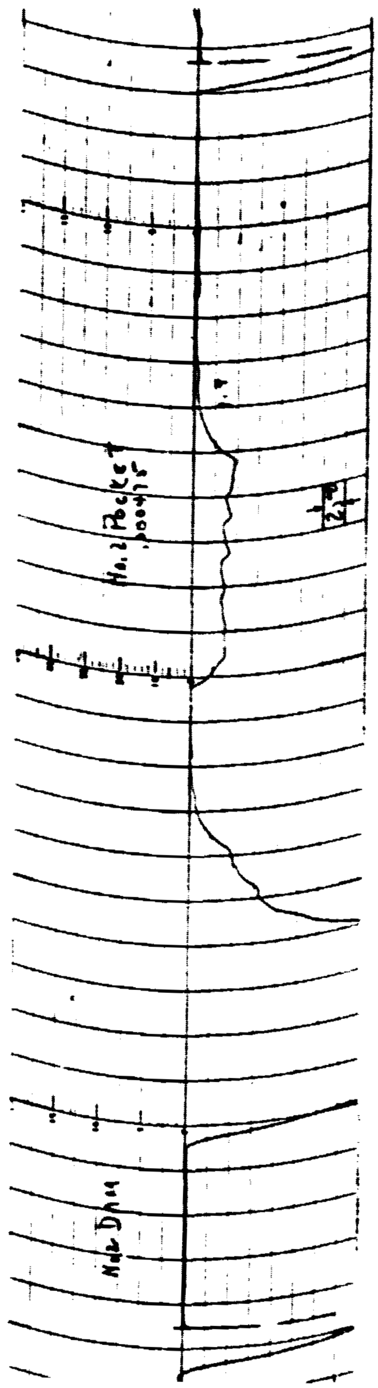
Evaluation Test
Location 1
Fwd Seal Prior to Build II



Fwd Seal After Build II



Evaluation Test
Location 2
Fwd Seal Prior to Build II



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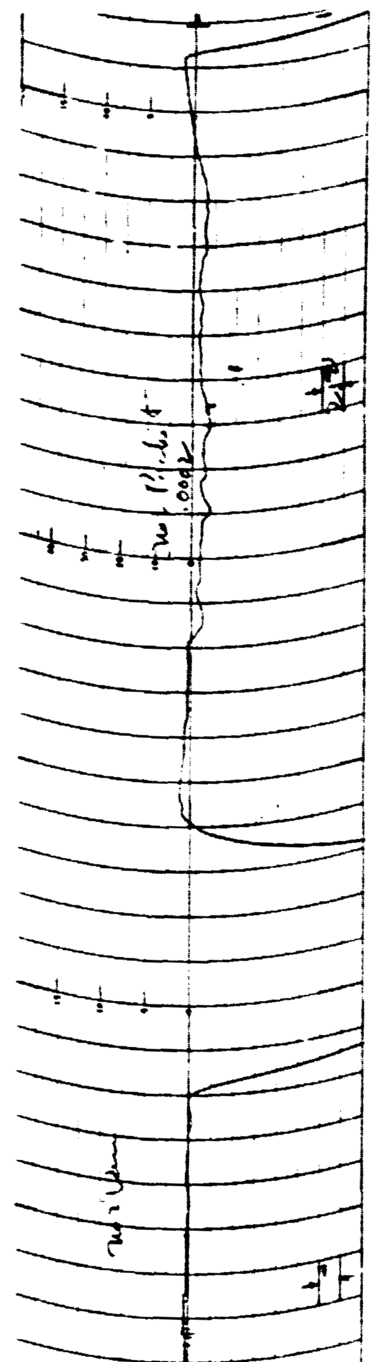
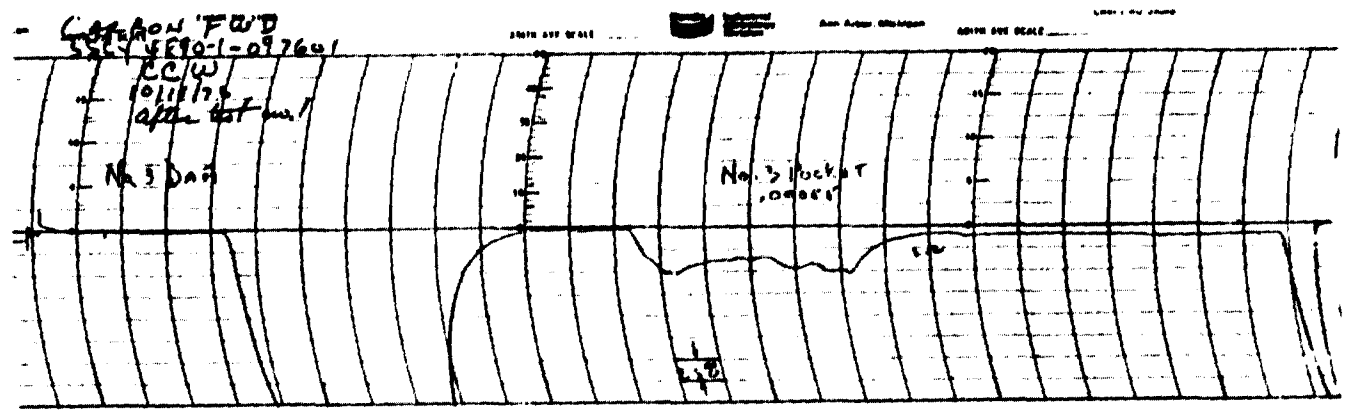
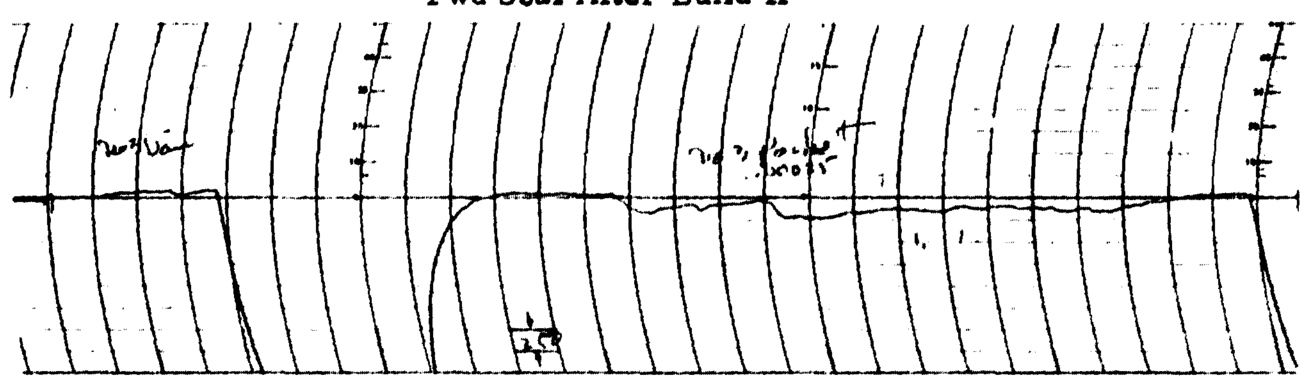


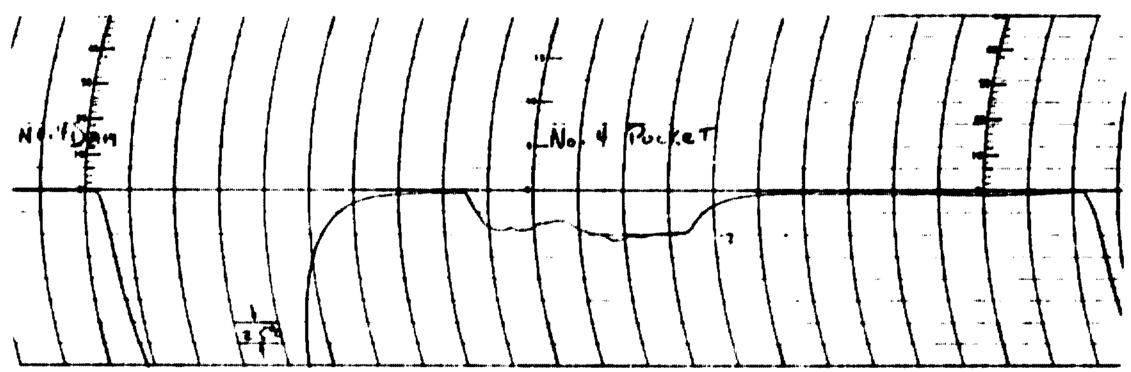
Evaluation Test
Location 3
Fwd Seal Prior to Build II



Fwd Seal After Build II



Evaluation Test
Location 4
Fwd Seal Prior to Build II



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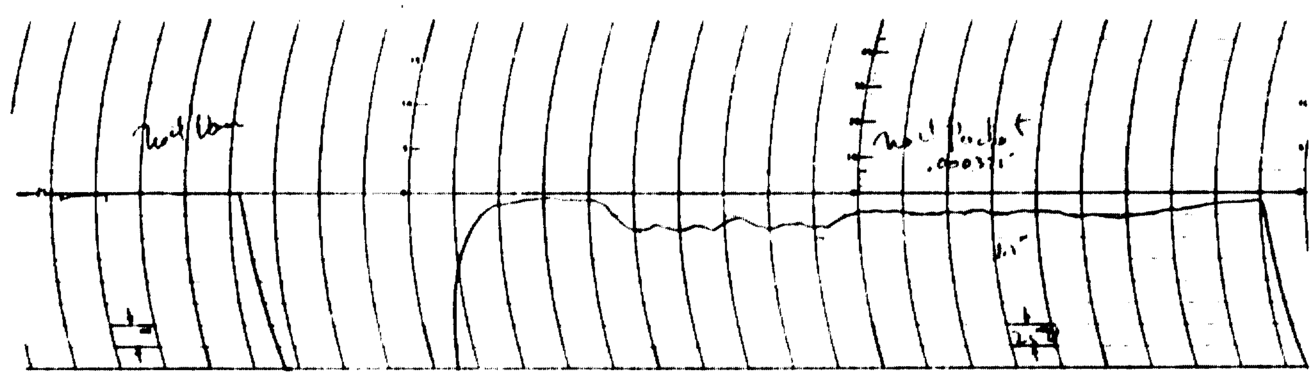
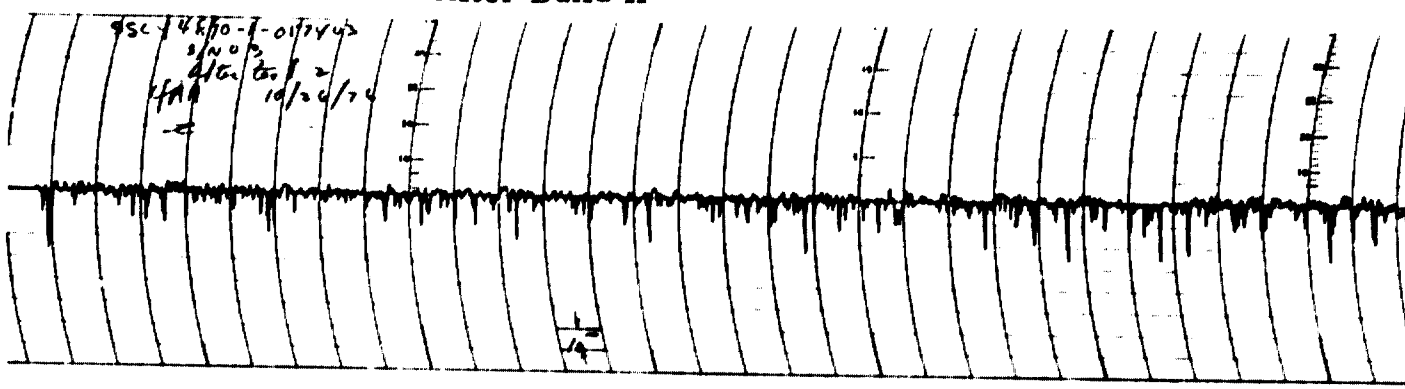
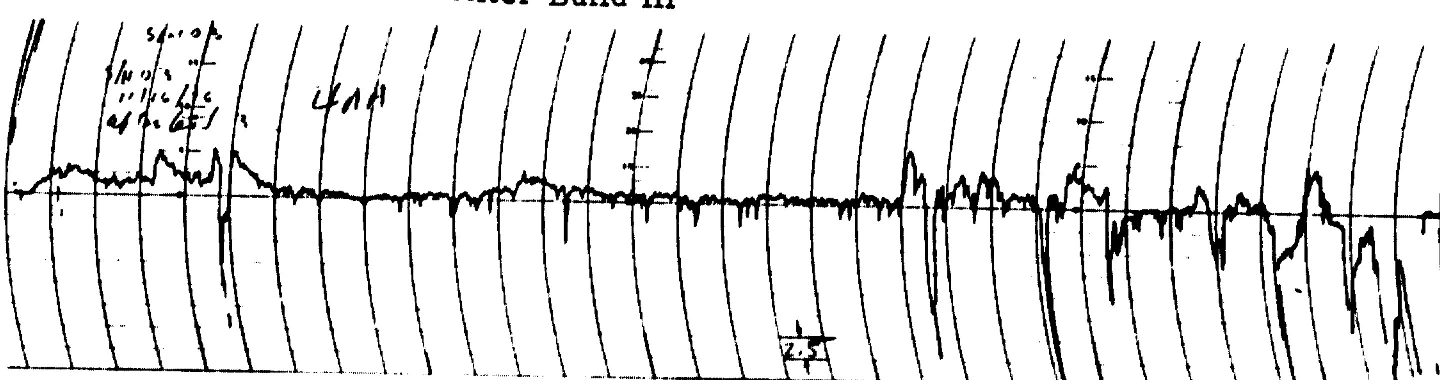
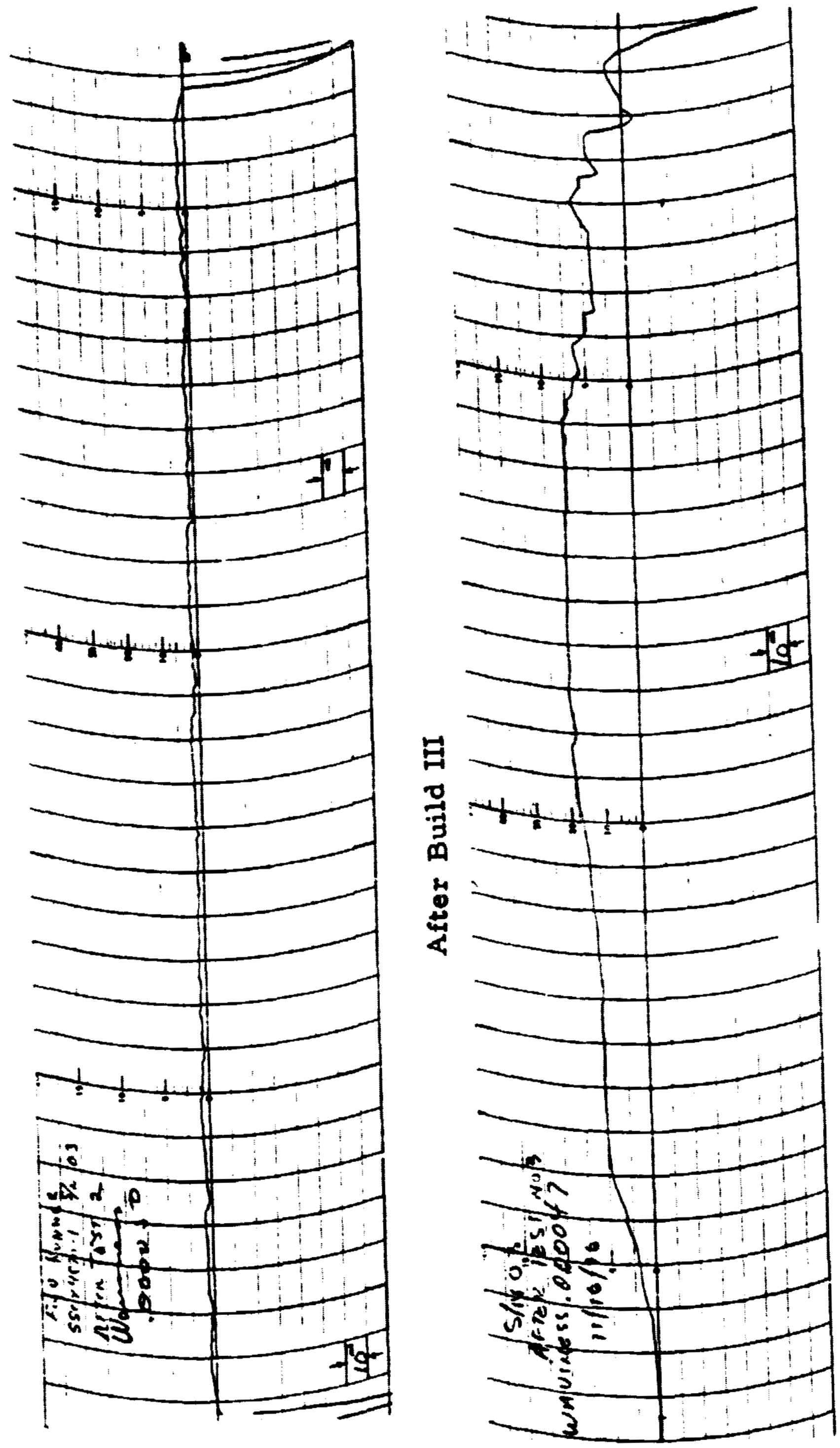


Fwd Seal Seat Finish
After Build II



After Build III

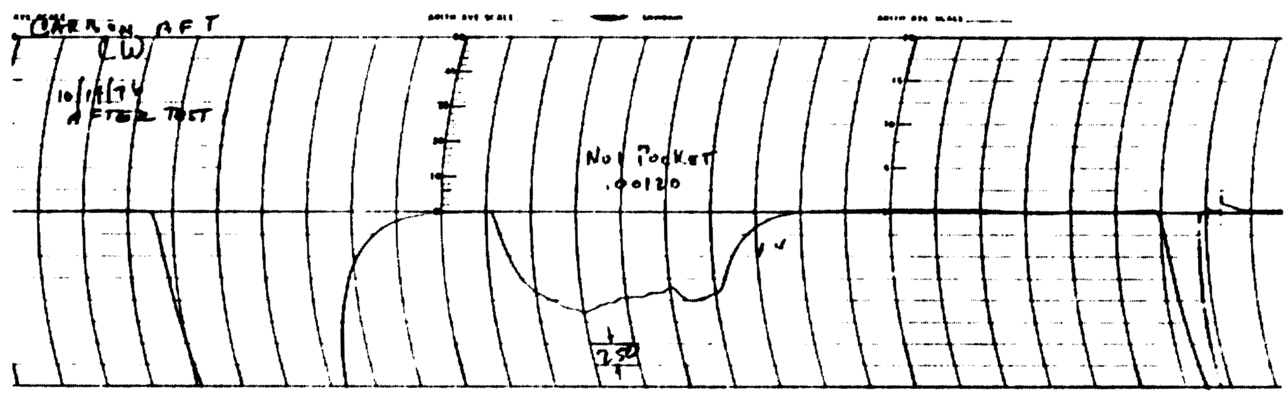




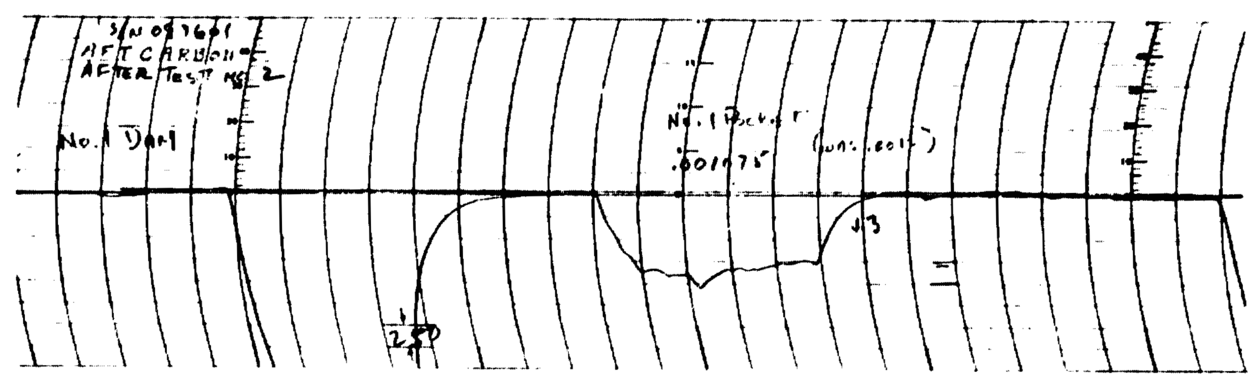
Fwd Seal Seat Waviness
After Build II

After Build III

Evaluation Test
Location 1
Aft Seal Prior to Build II



Aft Seal After Build II



Evaluation Test
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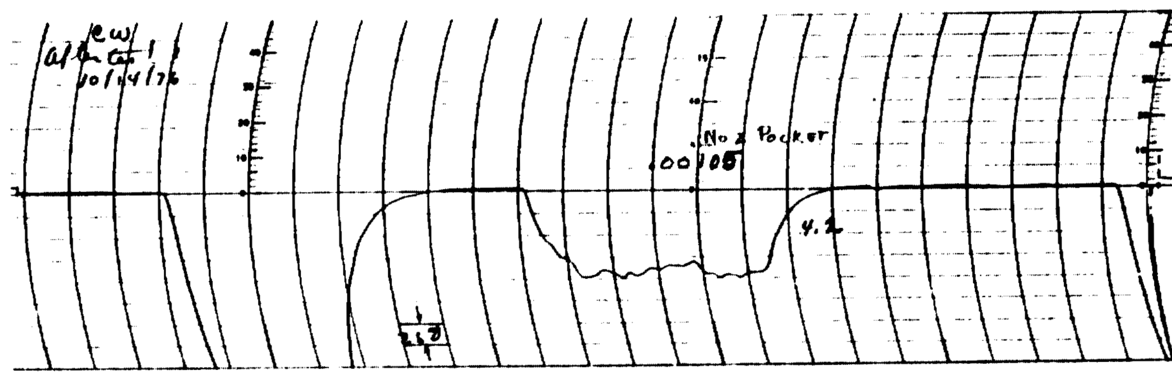
Aft Seal Prior to Build II



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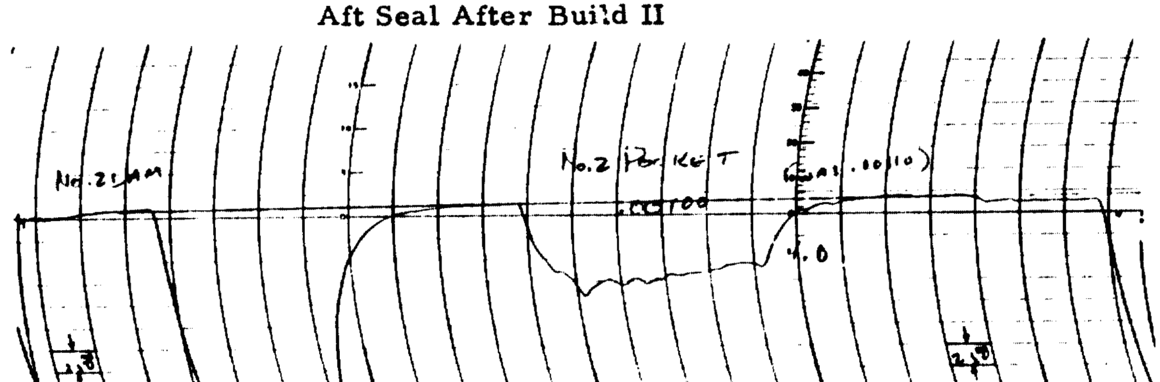

Evaluation Test
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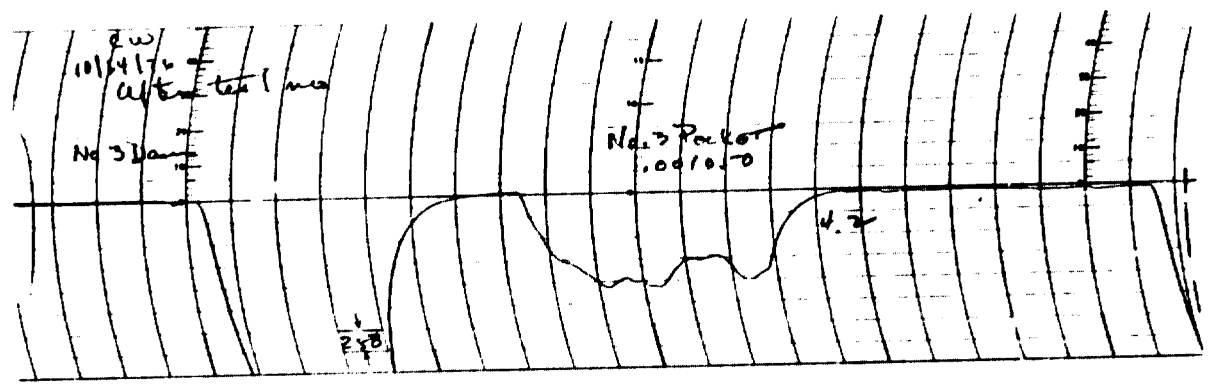
Aft Seal Prior to Build II



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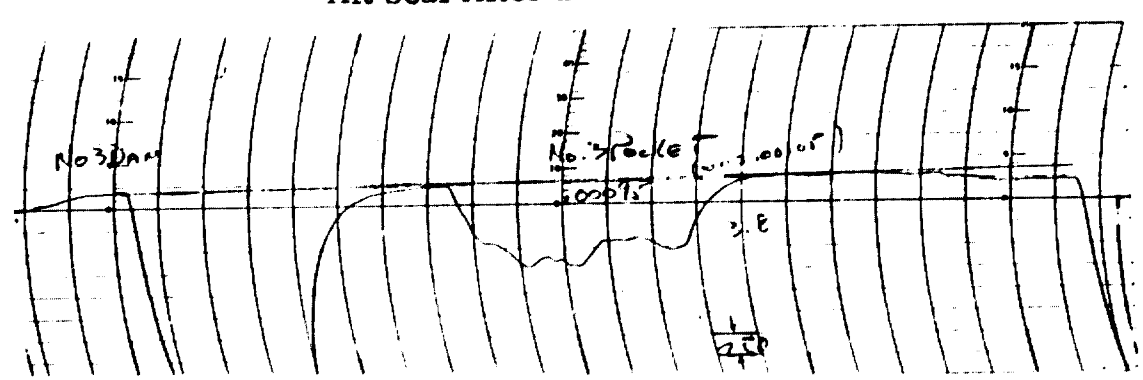
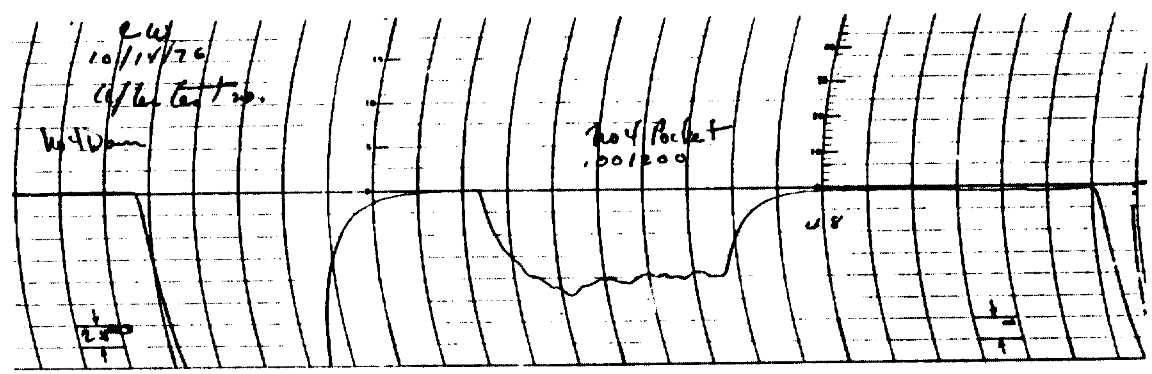


Evaluation Test
Location 4
Aft Seal Prior to Build II



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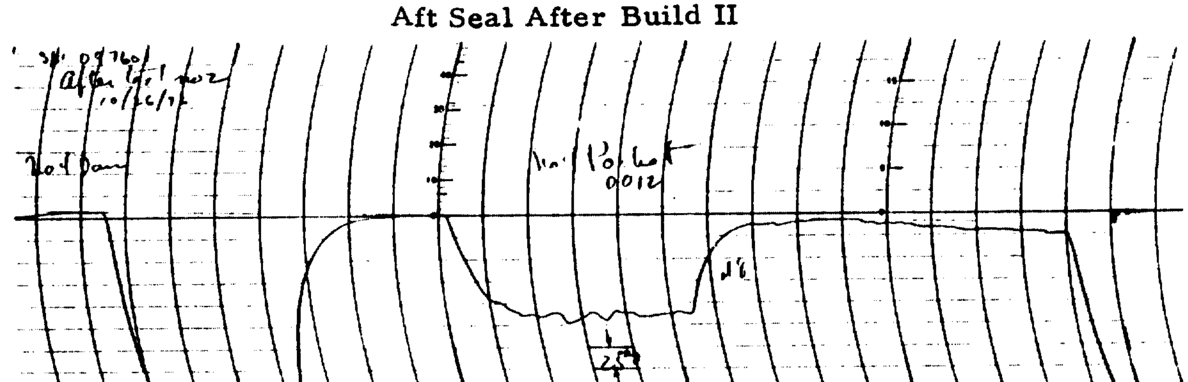
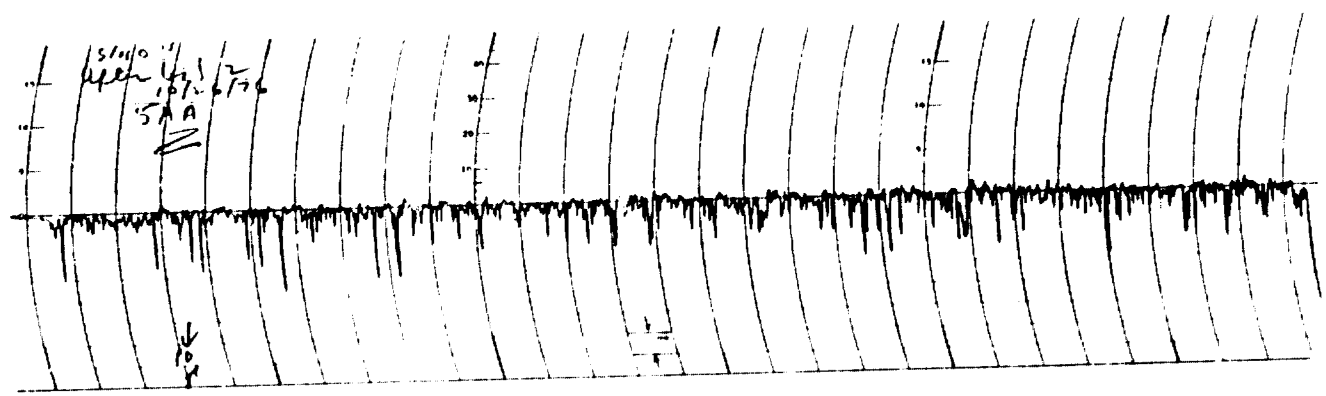
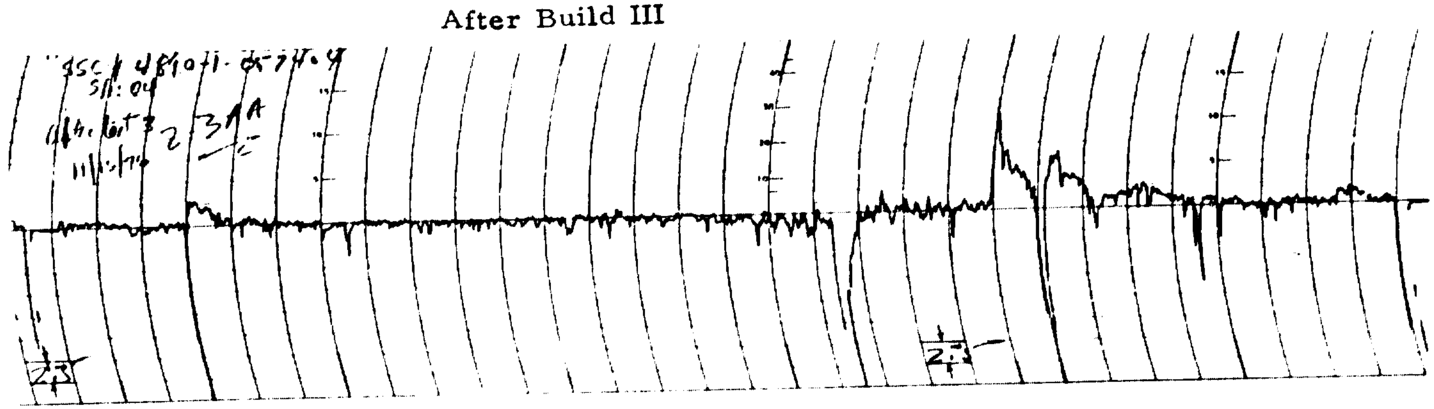


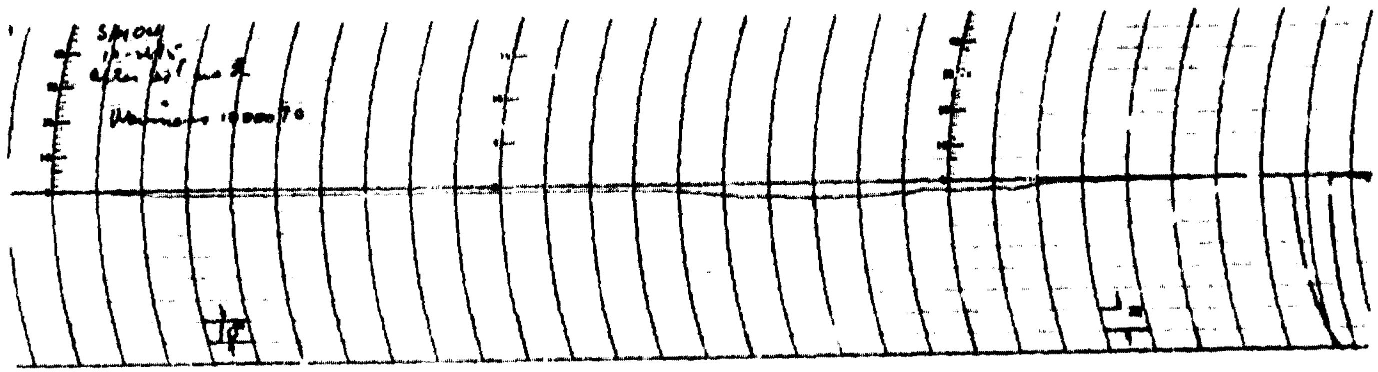
Aft Seal Seat Finish
After Build II



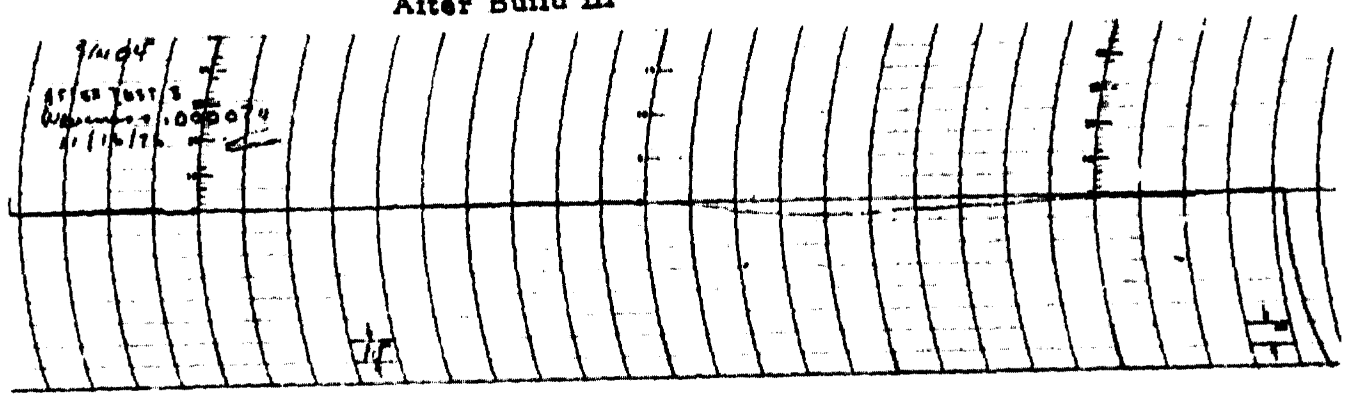
After Build III



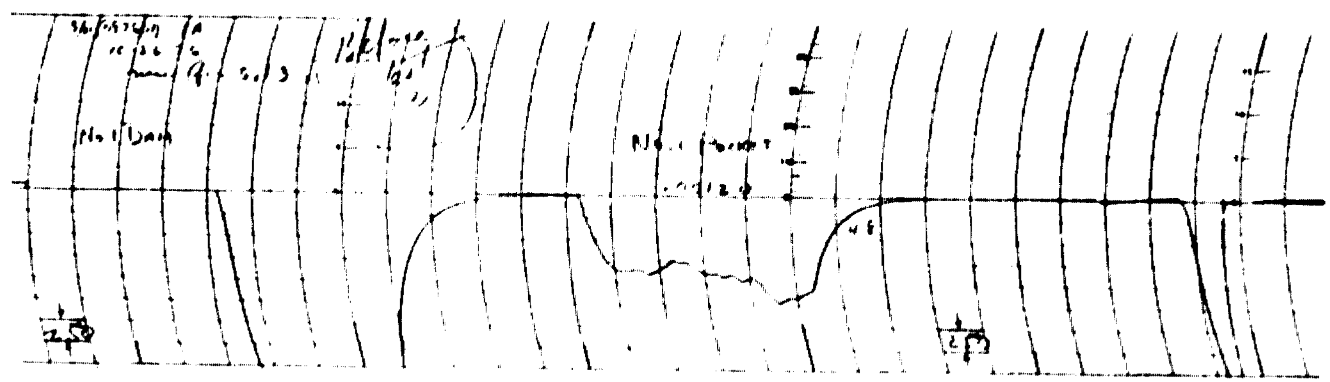
Aft Seal Seat Waviness
After Build II



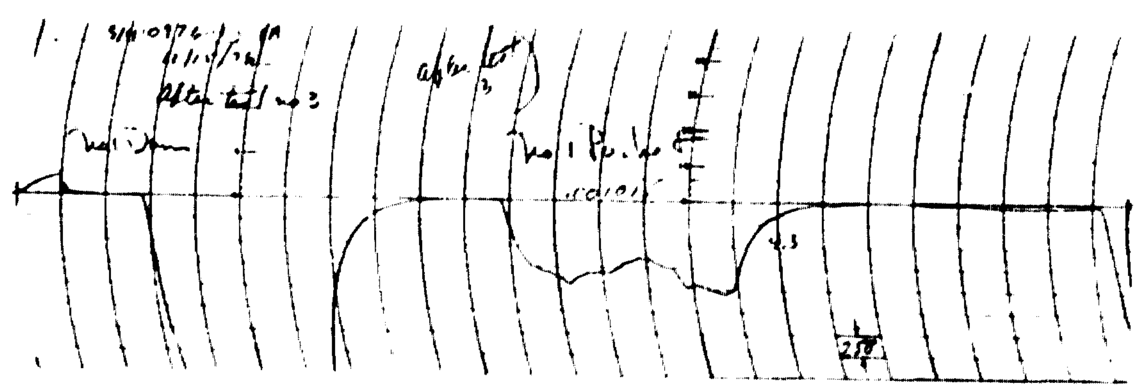
After Build III



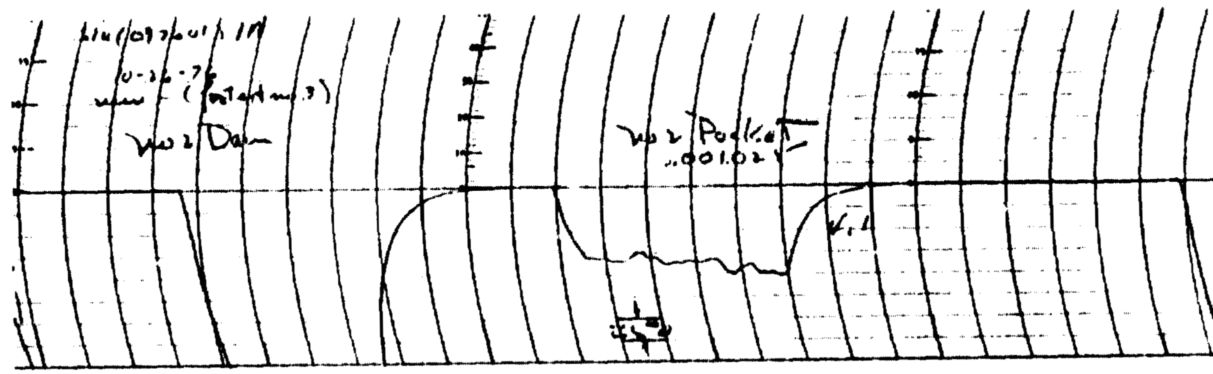
Evaluation Test
Location 1
Fwd Seal Prior to Build III



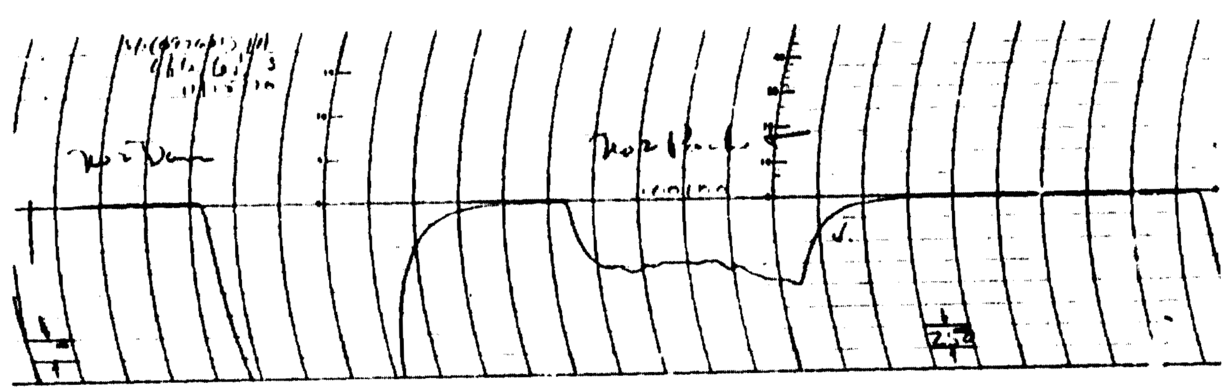
Fwd Seal After Build III



Evaluation Test
Location 2
Fwd Seal Prior to Build III



Fwd Seal After Build III



Evaluation Test
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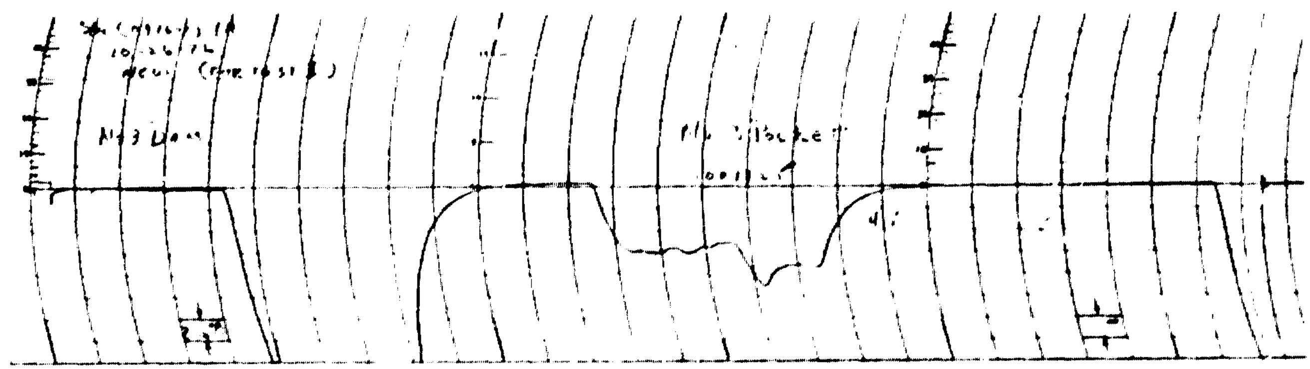
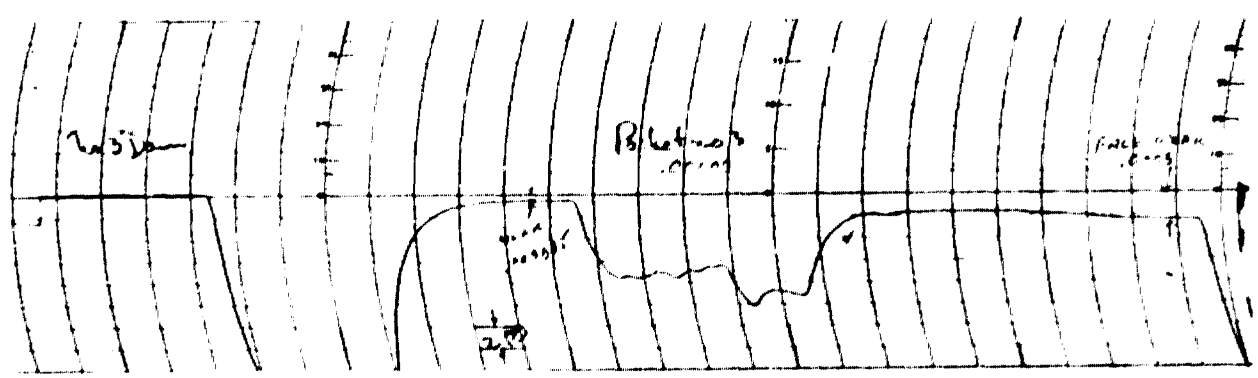
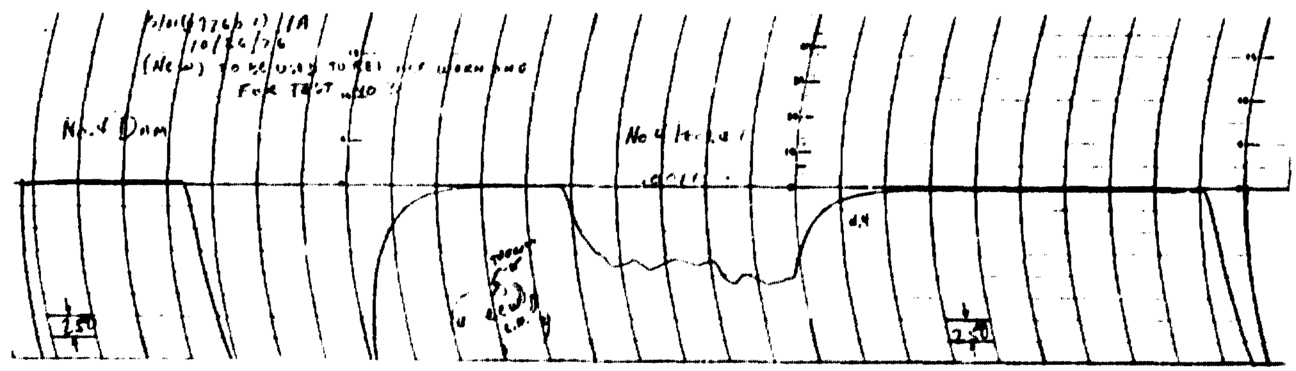
Fwd Seal Prior to Build III



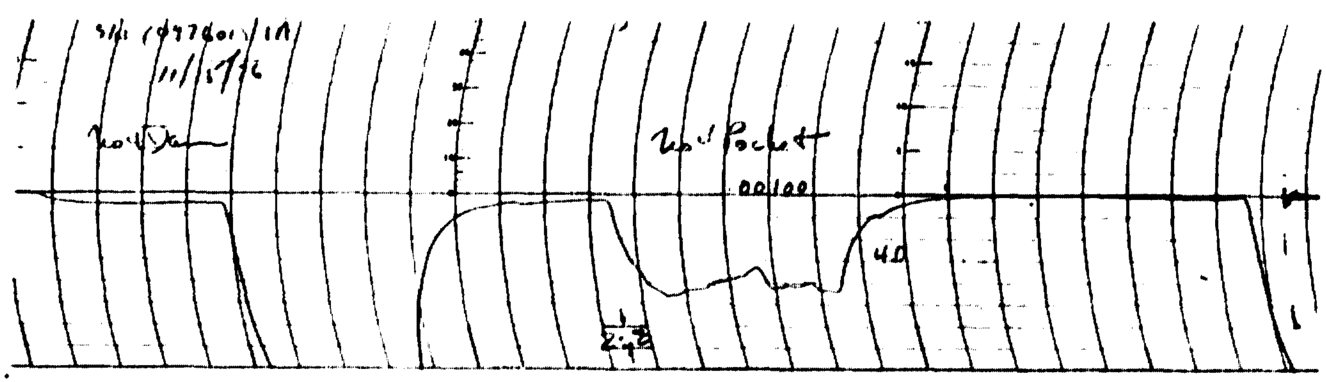
Fwd Seal After Build III



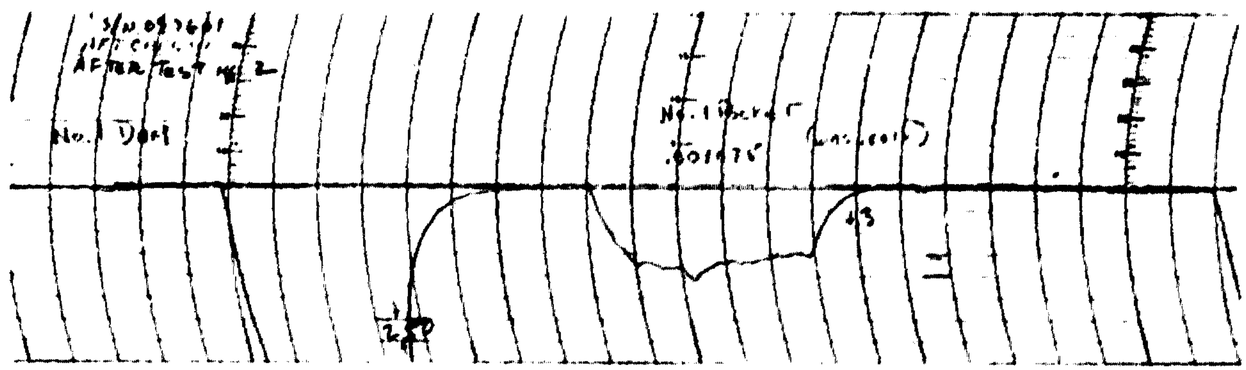
Evaluation Test
Location 4
Fwd Seal Prior to Build III



Fwd Seal After Build III



Evaluation Test
Location 1
Aft Seal Prior to Build III



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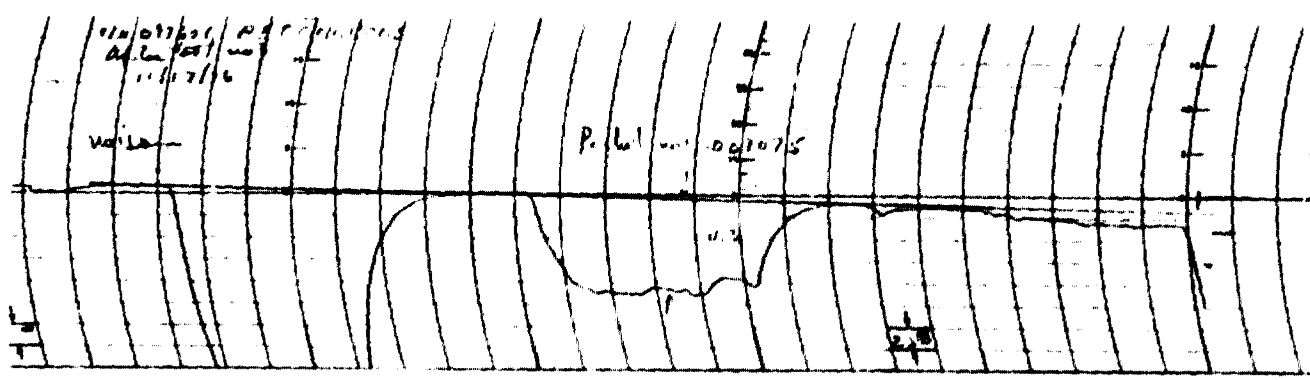
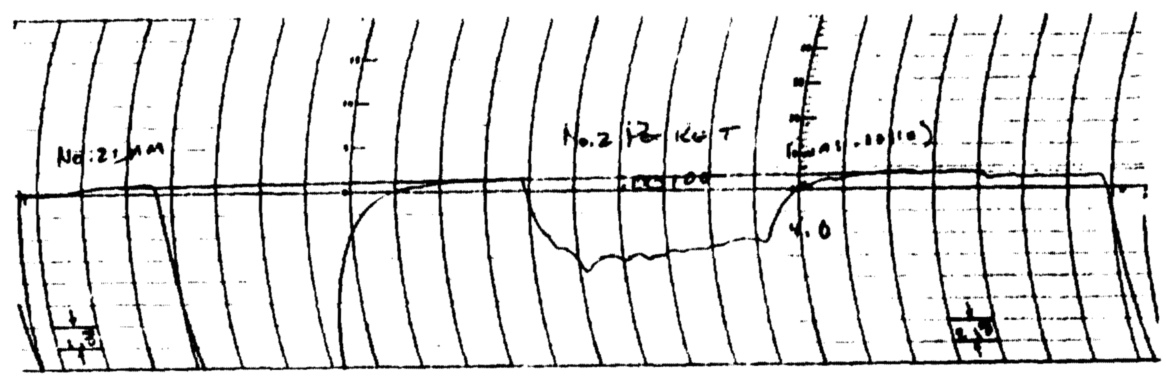


Evaluation Test
Location 2
Aft Seal Prior to Build III



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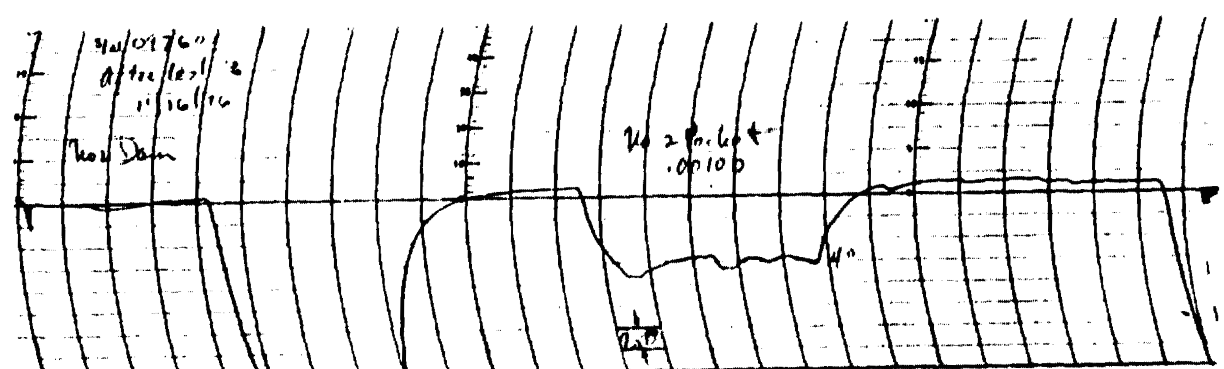
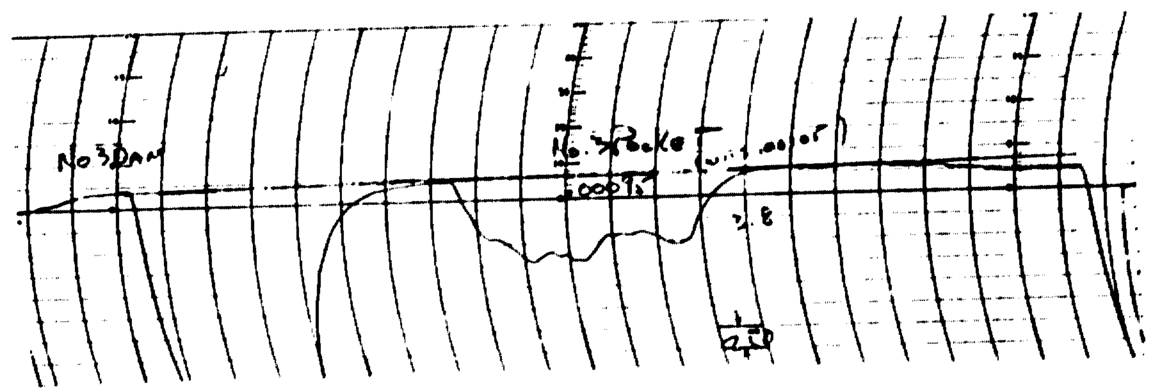
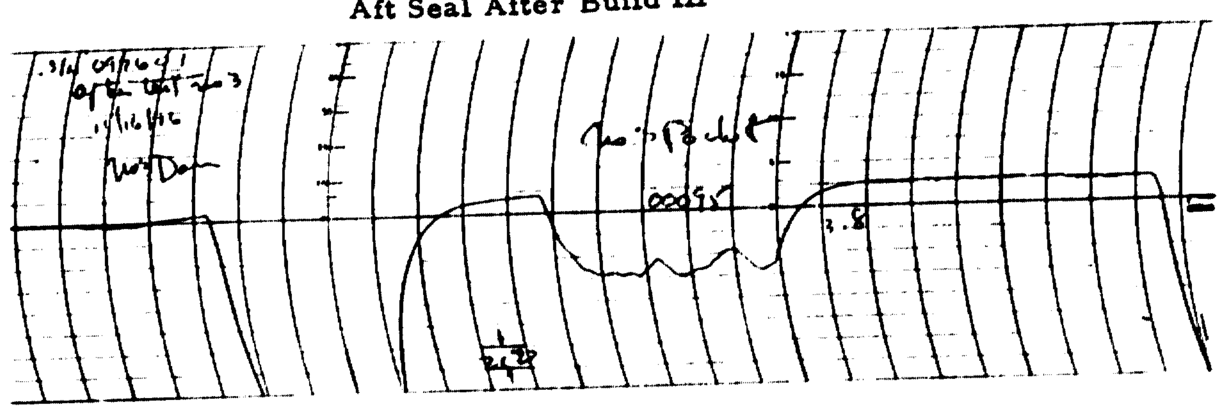


Evaluation Test
Location 3
Aft Seal Prior to Build III



Aft Seal After Build III



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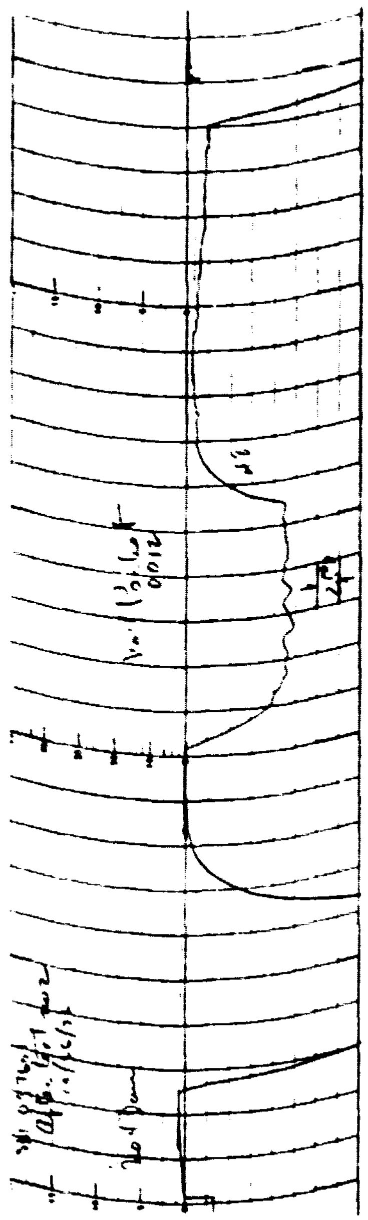
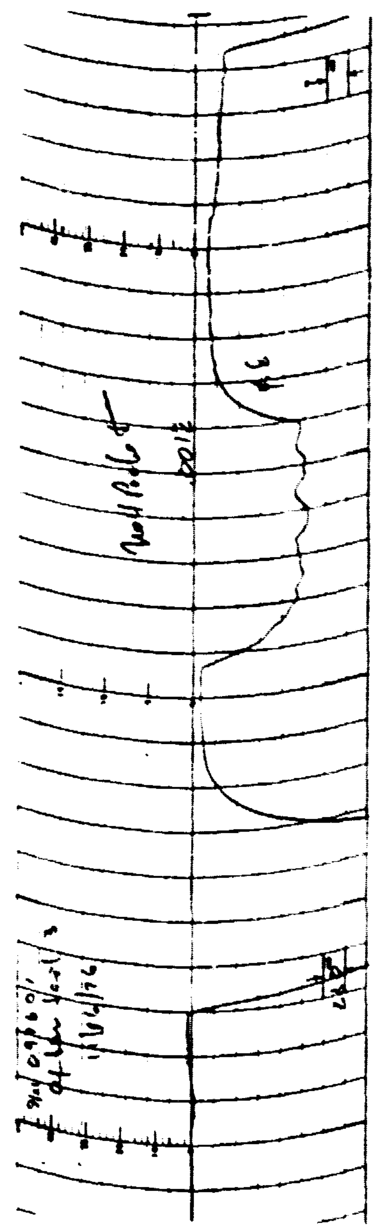
Evaluation Test
Location 4
Aft Seal Prior to Build III

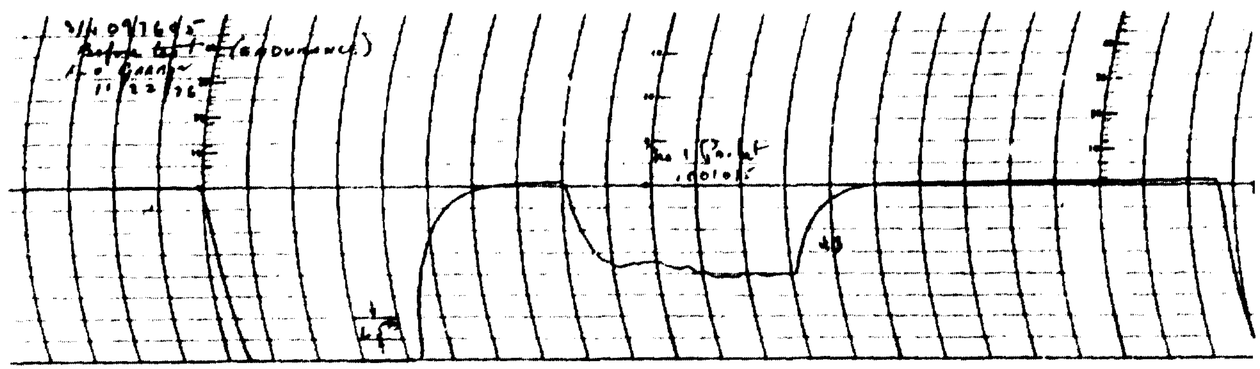


Aft Seal After Build III

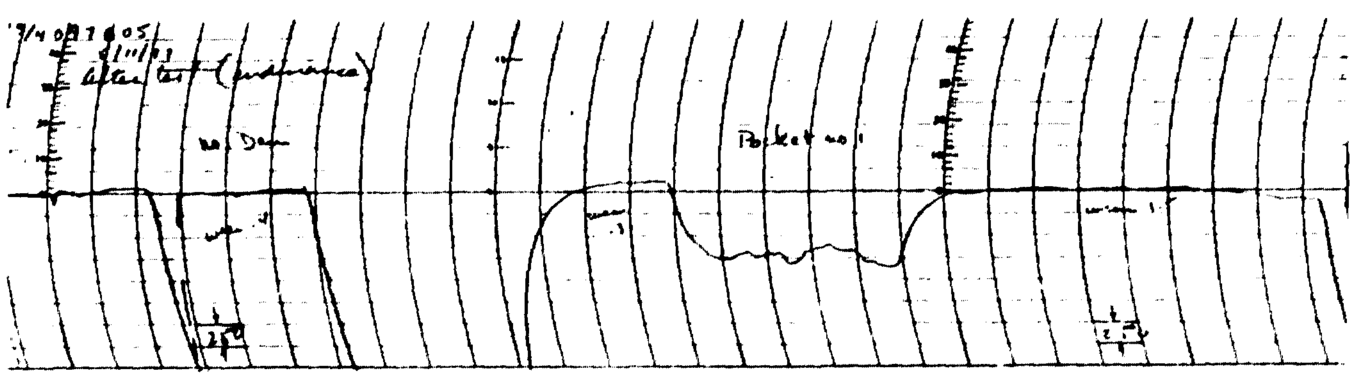


SECTION 3

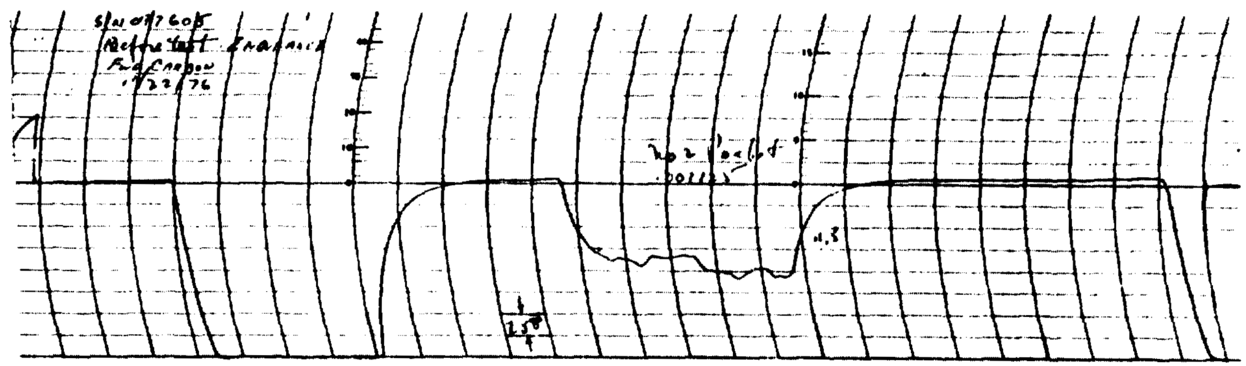
Prior to Endurance Test
Location 1
Fwd Seal



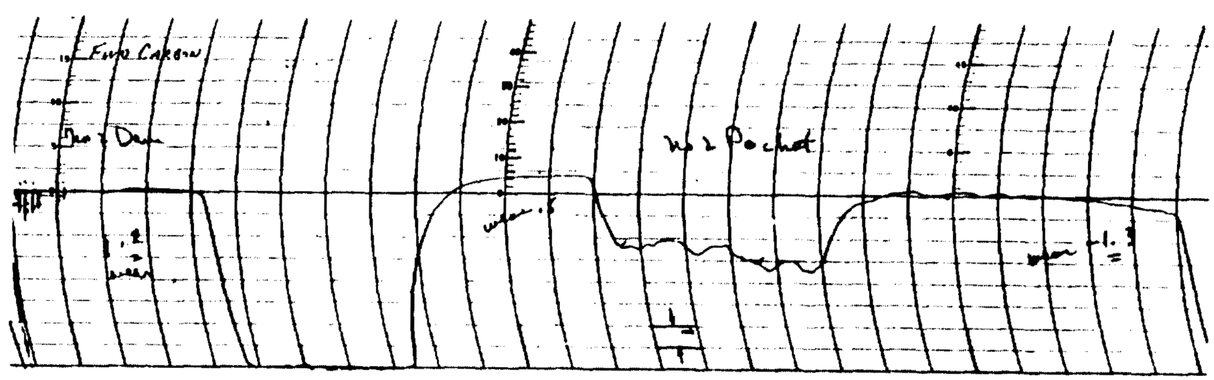
Fwd Seal After Endurance Test (Build I)



Prior to Endurance Test
Location 2
Fwd Seal



Fwd Seal After Endurance Test (Build I)



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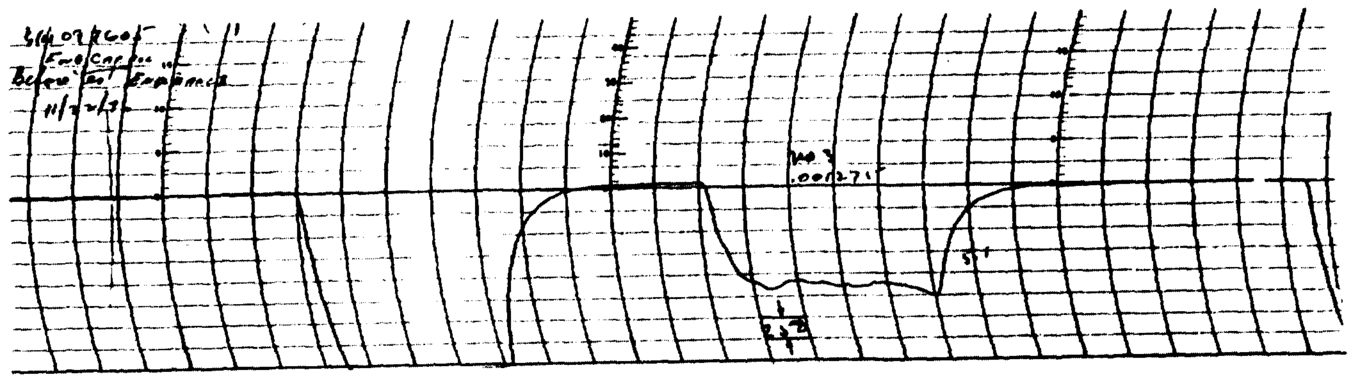
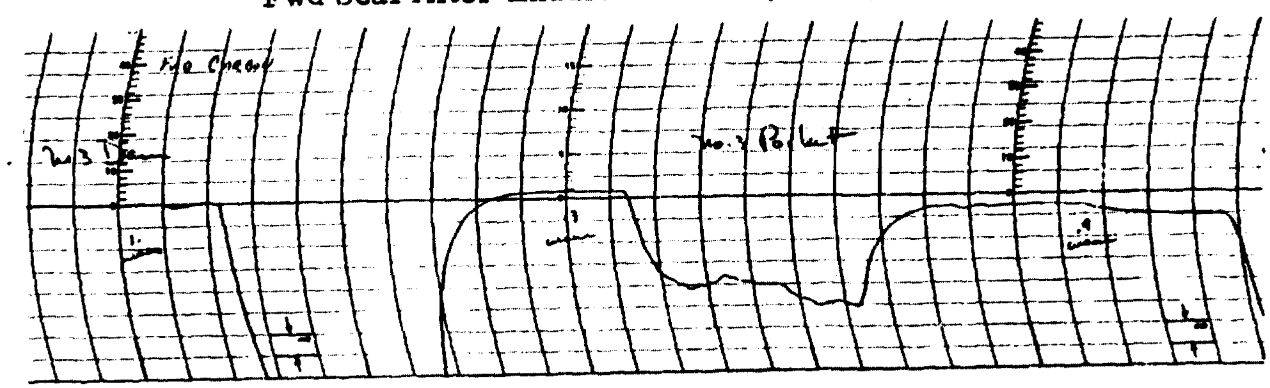
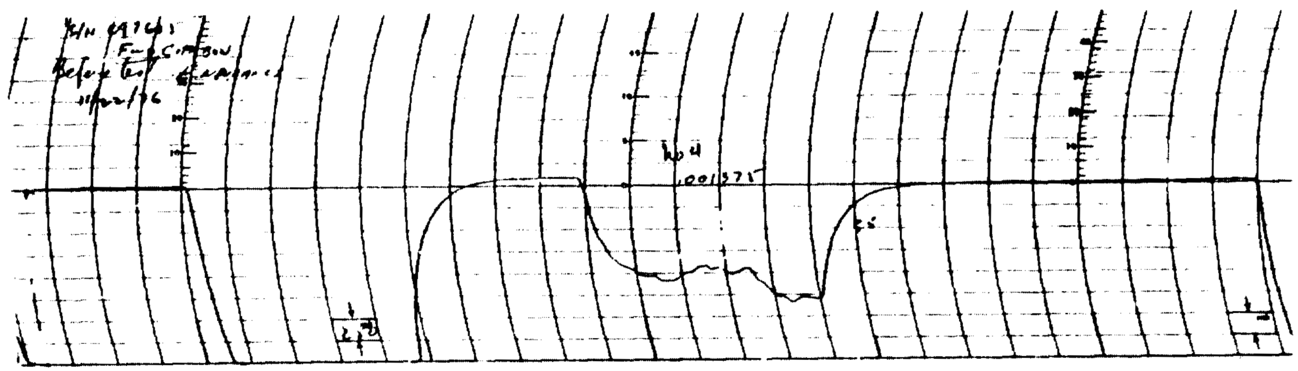
Prior to Endurance Test
Location 3
Fwd Seal



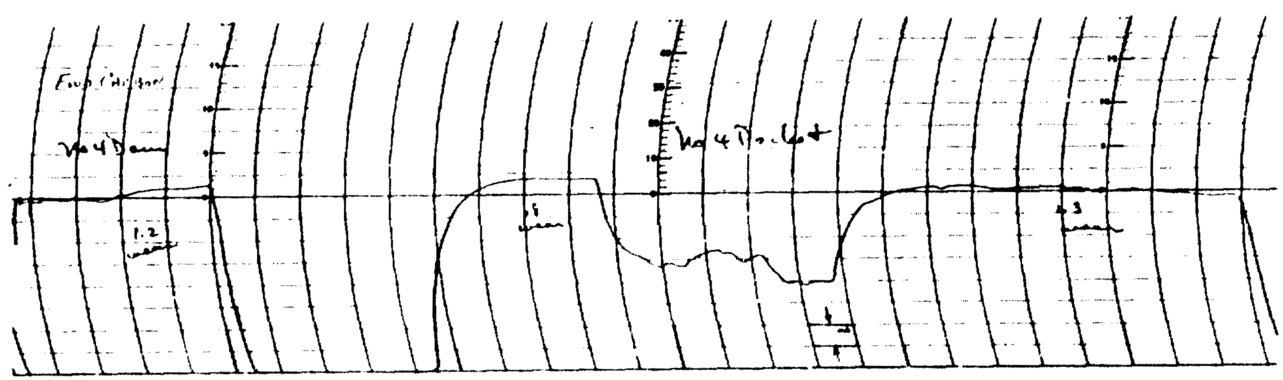
Fwd Seal After Endurance Test (Build I)



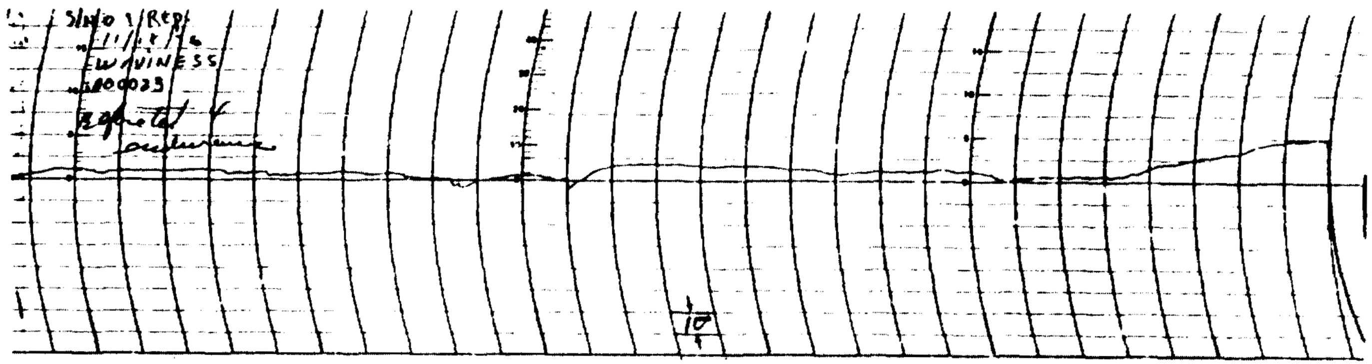
Prior to Endurance Test
Location 4
Fwd Seal



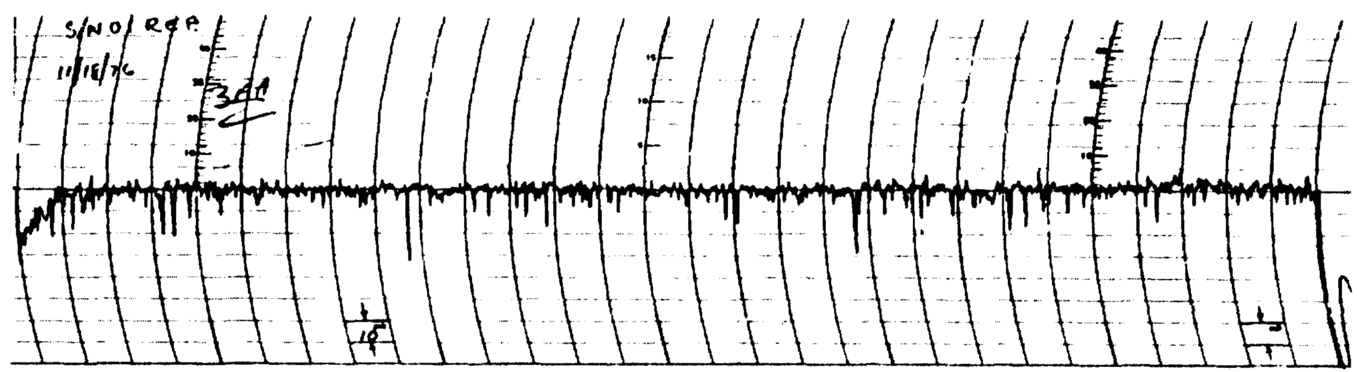
Fwd Seal After Endurance Test (Build I)



Fwd Seal Seat Waviness Prior to Endurance Test

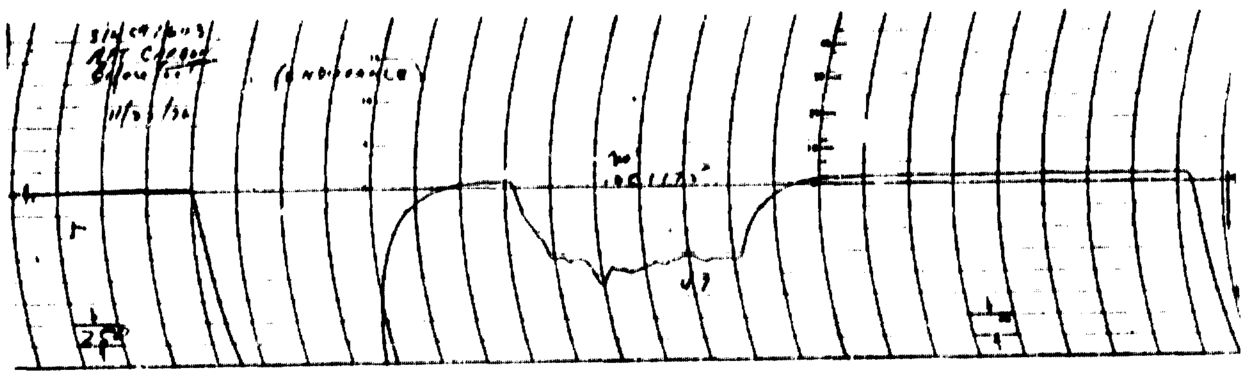


Fwd Seal Seat Finish Prior to Endurance Test

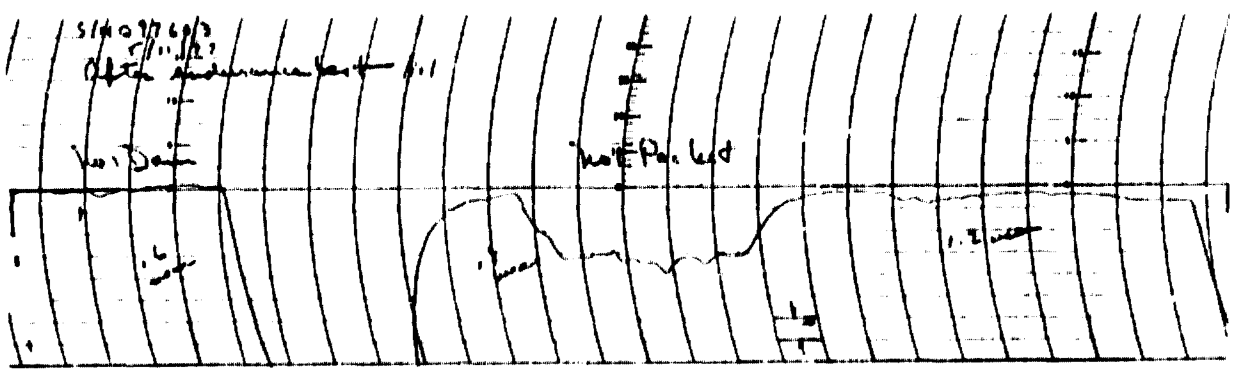


No After Test Traces Due To Damaged Parts

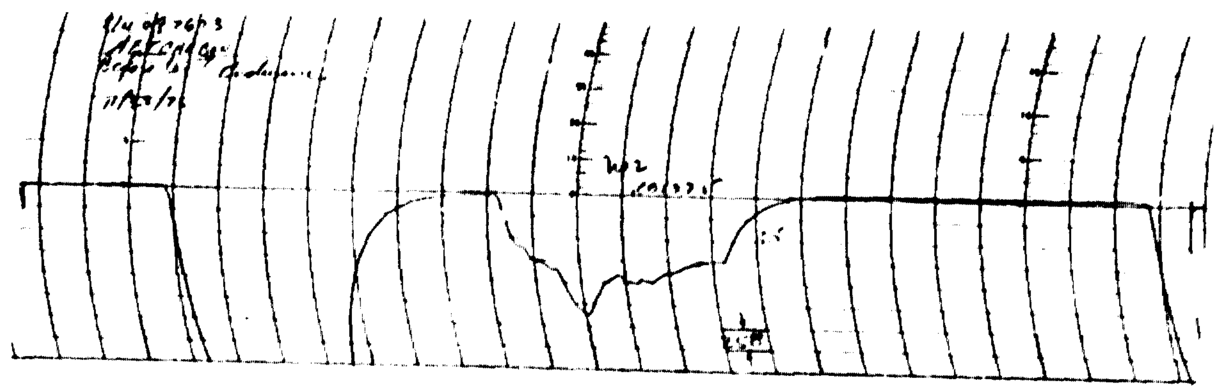
Prior to Endurance Test
Location 1
Aft Seal



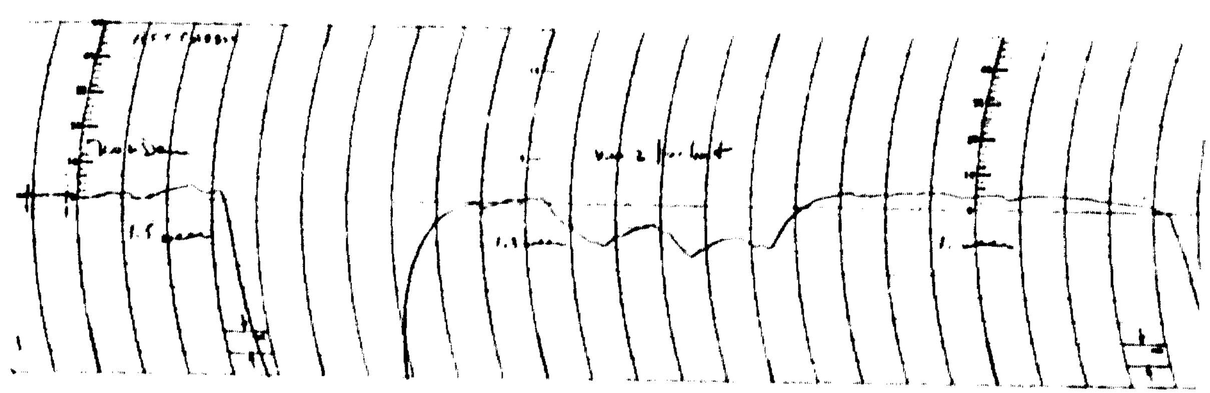
Aft Seal After Endurance Test (Build I)



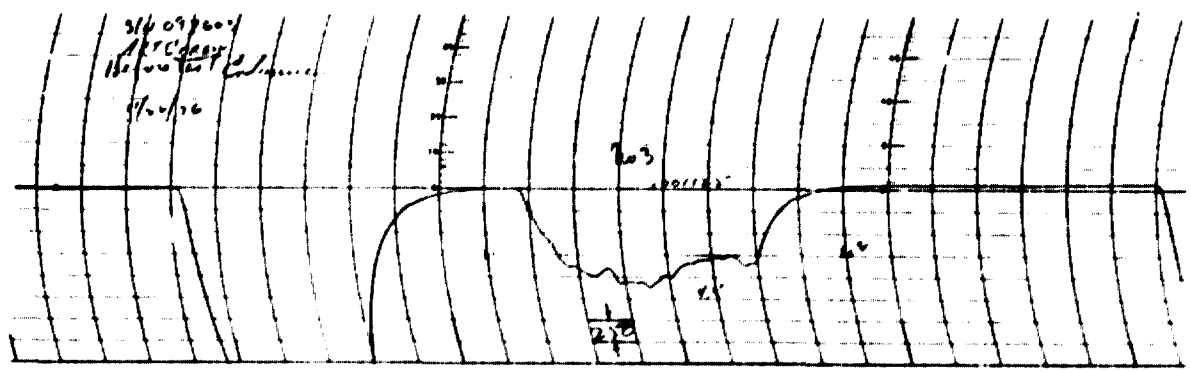
Prior to Endurance Test
Location 2
Aft Seal



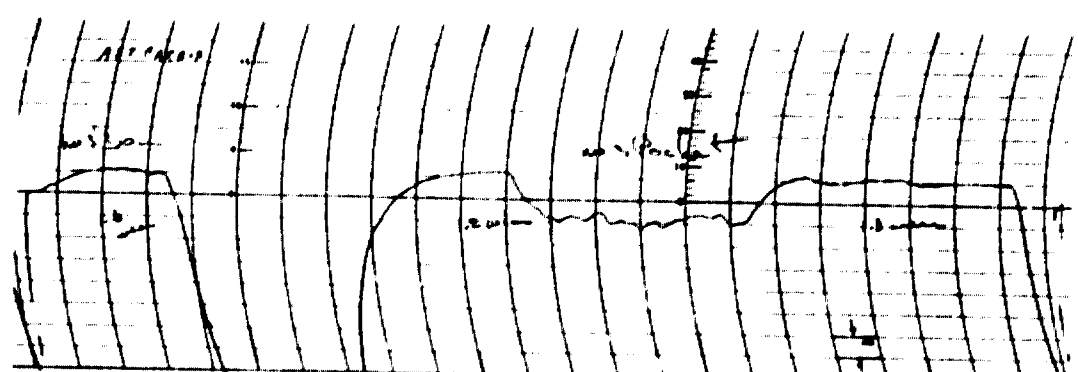
Aft Seal After Endurance Test (Build I)



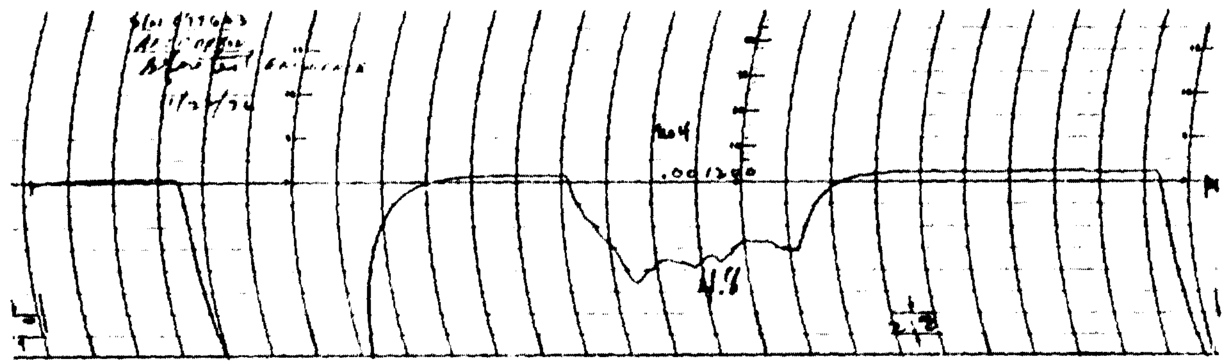
Prior to Endurance Test
Location 3
Aft Seal



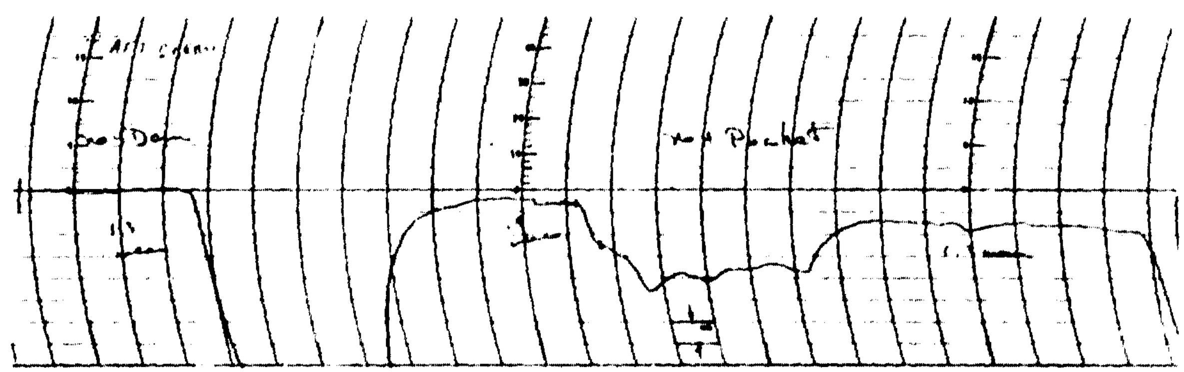
Aft Seal After Endurance Test (Build I)



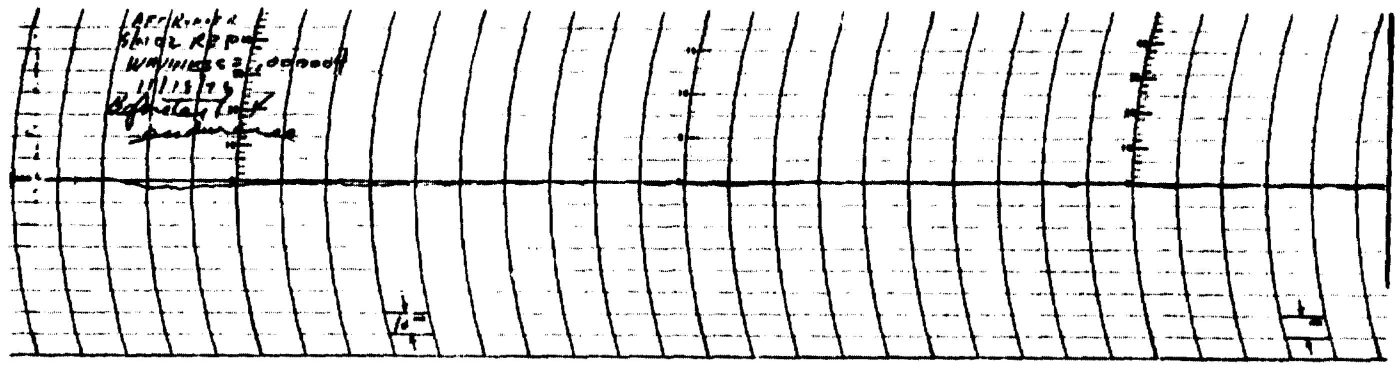
Prior to Endurance Test
Location 4
Aft Seal



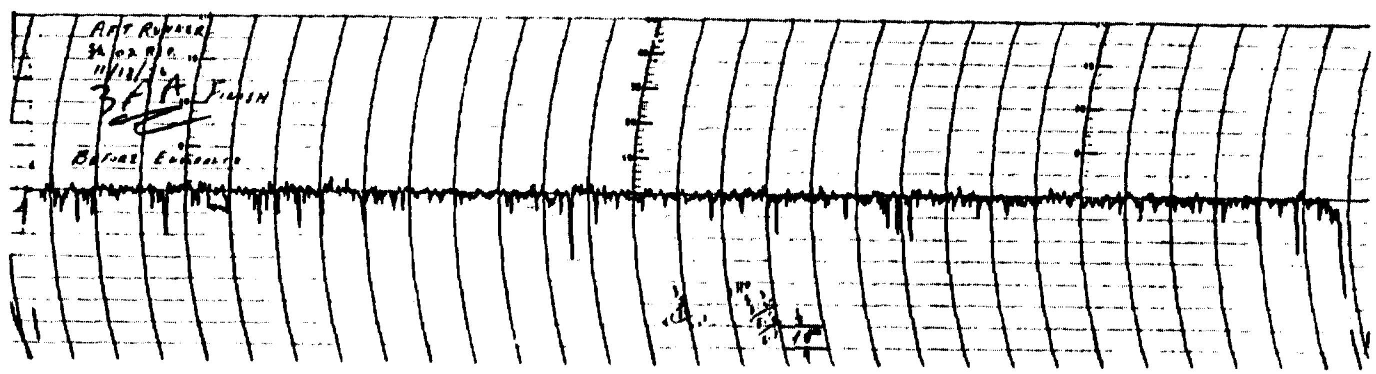
Aft Seal After Endurance Test (Build I)



Aft Seal Seat Waviness Prior to Endurance Test

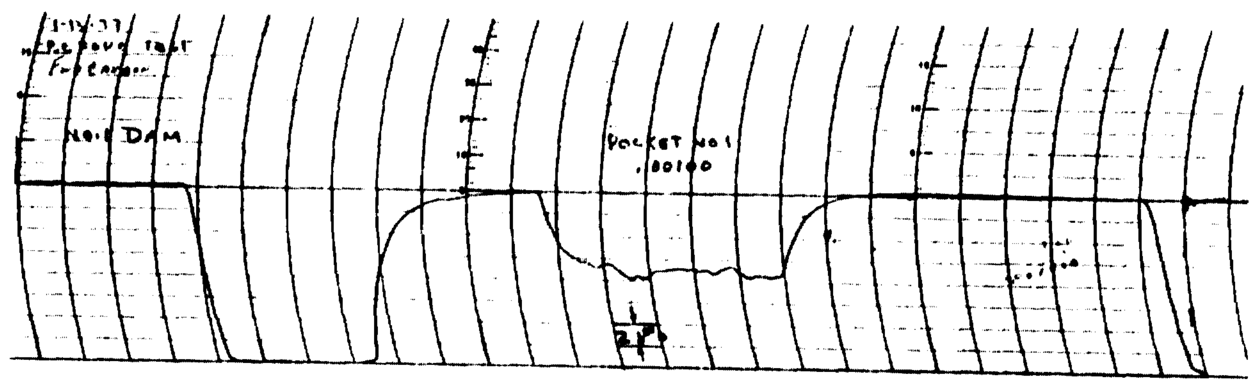


Aft Seal Seat Finish Prior to Endurance Test

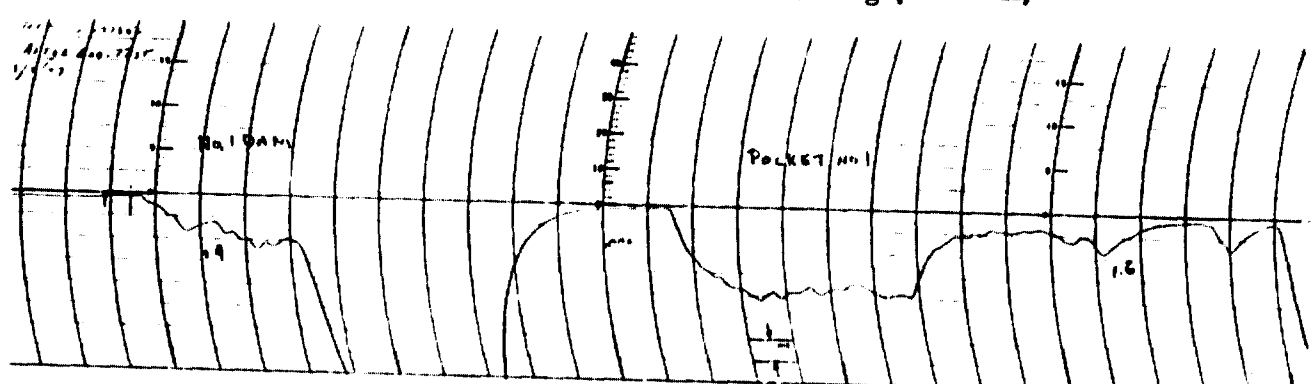


No After Test Traces Due to Damaged Parts

Endurance Test
Location 1
Fwd Seal Prior to Build II



Fwd Seal After Endurance Testing (Build II)



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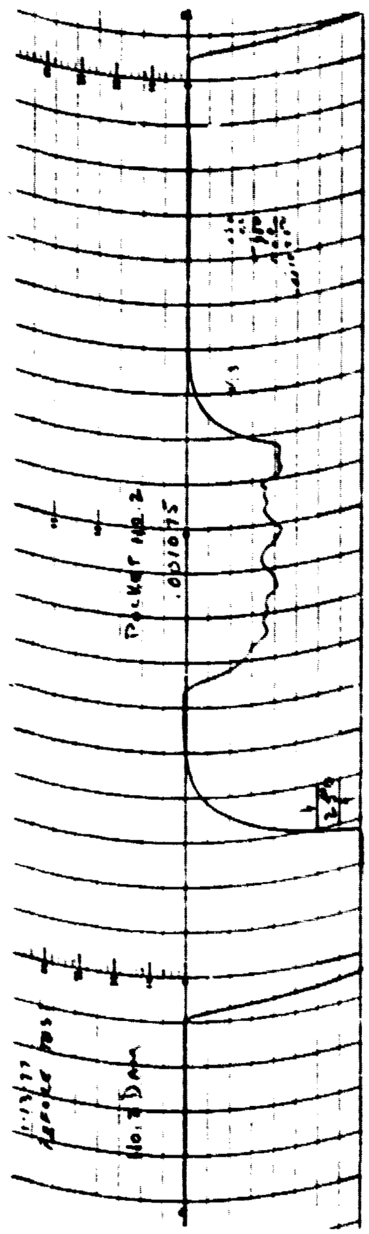
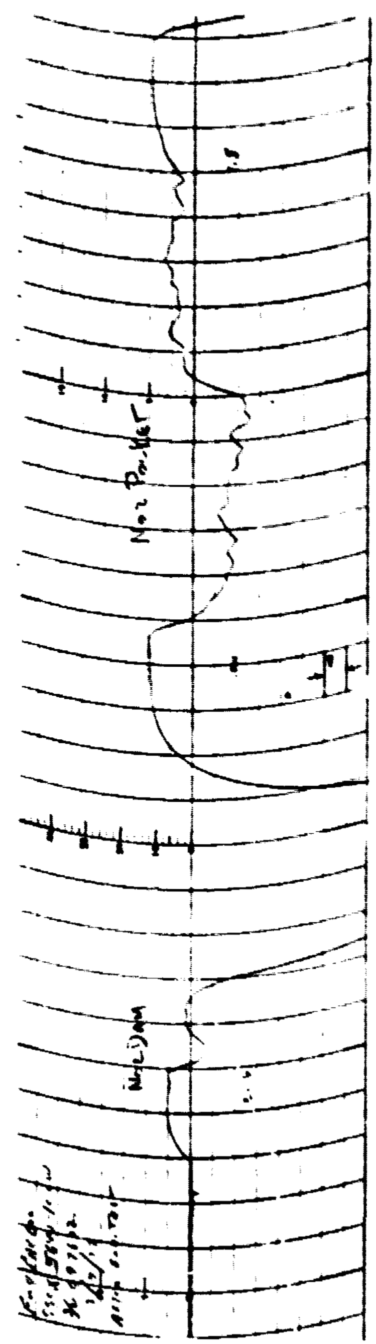
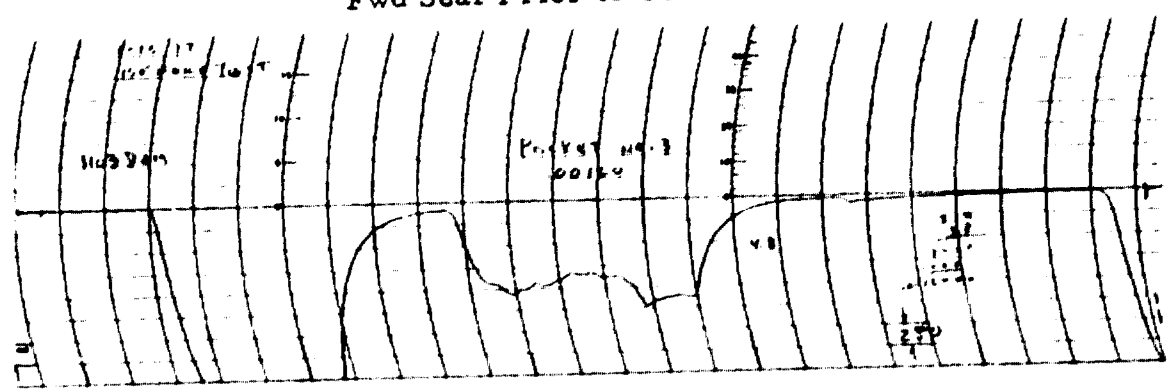
Endurance Test
Location 2
Fwd Seal Prior to Build II



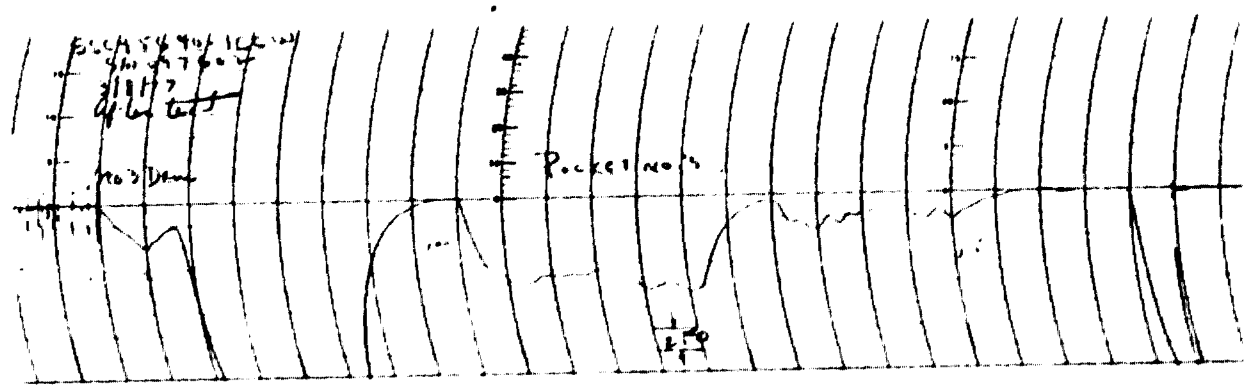
Fwd Seal After Endurance Testing (Build II)



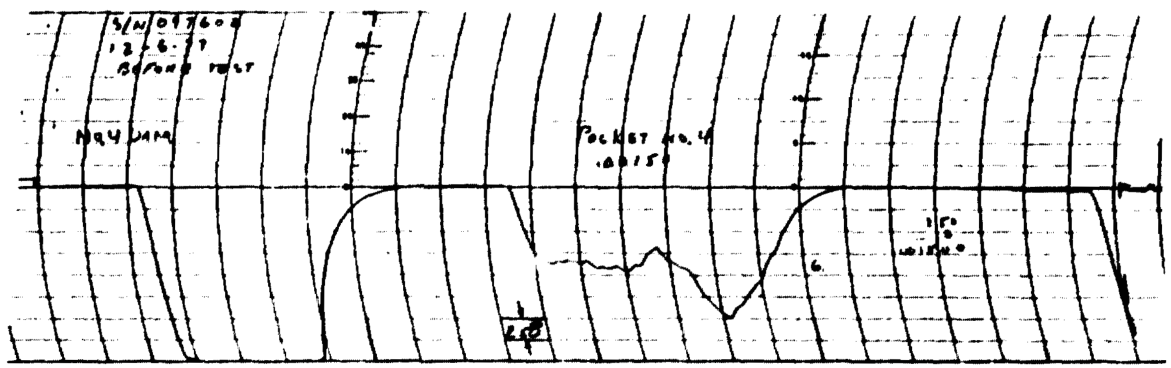
Endurance Test
Location 3
Fwd Seal Prior to Test



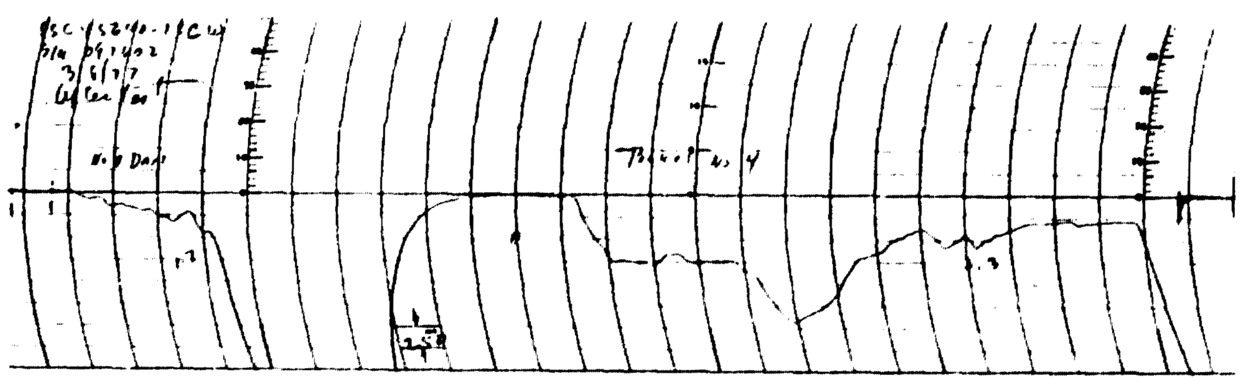
Fwd Seal After Endurance Test (Build II)

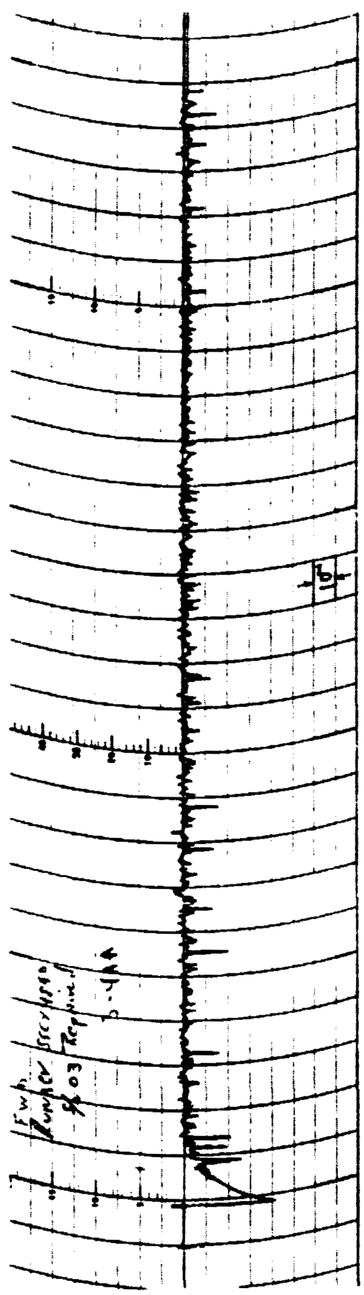


Endurance Test
Location 4
Fwd Seal Prior to Build II

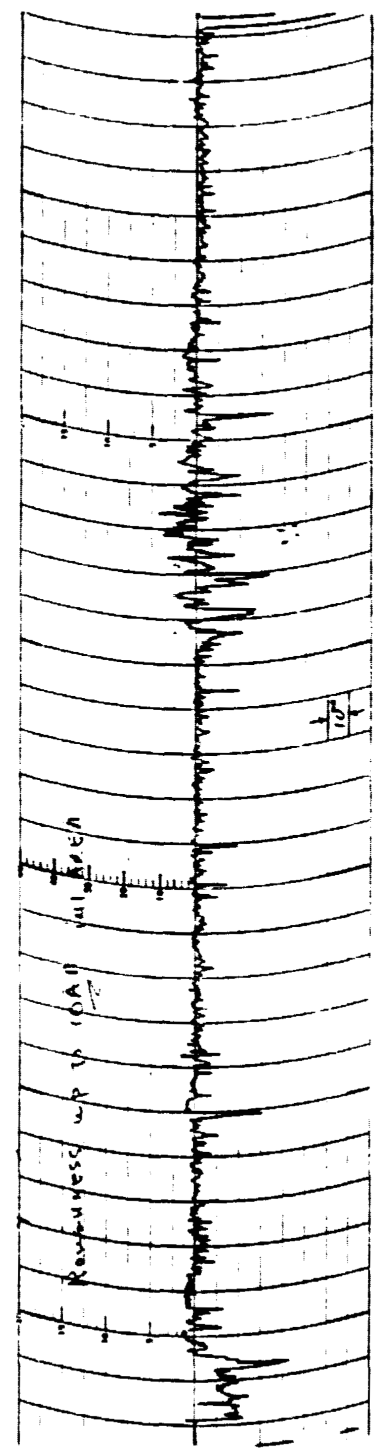


Fwd Seal After Endurance Testing (Build II)





Fwd Seal Seat Finish Prior to Endurance Test (Build II)



Fwd Seal Seat After Endurance Testing

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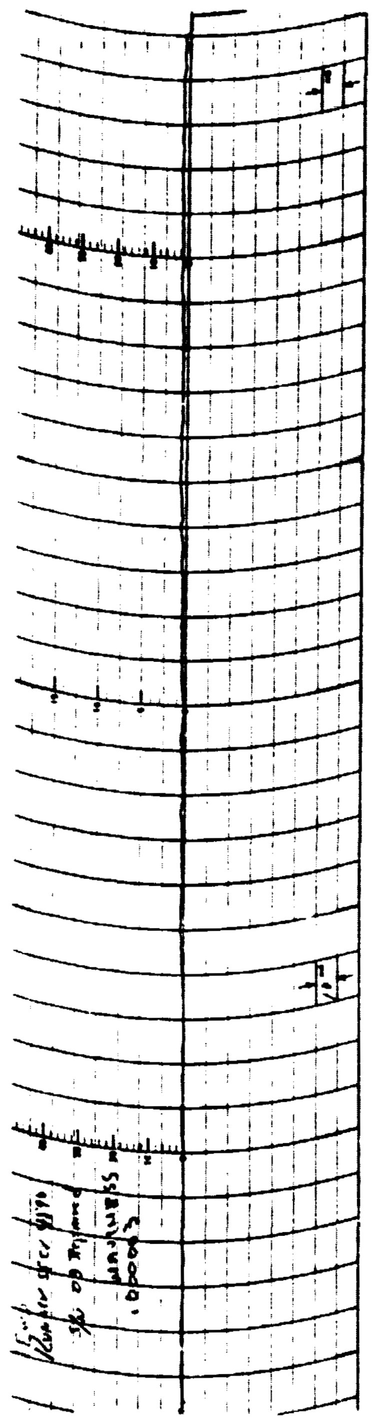
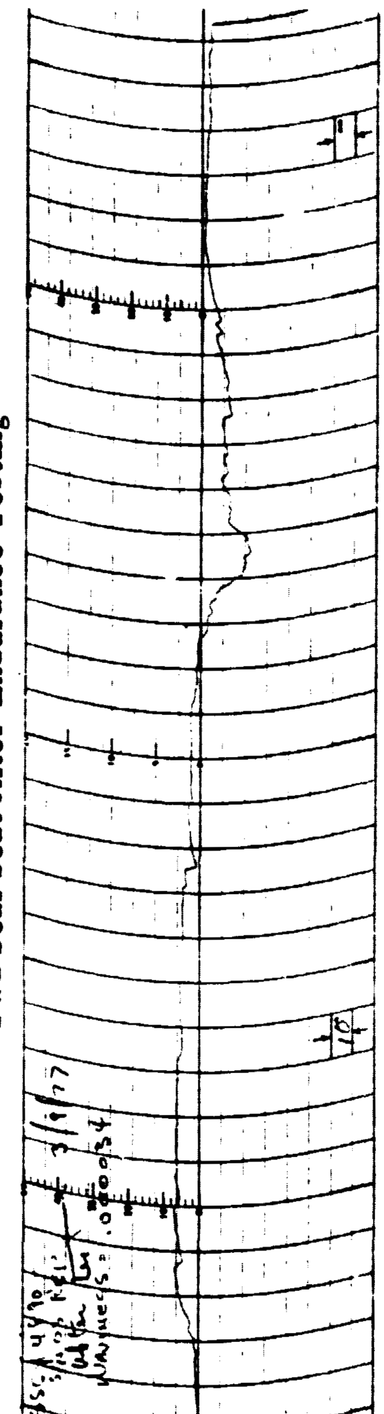
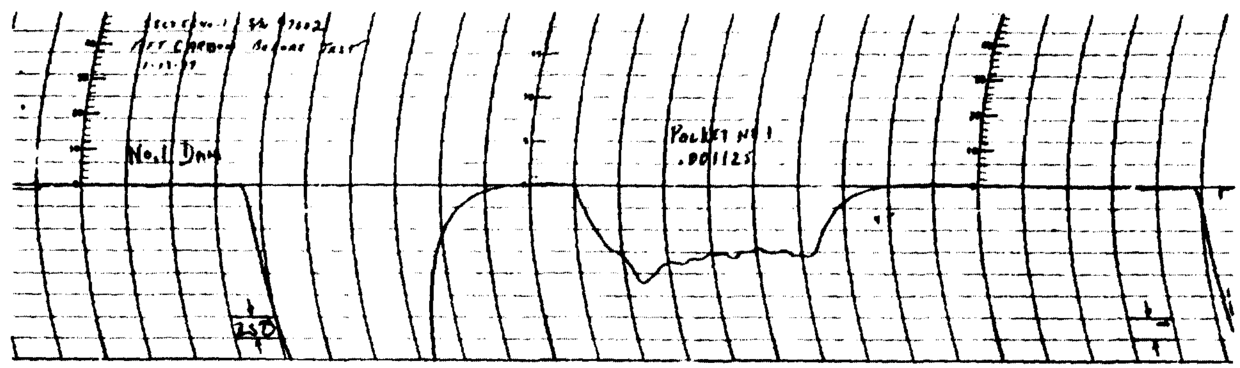


Fwd Seal Seat Waviness Prior to Endurance Test (Build II)

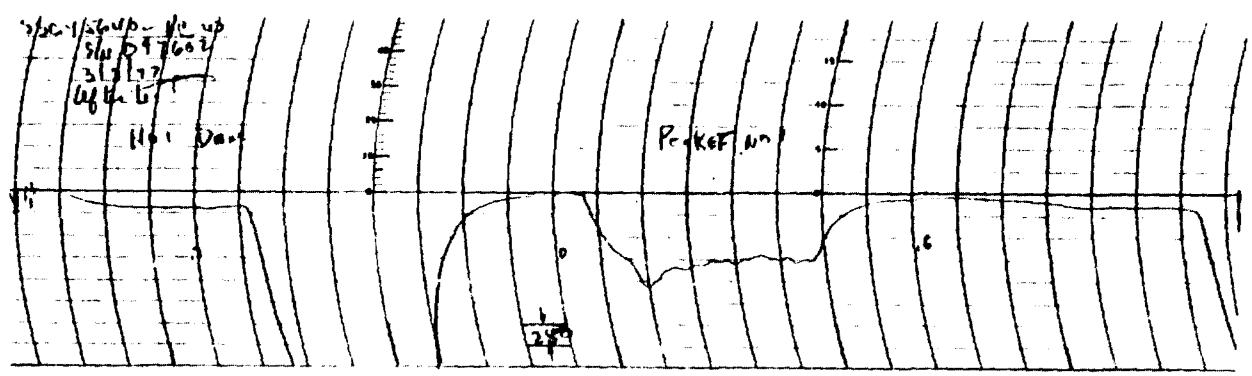


Fwd Seal Seat After Endurance Testing

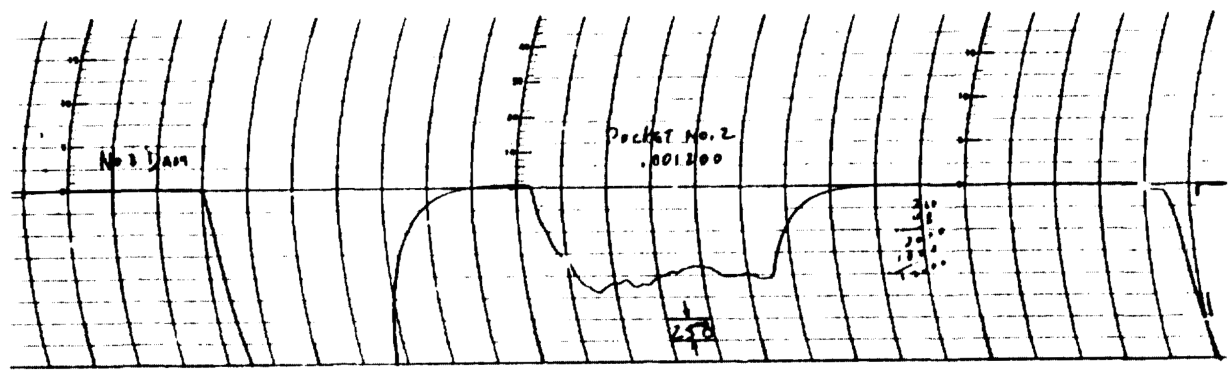
Endurance Test
Location 1
Aft Seal Prior to Build II



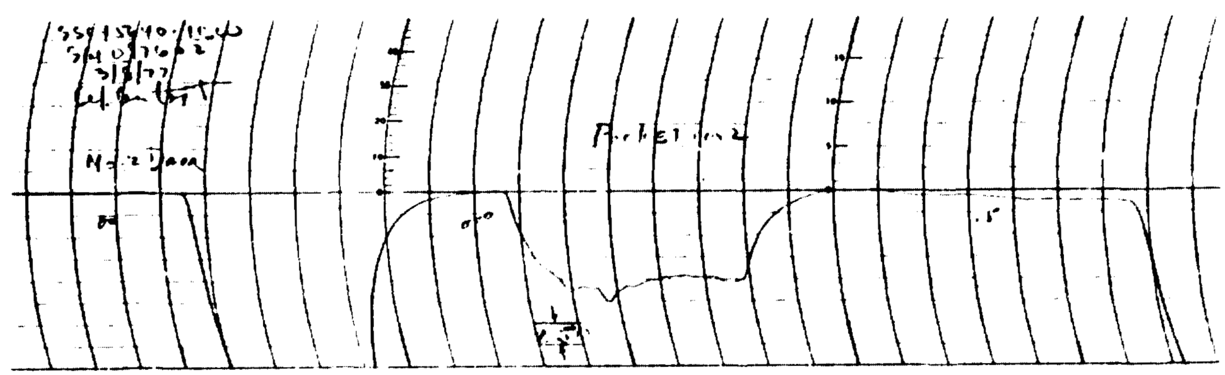
Aft Seal After Endurance Test (Build II)



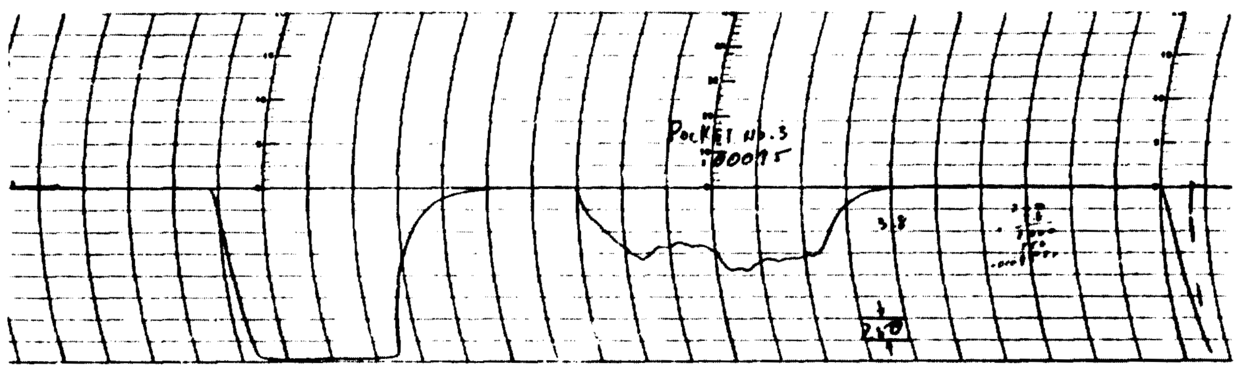
Endurance Test
Location 2
Aft Seal Prior to Build II



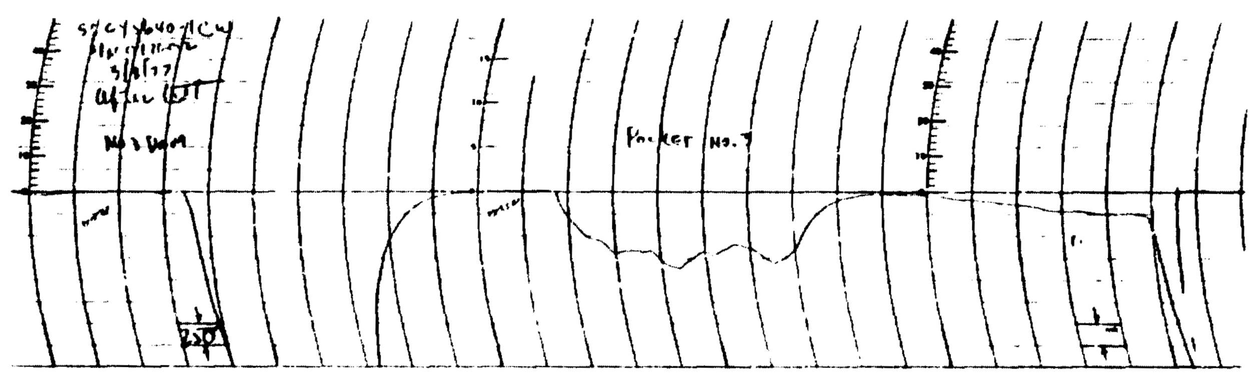
Aft Seal After Endurance Test (Build II)



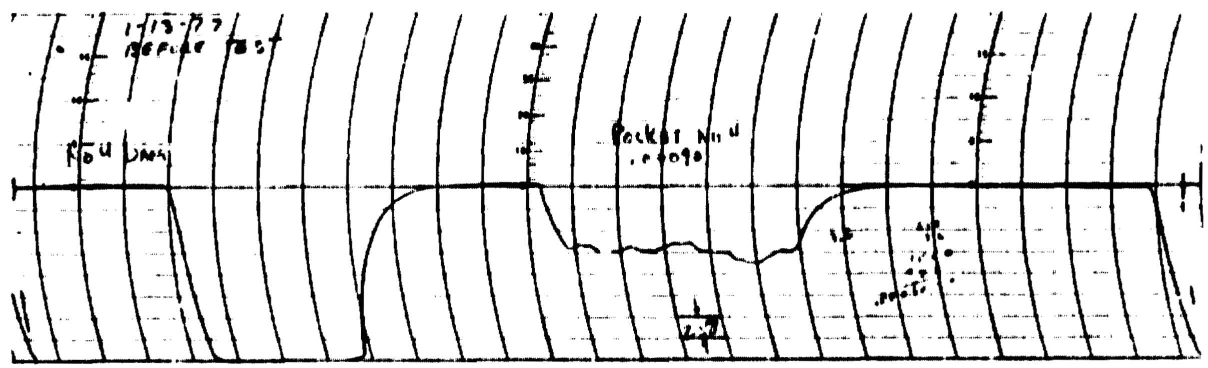
Endurance Test
Location 3
Aft Seal Prior to Build II



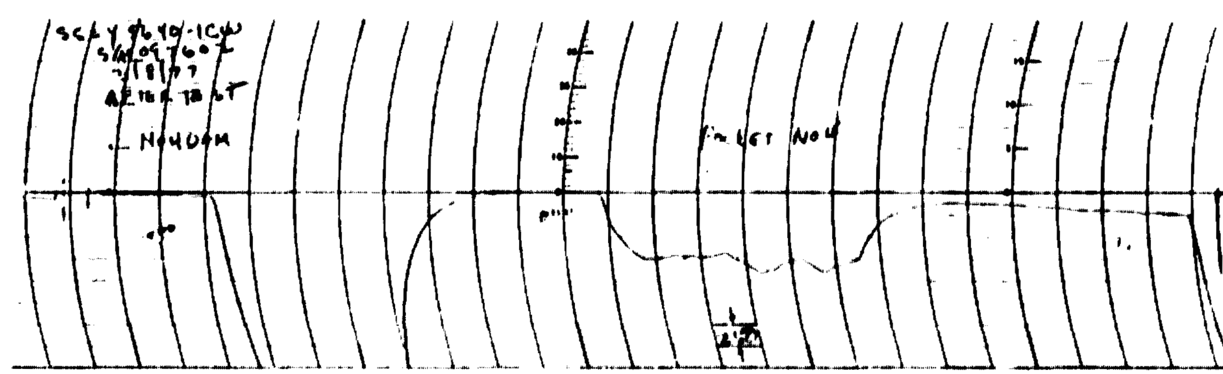
Aft Seal After Endurance Test (Build II)



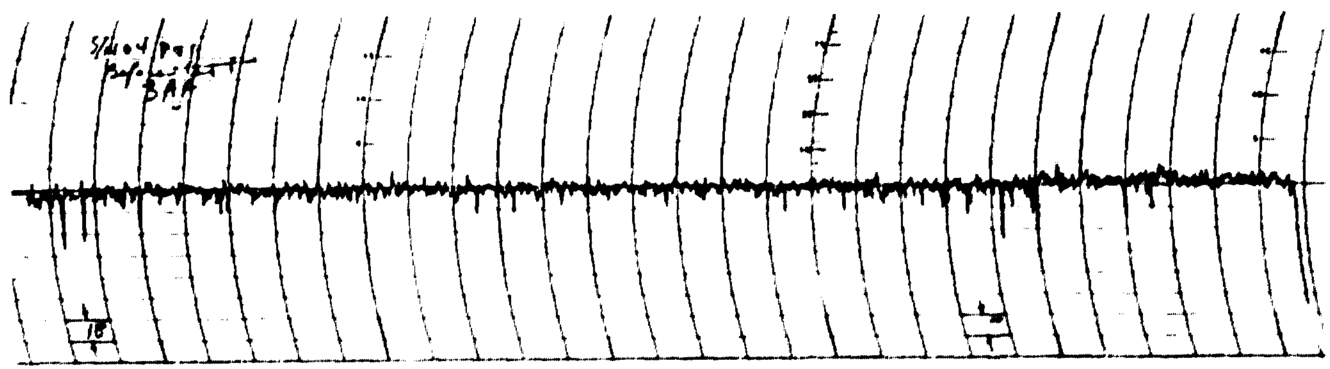
Endurance Test
Location 4
Aft Seal Prior to Build II



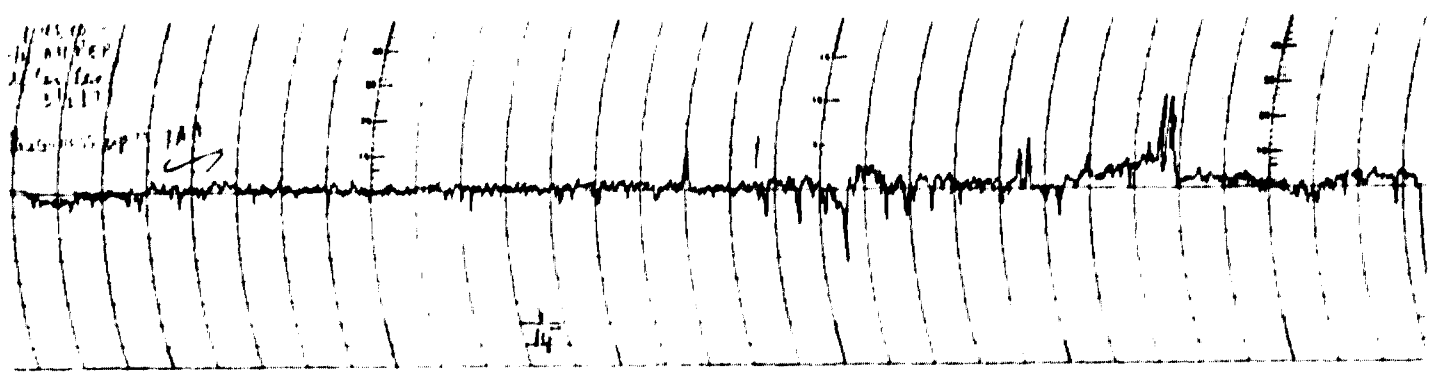
Aft Seal After Endurance Test (Build II)



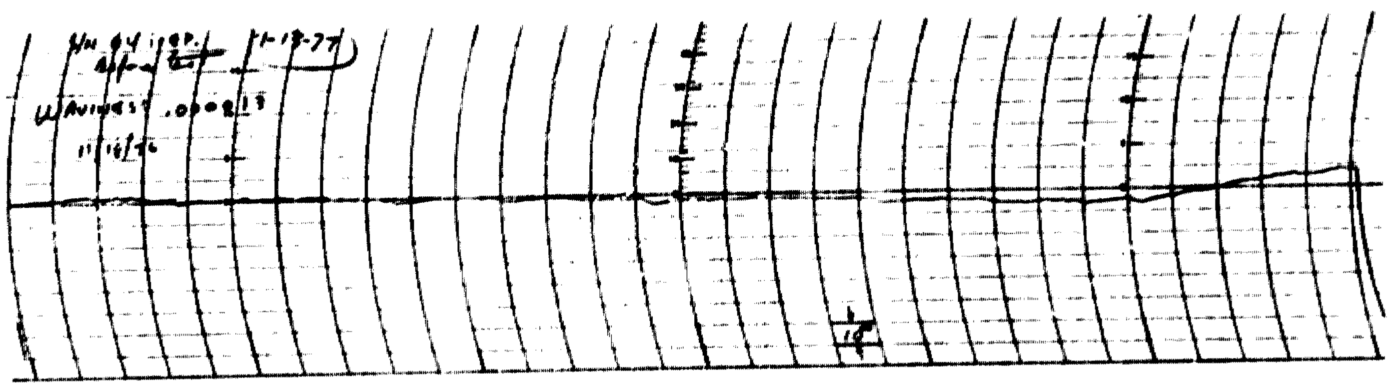
Aft Seal Seat Finish Prior to Endurance Test (Build II)



Aft Seal Seat After Endurance Testing



Aft Seal Seat Waviness Prior to Endurance Test (Build II)



Aft Seal Seat After Endurance Testing