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FINAL REPORT

SELF-ACTING SEALS FOR HELICOPTER ENGINES

by

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16. Abstract

An experimental evaluation was conducted with NASA-designed self-acting face and circumferential seals for use in the main shaft positions of advanced gas turbine engines. The seals featured Rayleigh step pads (self-acting geometry) for lift augmentation. The tested seals incorporated design improvements over previous self-acting configurations.

Self-acting face seals were tested to speeds of 214 m/s (700 ft/sec, 63700 rpm), air pressures of 216.8 N/cm^2 abs (314.7 psia), and air temperatures of 688K (778°F). Self-acting circumferential seals were tested to speeds of 183 m/s (600 ft/sec, 47700 rpm), air pressures of 61.8 N/cm^2 abs (89.7 psia), and air temperatures of 711 K (820°F).

Self-acting face-seals are capable of operating at conditions exceeding conventional seal capability. The limit on speed capability was found to be the flatness of the seal-seat.

The self-acting circumferential seal design tested requires further development for use in advanced engines.

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FOREWORD

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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 test program was carried out by Mr. Harry Thornton.

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SUMMARY

An experimental evaluation was conducted with NASA-designed self-acting face and circumferential seals intended for use in the main shaft positions of gas turbine engines. Self-acting seals incorporated Rayleigh step-lift pads on the carbon sealing faces to provide a self-acting force that separates the sealing surfaces during operation.

In a previous program (Reference 1) the self-acting seals were evaluated, and the face seal configuration proved superior to conventional seals for advanced gas turbine engine operation. Areas of design improvement for both the face and circumferential seal were determined from these tests; as a result, modifications were incorporated in the seals evaluated in the subject test program.

A total of 126 hours of testing were conducted on the self-acting face-seal design at speeds to 214 m/s (700 ft/sec, 63700 rpm), air pressures to 216.8 N/cm^2 abs (314.7 psia), and air temperatures to 688 K (778 °F).

A problem involving carbon oxidation was encountered during testing at temperatures above 650K (710 °F). Also at speeds of 198 m/s (650 ft/sec, 59150 rpm), seal-seat distortion resulted in carbon contact and wear.

A total of 138 hours of testing were conducted on the self-acting circumferential design at speeds to 183 m/s (600 ft/sec, 47700 rpm), air pressure to 61.8 N/cm^2 (89.7 psia), and air temperatures to 711 K (820 °F). Some wear was experienced at pressure differentials of 13.1 N/cm^2 (19 psi) when operating at speeds of 183 m/s (600 ft/sec, 47700 rpm).

The self-acting face seal was shown to be capable of operating at conditions more severe than experienced in present gas turbine mainshaft applications.

Air pressures of 216.8 N/cm^2 abs (314.7 psia) were successfully sealed at at high speeds, and pressure does not appear to be a limiting factor to seal operation.

The TZM seal seat extended the speed and temperature capabilities of the self-acting face seal by reducing distortion caused by temperature. Also, the result of carbon-seal seat contact was not as catastrophic as experienced in the previous test program (Reference 1) with a 4340 seal seat.

INTRODUCTION

The performance of main shaft seals in advanced gas turbine engines for helicopters has become increasingly critical. As shaft speed, air temperature, and air pressure have increased, engine size has decreased, leaving less envelope to accomplish the sealing function.

The purpose of this program was to develop main shaft seals that are capable of operating in gas turbine engines at conditions more severe than those experienced in engines currently in operation.

Advanced Avco Lycoming engines in the 1.36 to 4.54 kg/s (3 to 10 lb/sec) class incorporate main shaft seals of positive-contact configuration that operate with surface speeds to 137 m/s (450 ft/sec), air pressure differential to 55 N/cm^2 (80 psi), and air temperatures to 810 K (1000°F). In future high-performance engines, operating conditions that seals are subjected to will be more severe, and existing seals of the positive-contact configurations may not be adequate. At high speed and pressures, positive-contact carbon seals have a tendency to wear, generate heat, and coke-up.

An alternative to the positive-contact type seal is the labyrinth type of seal. Because of its noncontacting feature, labyrinth seals offer infinite life; however, at high air pressures and temperatures, simple labyrinths will not suffice, and complicated multistage labyrinths must be used. These latter configured seals incorporate venting and pressurization passages that are costly to produce and difficult to accommodate in small, high-performance engines. Compared with positive-contact seals, labyrinths also permit higher leakage airflows that must be absorbed by the lubrication system; this causes a loss in engine performance.

The self-acting seal, a newly designed concept, incorporates the best features of positive-contact seals (low leakage) and labyrinth seals (noncontacting). During operation, self-acting seals are noncontacting because the sealing surfaces are separated by a thin gas film (sealing gap) that limits gas leakage; also at shutdown, the seal faces are in contact. Self-acting seal designs incorporate Rayleigh step lift pads on the primary (carbon) sealing faces. These lift pads provide a hydrodynamic force that separates the sealing surfaces, and the gas film is sufficiently stiff so that the primary (carbon) ring tracks the runout motions of the seat without rubbing contact.

Previous programs (References 1 and 2) have demonstrated the speed and pressure capability of self-acting seals under environments more severe than experienced in present engines. Face seals successfully completed 500 hours of endurance testing at speeds of 183 m/s (600 ft/sec, 54600 rpm) and pressure differentials of 137 N/cm^2 (198.7 psi). In addition, tolerance for sand and dust environments and seal-seat axial runout were demonstrated.

Initial operation of the face-seal configuration revealed the following areas of potential design improvements:

a. Use of a seal-seat material with low coefficient of expansion and high thermal conductivity to reduce distortion caused by temperature. TZM, a Titanium -Molybdenum alloy, was chosen.

b. Reduction of the carbon sealing nose mass to reduce dynamic effects at high speed.

c. Redesign of the oil dam and heat shield to provide better support for the seal seat.

Operation with the circumferential seal revealed that changes in the lift-pad geometry would increase the lift force.

The objective of this program was to incorporate the modifications described above and experimentally evaluate seal performance.

The experimental evaluation was carried out in a test rig that simulates engine conditions in an advanced gas producer turbine bearing location. All seal and bearing package hardware was lightweight and typical of Avco Lycoming engine design practice.

APPARATUS AND PROCEDURE

Test Vehicle

The test rig bearing compartment (Figure 1) is typical of advanced, high-speed gas turbine packages. Sealing positions are located forward and aft of the bearing, which enabled two seal samples to be tested simultaneously.

The rig prime mover is a 100-horsepower, 20,000 - rpm steam turbine. Connecting the steam turbine to the rig is a 3:1 ratio speed increaser. The test installation is shown in Figure 2.

The shaft is supported by a 35 - mm, split, inner - race ball bearing in the test position; and by a 25 - mm split, inner - race bearing in the support position. Both bearings are hydraulically mounted, and thrust loading is supplied by coil springs acting on the outer race of the support bearing and by pressure differentials across the loading wheel.

A single batch of MIL-L-23699 oil at 367 ± 5K (200 ± 10°F) was used throughout the test program. Oil flow to the face seal test package was 180 kg/hr (400 lb/hr). The bearing was lubricated by four 0.81 mm (0.032 in.) jets and each seal by two 0.81 mm (0.032in.) jets. Maximum oil flow to the circumferential seal package was 136 kg/hr (314 lb/hr).

Oil from the bearing compartment drains by gravity into a static air-oil separator. The minimum scavenge area is 93 mm^2 (0.144 $in.^2$). Desired air pressure is introduced into the cavities adjacent to the test seals, and the air that leaks past the test seals is conveyed through a flowmeter from the air-oil separator to obtain a measure of seal performance.

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.

Test Seals

The test program was conducted with NASA-designed self-acting face and circumferential seals for use in the main shaft position of advanced gas turbine engines.

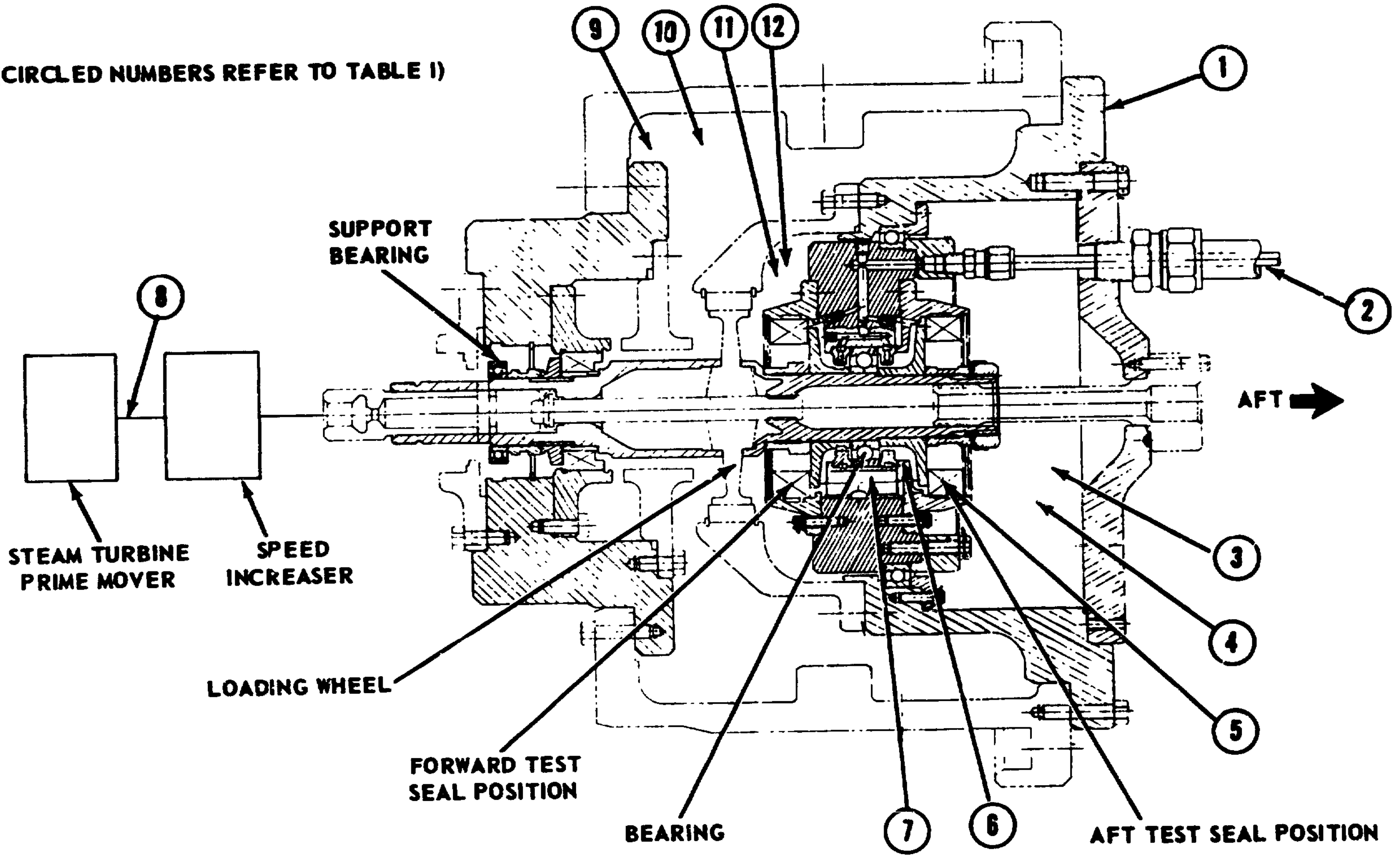

(CIRCLED NUMBERS REFER TO TABLE I)

Figure 1. Test Vehicle and Instrumentation Plan.

Figure 2. Test Rig Installation.

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		1
Chips	Chip detector	Scavenge line	7

RESULTS AND DISCUSSION

Self-Acting Face Seal Design

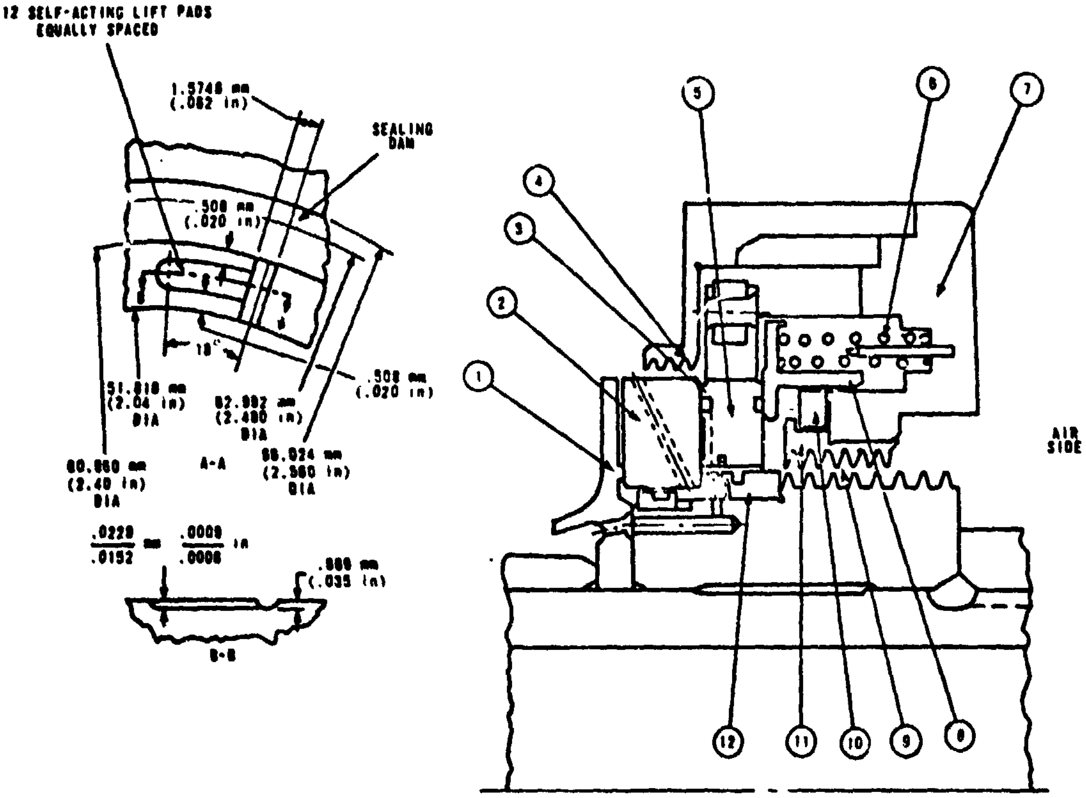
The self-acting face seal used in the test program is shown in Figure 3. It is similar to a conventional face seal except for the addition of the self-acting geometry for lift augmentation.

The primary sealing interface consists of the rotating seat, which is keyed to the shaft, and the nonrotating primary ring assembly, which is free to move in an axial direction; this configuration accommodates axial motions caused by thermal expansion. Axial springs provide a mechanical force of 31N (7lb) to maintain contact between the seat and primary ring at shutdown. The secondary seal is a carbon piston ring that is subjected to only the axial motion of the carrier assembly.

Great care is taken to ensure flatness of the sealing surfaces. The rotating seat is keyed to the shaft spacer and is clamped axially by a machined bellows that minimizes distortion of the seat, since the major portion of the clamping force acts through the shaft spacers. The bellows also acts as a static seal between the seat and the shaft spacer. Oil for cooling is passed through the seat to reduce thermal gradients, and an oil-dam disc also serves as a heat shield. Windbacks are used to prevent contaminants from approaching the sealing surfaces.

In operation, the sealing faces are separated slightly, in the order of 0.00508 mm (0.0002 in.), by action of the self-acting lift geometry. This positive separation results from the balance of seal forces and the gas-film stiffness of the self-acting geometry. The primary ring carbon face with the lift pads is shown in Figure 4.

To determine film thickness and air leakage in a self-acting face seal, the axial forces acting on the primary ring assembly must be determined for each operating condition. These forces comprise the self-acting lift force, the spring force, and the pneumatic forces due to the sealed pressure. Essentially, the analysis requires finding the film thickness for which the opening forces balance the closing forces. When this equilibrium film thickness is known, the leakage rate can be calculated. References 3 through 9 detail the design procedure.



1.	OIL DAM & HEAT SHIELD	4340
2.	SEAL SEAT	TZM SPRAYED WITH CHROME CARBIDE
3.	THERMOCOUPLE LOCATION	
4.	OIL WINDBACK	INCONEL 750
5.	NOSEPIECE	HIGH TEMPERATURE CARBON & TZM
6.	COMPRESSION SPRING	INCONEL 750
7.	HOUSING	INCONEL 750
8.	PISTON RING CARRIER	CARPENTER 42
9.	CONTAMINATE WINDBACK	
10.	PISTON RING	HIGH TEMPERATURE CARBON
11.	PISTON RING HOLDER	INCONEL 750 .
12.	BELLOWS SPACER	INCONEL 750

Figure 3. Self-Acting Face Seal.

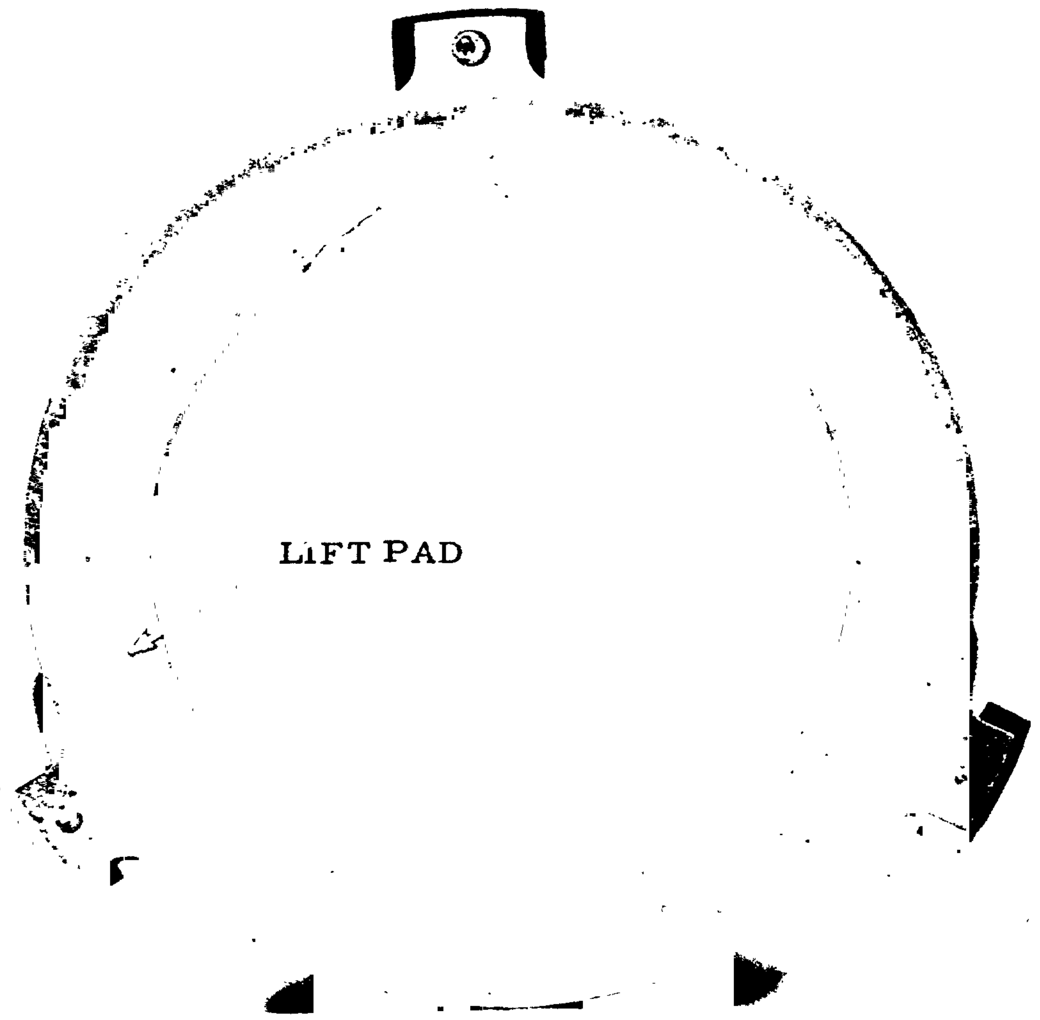


Figure 4. Primary Ring Carbon Face.

Previous self-acting face-seal test programs (References 1 and 2) revealed the following areas in which the seal design could be modified to improve operations:

a. Seal Seat Distortion - Previous testing showed that at seal temperatures of approximately 450 K (350 °F) seal-seat distortion became a problem. The face of the seat closest to the hot ambient air tends to expand more quickly than the face exposed to the oil side, resulting in a rotation of the seat and contact with the carbon at the inside diameter of the sealing interface. This carbon-seat contact generates additional heat; this causes increasing distortion and increasingly severe rubbing contact that finally results in seal failure.

   In order to minimize seal seat distortion, TZM, a Titanium-Molybdenum alloy, was chosen as the material for the seat. This alloy has a low coefficient of expansion and high thermal conductivity. The previous seal seat was made of SAE 4340 material.

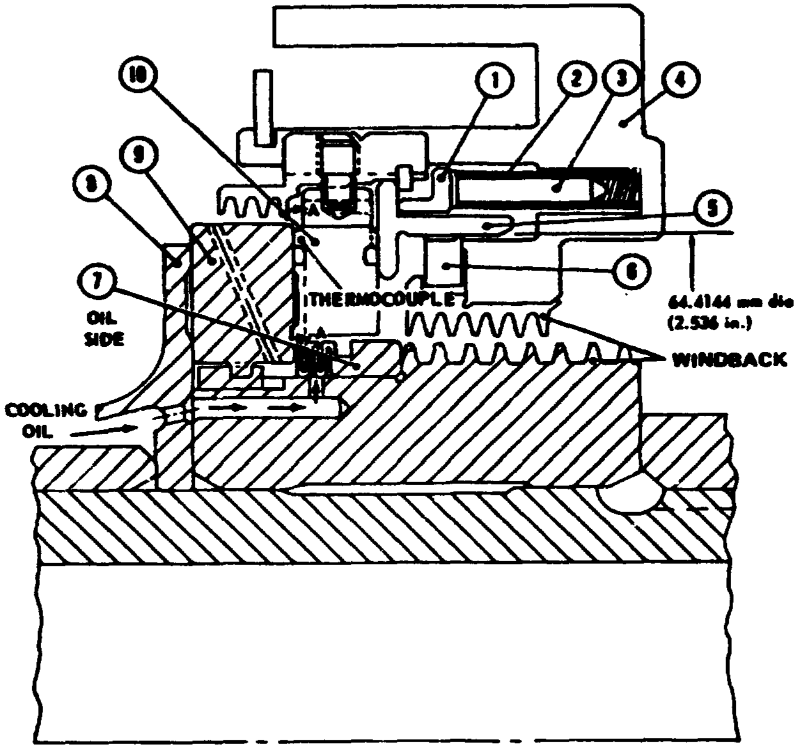
b. High-Speed Dynamics - In order to minimize inertia loads, the primary carbon ring was redesigned to reduce its mass.

c. Oil Dam and Heat Shield - The oil dam was redesigned to provide better support for the seal seat and, thereby, reduce distortions.

   The previous design, which was modified, is shown in Figure 5.

Results

A series of ten tests was performed on the self-acting face seal configuration. Table II lists test duration and maximum operating parameters. Tests 4, 5, 8, and 10 consisted of endurance operation at elevated temperature. Tests 1, 2, 3, 6, and 7 were shorter evaluation runs at ambient air temperatures. One set of seals was used for the first 8 tests and then replaced with new forward and aft carbons and seats for Tests 9 and 10.



1. SPRING PLATE	INCONEL X750	6. PISTON RING	HIGH-TEMPERATURE CARBON
2. COMPRESSION SPRING	INCONEL X750	7. BELLOWS SPACER	INCONEL X750
3. SPRING PIN	18-8 SST	8. OIL DAM AND HEAT SHIELD	440 SST
4. HOUSING	INCONEL X750	9. SEAT	4340 FLAME SPRAYED WITH LINDE LCIC (CHROME CARBIDE)
5. CARRIER	INCONEL X750	10. PRIMARY RING	HIGH-TEMPERATURE CARBON AND TZM

Figure 5. Self-Acting Face Seal - Previous Design.

TABLE II. SELF-ACTING FACE SEAL TEST PROGRAM

Test	Duration	Max Speed			Max. Air Pressure		Max. Air Temperature	
	(hr)	(m/s)	(ft/sec)	(rpm)	(N/cm^2)	(psia)	(K)	(°F)
1	4.00	122	400	36400	147.9	214.7	376	216
2	4.50	152	500	45500	147.9	214.7	341	154
3	3.25	183	600	54600	147.9	214.7	342	156
4	25.00	183	600	54600	147.9	214.7	439	330
5	25.00	183	600	54600	147.9	214.7	584	592
6	5.25	183	600	54600	216.8	314	353	175
7	6.25	214	700	63700	182.4	264.7	392	245
8	19.25	198	650	59150	147.9	214.7	688	778
Subtotal	92.50	(Seals were replaced at this point)						
9	2.00	198	650	59150	182.4	264.7	454	358
10	31.50	198	650	59150	182.4	264.7	667	740
Total Test Time	126.00							

The most critical parameter for judging seal performance is airflow into the bearing cavity. As the test program progressed, airflow through the seals increased. Figure 6 shows the envelope of test results for evaluation Tests 1, 2, and 3 compared with evaluation Test 6 and 7, illustrating the performance degradation. The magnitude of airflow, however, is significantly less than that experienced with conventional seals at these operating conditions (Reference 1).

The carbon-lift pad depth, prior to testing and after Test 8, was measured at 4 pads of both the forward and aft seal and found to be as shown on Table III.

Table IV lists the carbon wear during each of the first eight tests. To illustrate the measuring technique used, Figures 7 through 12 show charts of Pad 4 of the aft seal new, and after Tests 2, 4, 6, 7, and 8 to illustrate the wear progression.

Table V lists the seal seat surface textures. Figures 13 through 18 illustrate the measuring technique showing the aft seat new, and after Tests 2, 4, 6, 7, and 8. The carbon sealing face is superimposed on these charts to show where the contacting areas are. Figures 19, 20, and 21 depict seal-seat flatness before and after testing.

Flatness of the assembled seats was held below 2.54 μm (100 μin).

Test 1

Table VI lists operating conditions and test results. The forward carbon did not wear during these runs. The aft carbon wore an average of 0.0013 mm (0.00005 in.). Seal seat surface texture did not change on the forward seat and there were negligible changes on the aft seat (Tables IV and V).

Test 2

Table VII lists operating conditions and test results. The forward carbon did not wear and the aft carbon wore an average of 0.0010 mm (0.00004 in.). The aft seat surface did not change during this test; however, the waviness and flatness of the forward seat increased (Tables IV and V).

Test 3

Table VIII lists operating conditions and test results. Inspection following testing revealed negligible carbon or seat wear. Waviness and flatness of the aft seal increased slightly (Tables IV and V).

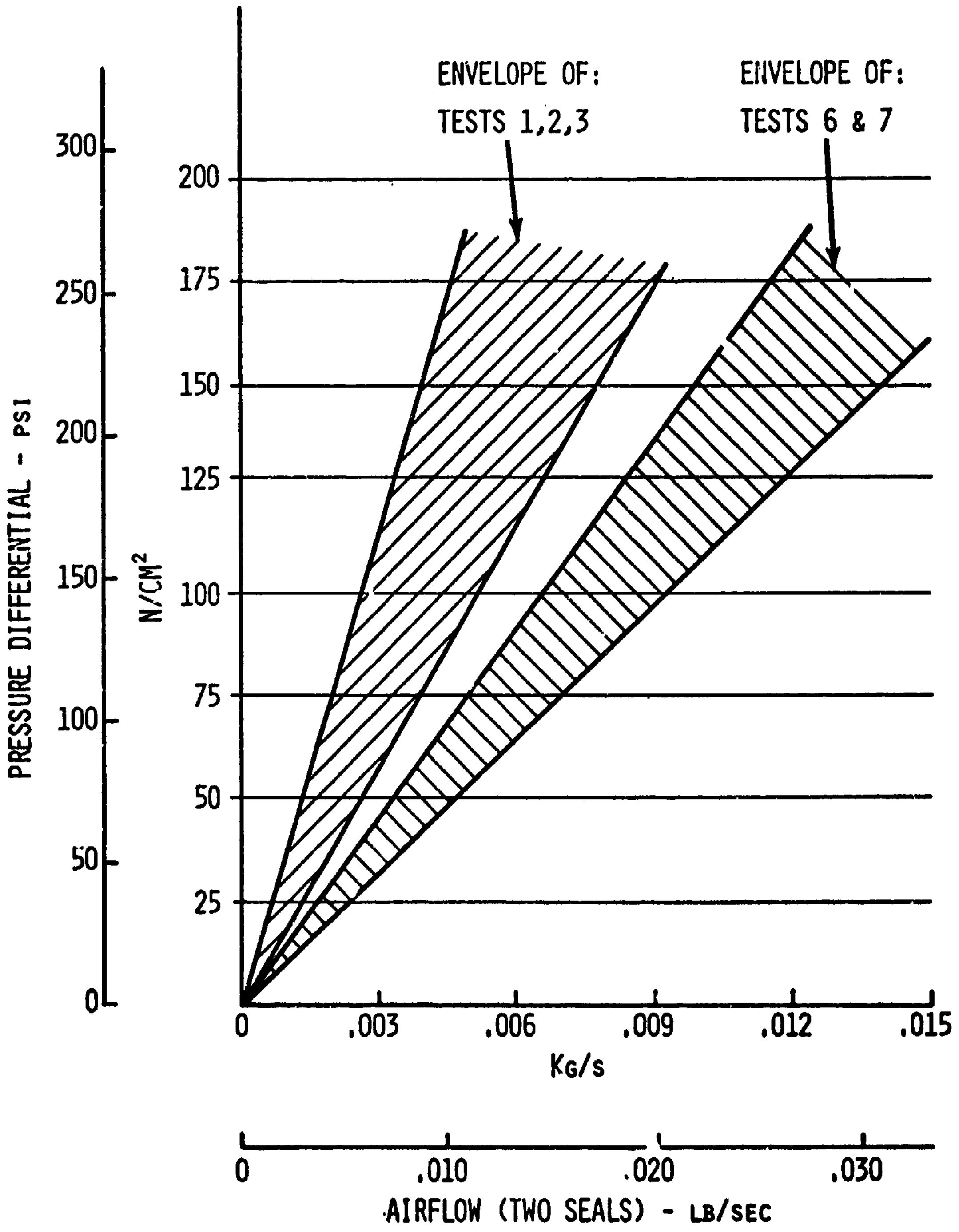


Figure 6. Self-Acting Face Seal - Airflow.

TABLE III. CARBON-LIFT PAD DEPTH (NEW AND AFTER TEST)

Pad Pos.	No.	New		After Test 8	
Fwd Seal		(mm)	(in.)	(mm)	(in.)
	1	0.019 mm	(0.00075 in.)	0.016 mm	(.00065 in.)
	2	0.024	(0.000925)	0.022	(.000875)
	3	0.020	(0.0008)	0.018	(.0007)
	4	0.022	(0.000875)	0.019	(.00075)
Aft Seal					
	1	0.018 mm	(0.0007 in.)	0.008 mm	(.00035 in.)
	2	0.018	(0.0007)	0.006	(.00025)
	3.	0.018	(0.0007)	0.0	(0.0)
	4	0.014	(0.00055)	0.004	(.000175)

TABLE IV. CARBON NOSE WEAR (TESTS 1-8)

Test		1	2	3	4	5	6	7	8
				(mm)					
Fwd Seal									
Pocket	1	0.0	0.0	0.0	0.0019	0.0	0.0	0.0013	0.0
	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0013	0.0
	3	0.0	0.0	0.0	0.0013	0.0	0.0	0.0013	0.0
	4	0.0	0.0	0.0	0.0064	0.0	0.0013	0.0013	0.0
Aft Seal									
Pocket	1	0.0	0.0019	0.0	0.0013	0.0	0.00064	0.00064	0.0044
	2	0.0019	0.00064	0.0	0.0025	0.0	0.0	0.0019	0.0044
	3	0.0019	0.0013	0.0	0.0025	0.0	0.0	0.0013	0.0051
	4	0.0013	0.0	0.0	0.0025	0.0	0.00064	0.00064	0.0044
				(in.)					
Fwd Seal									
Pocket	1	0.0	0.0	0.0	0.000075	0.0	0.0	0.00005	0.0
	2	0.0	0.0	0.0	0.0	0.0	0.0	0.000025	0.0
	3	0.0	0.0	0.0	0.00005	0.0	0.0	0.00005	0.0
	4	0.0	0.0	0.0	0.000025	0.0	0.00005	0.00005	0.0
Aft Seal									
Pocket	1	0.0			0.00005	0.0	0.000025	0.000025	0.000175
	2	0.000075			0.0001	0.0	0.0	0.000075	0.000175
	3	0.000075			0.0001	0.0	0.0	0.00005	0.00020
	4	0.00005			0.0001	0.0	0.000025	0.000025	0.000175

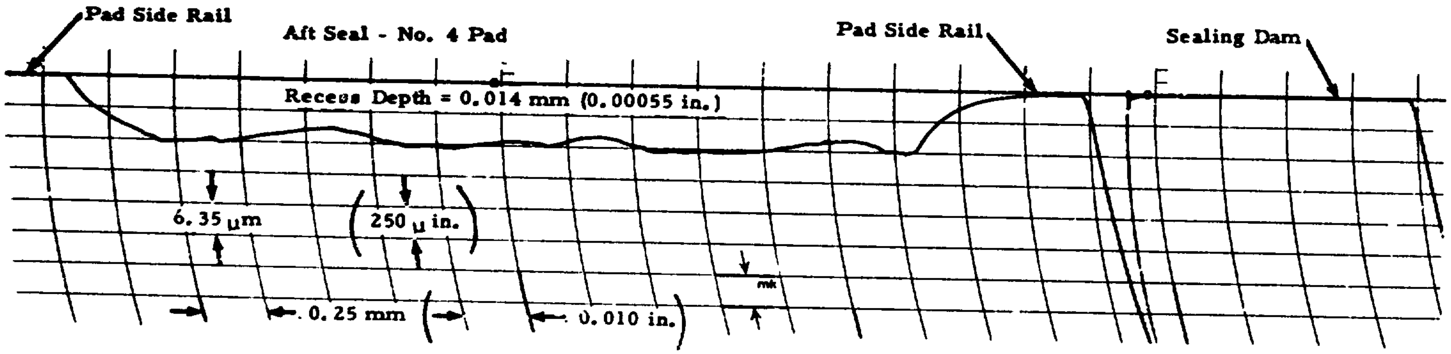


Figure 7. Trace of Aft Self-Acting Face Seal Carbon Before Testing.

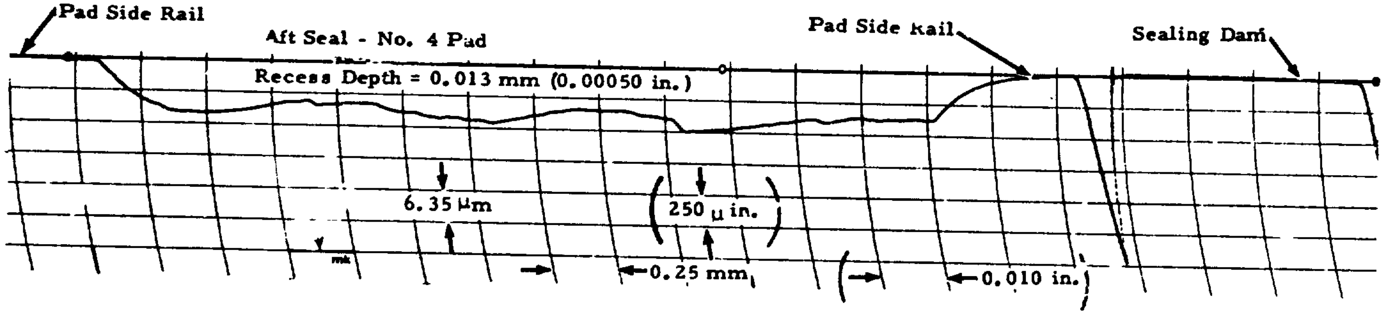


Figure 8. Trace of Aft Self-Acting Face Seal Carbon After Test 2.

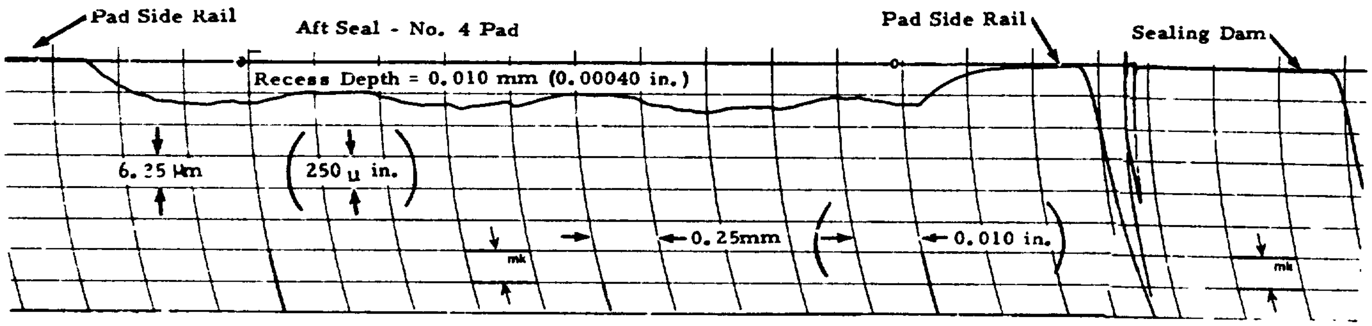


Figure 9. Trace of Aft Self-Acting Face Seal Carbon After Test 4.

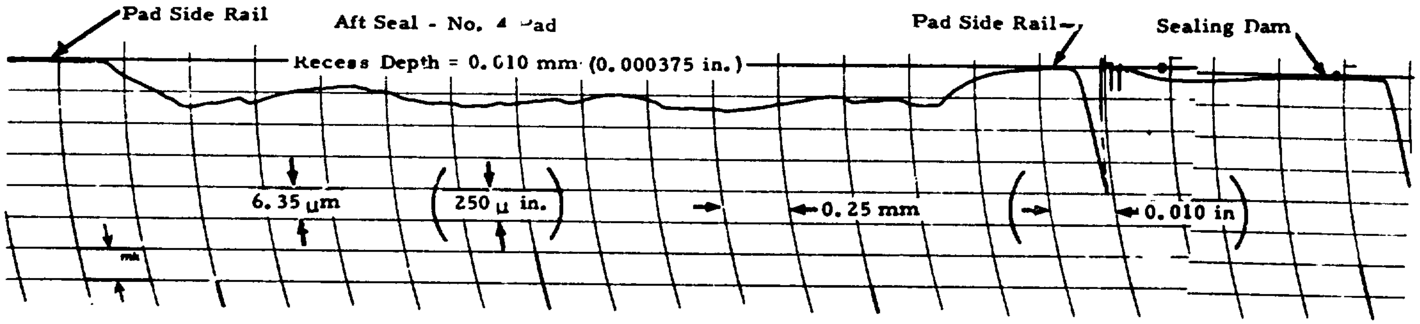


Figure 10. Trace of Aft Self-Acting Face Seal Carbon After Test 6.

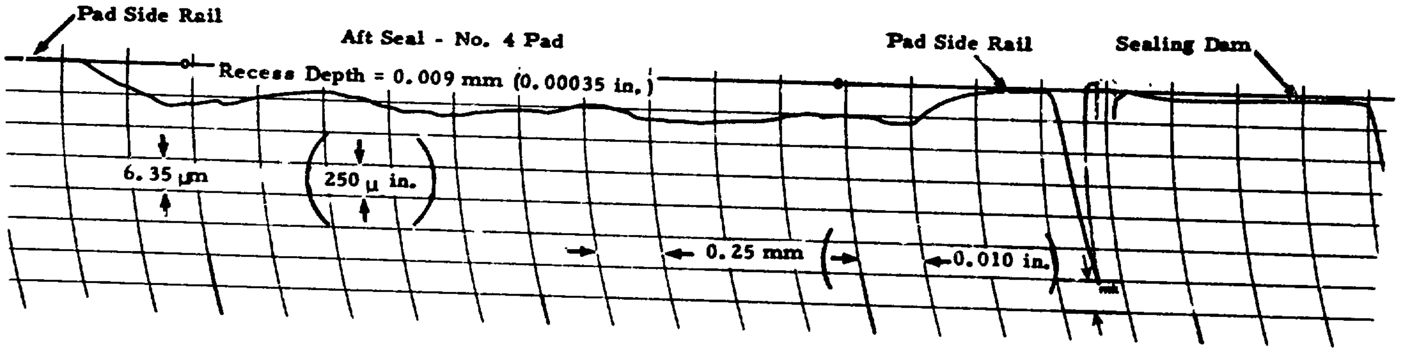


Figure 11. Trace of Aft Self-Acting Face Seal Carbon After Test 7.

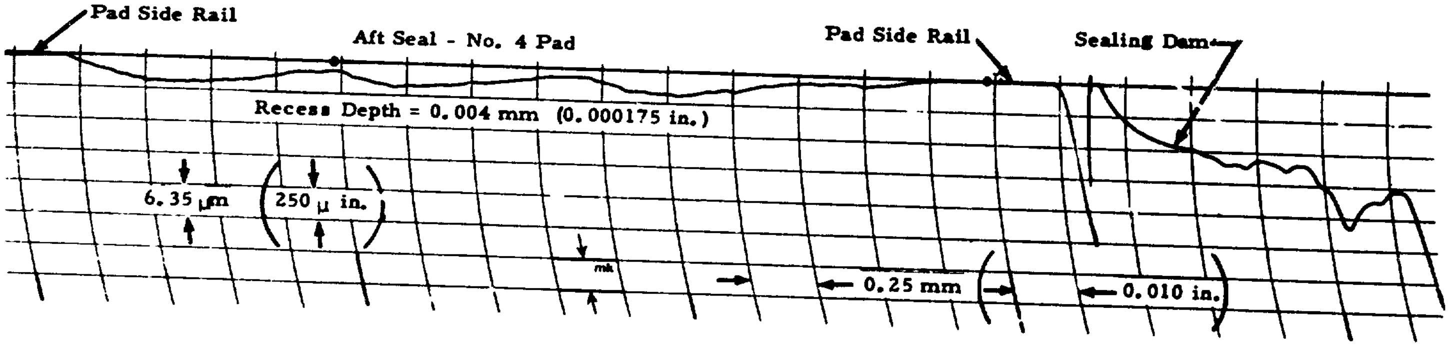


Figure 12. Trace of Aft Self-Acting Face Seal Carbon After Test 8.

TABLE V. SEAL SEAT INSPECTION RESULTS (TESTS 1-8)

Test		New	1	2	3	4	5	6	7	8
Fwd Seal										
Dam Area Roughness	(µm)	0.051	0.076	0.051	0.076	0.102	0.102	0.102	0.076	0.102
Waviness	(µm)	0.102	0.102	0.178	0.178	0.254	0.228	0.305	0.330	0.330
Flatness	(µm)	0.305	0.305	0.508	0.635	0.685	0.813	0.965	1.220	1.522
Aft Seat										
Dam Area Roughness	(µm)	0.127	0.152	0.152	0.203	0.203	0.203	0.203	0.051	0.228
Waviness	(µm)	0.127	0.203	0.203	0.330	0.356	0.305	0.380	0.432	0.483
Flatness	(µm)	0.305	0.305	0.254	0.330	0.533	0.508	0.508	0.635	1.677
Fwd Seat										
Dam Area Roughness	(µin. AA)	2	3	2	3	4	4	4	3	4
Waviness	(µin)	4	4	7	7	10	9	12	13	13
Flatness	(µn)	12	12	20	25	27	32	38	48	60
Aft Seat										
Dam Area Rougness	(µin. AA)	5	6	6	8	8	8	8	2	9
Waviness	(µin)	5	8	8	13	14	12	15	17	19
Flatness	(µin)	12	12	10	13	21	20	25	25	56

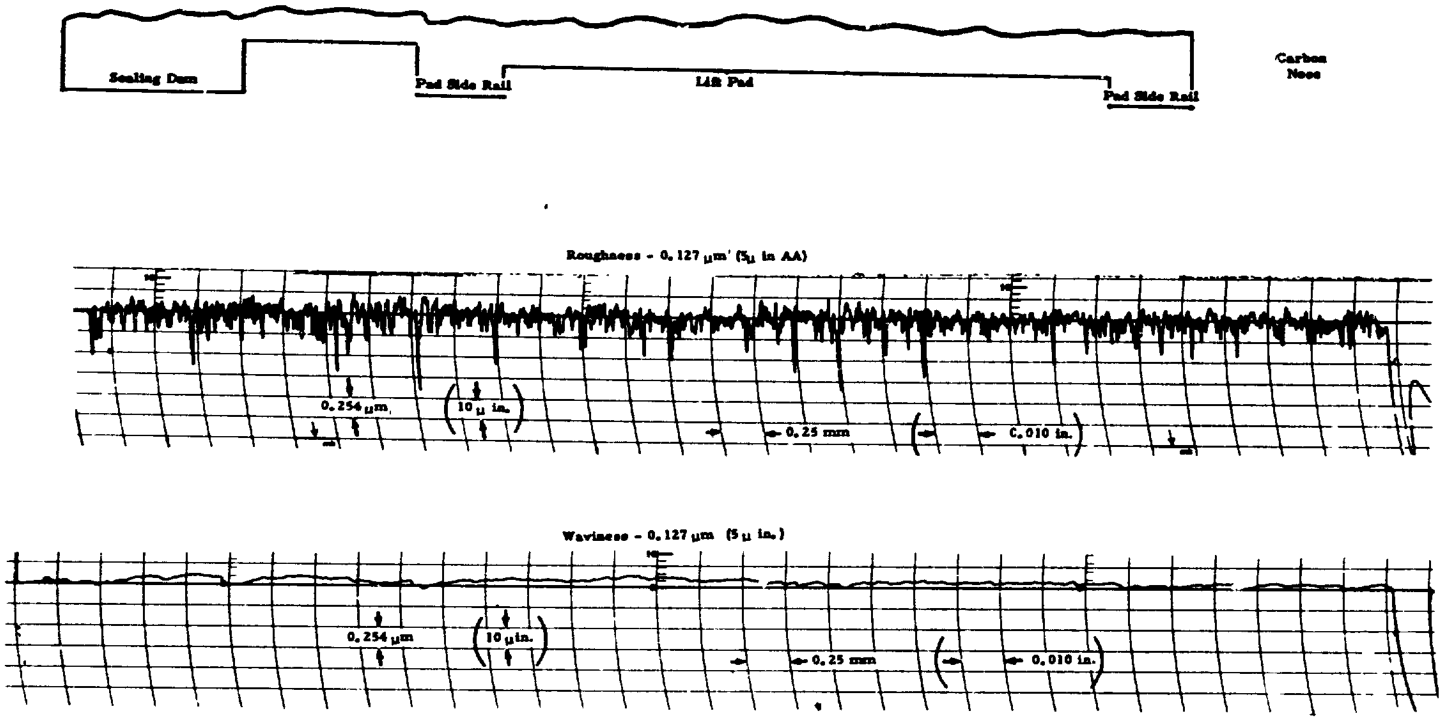


Figure 13. Trace of Aft Self-Acting Face Seal Seat Before Testing- Taken in a Radial Direction on the Seat Face Across the Running Track.

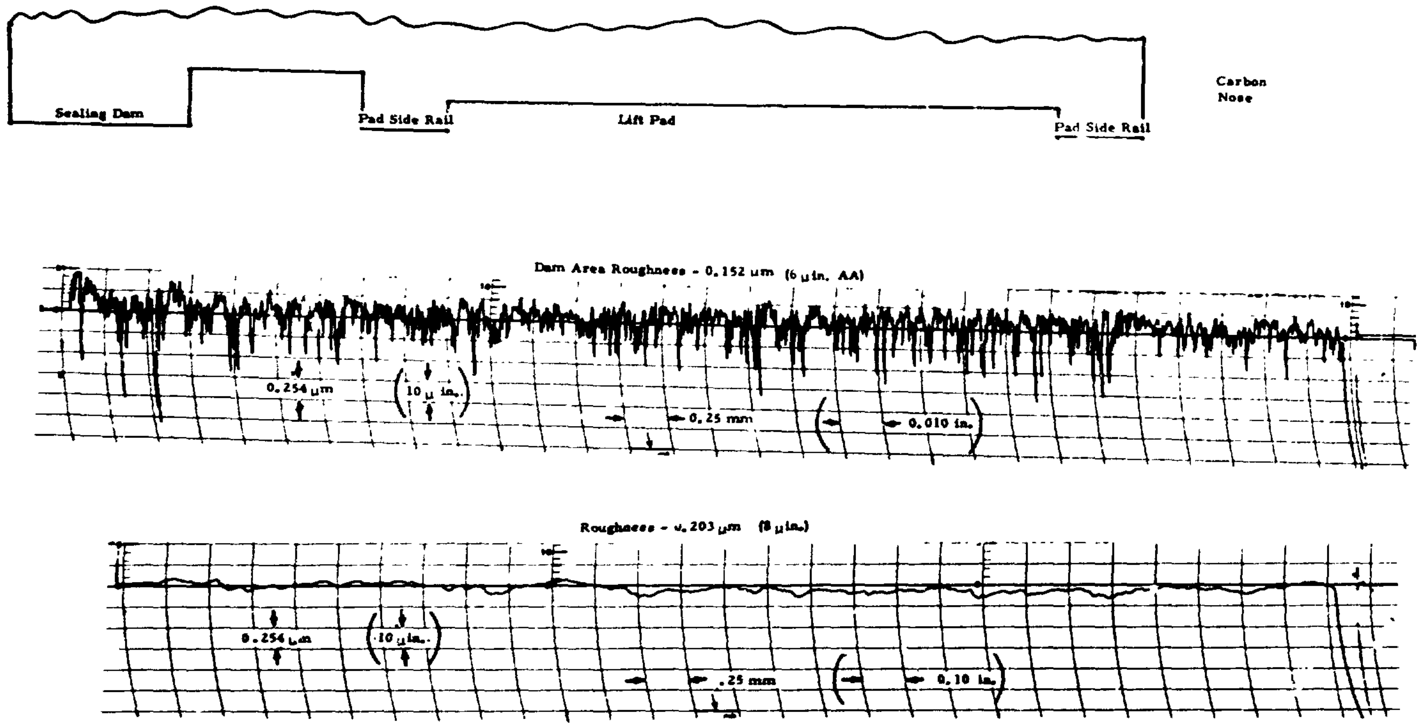


Figure 14. Trace of Aft Self-Acting Face Seal Seat After Test 2 - Taken in a Radial Direction on the Seat Face Across the Running Track.

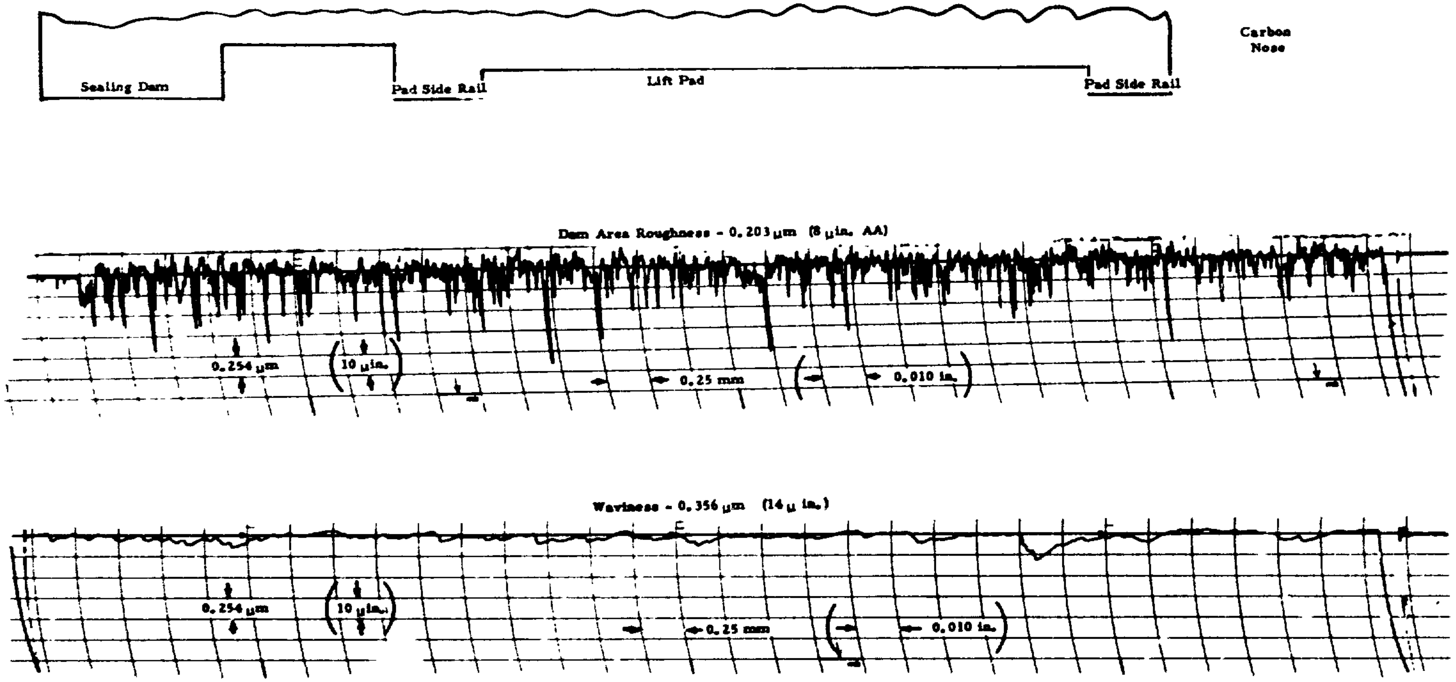


Figure 15. Trace of the Aft Self-Acting Face Seal After Test 4 - Taken in a Radial Direction on the Seat Face Across the Running Track.

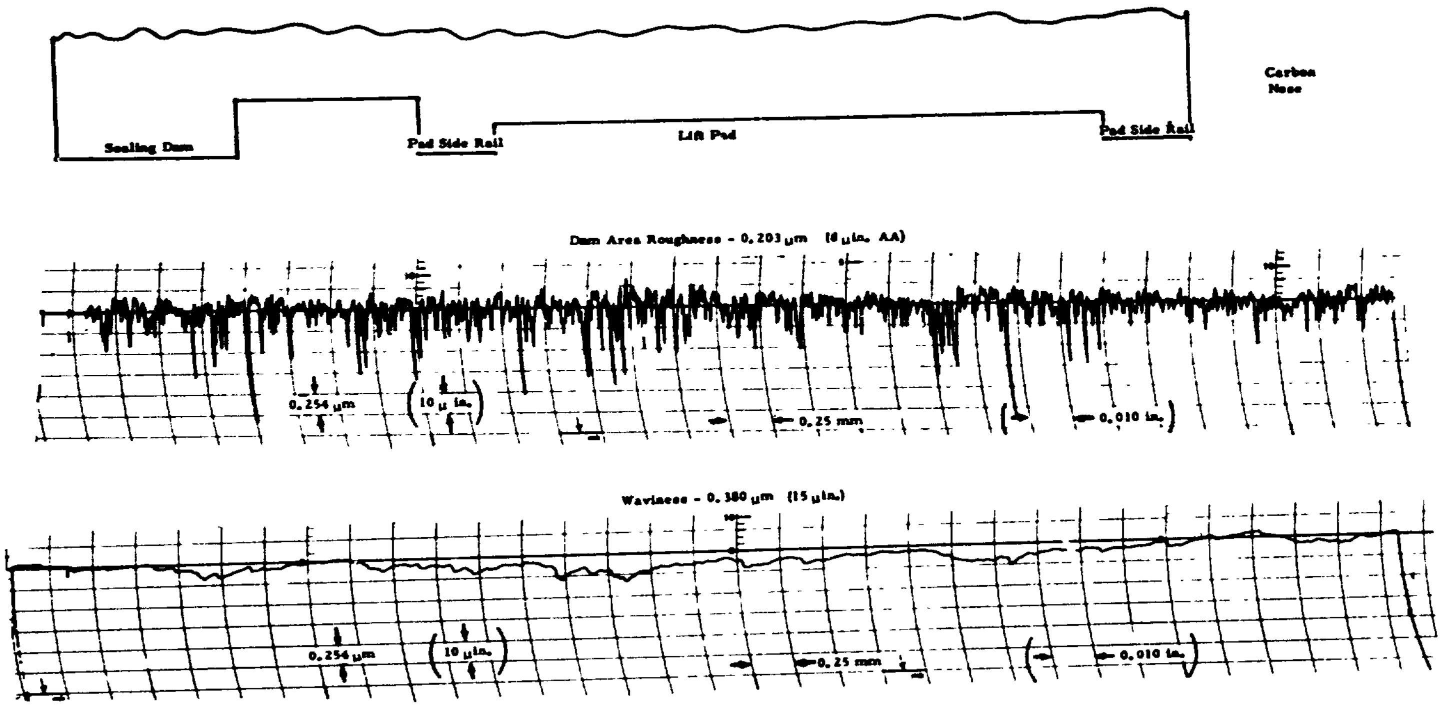


Figure 16. Trace of aft Self-Acting Face Seal Seat After Test 6 - Taken in a Radial Direction on the Seat Face Across the Running Track.

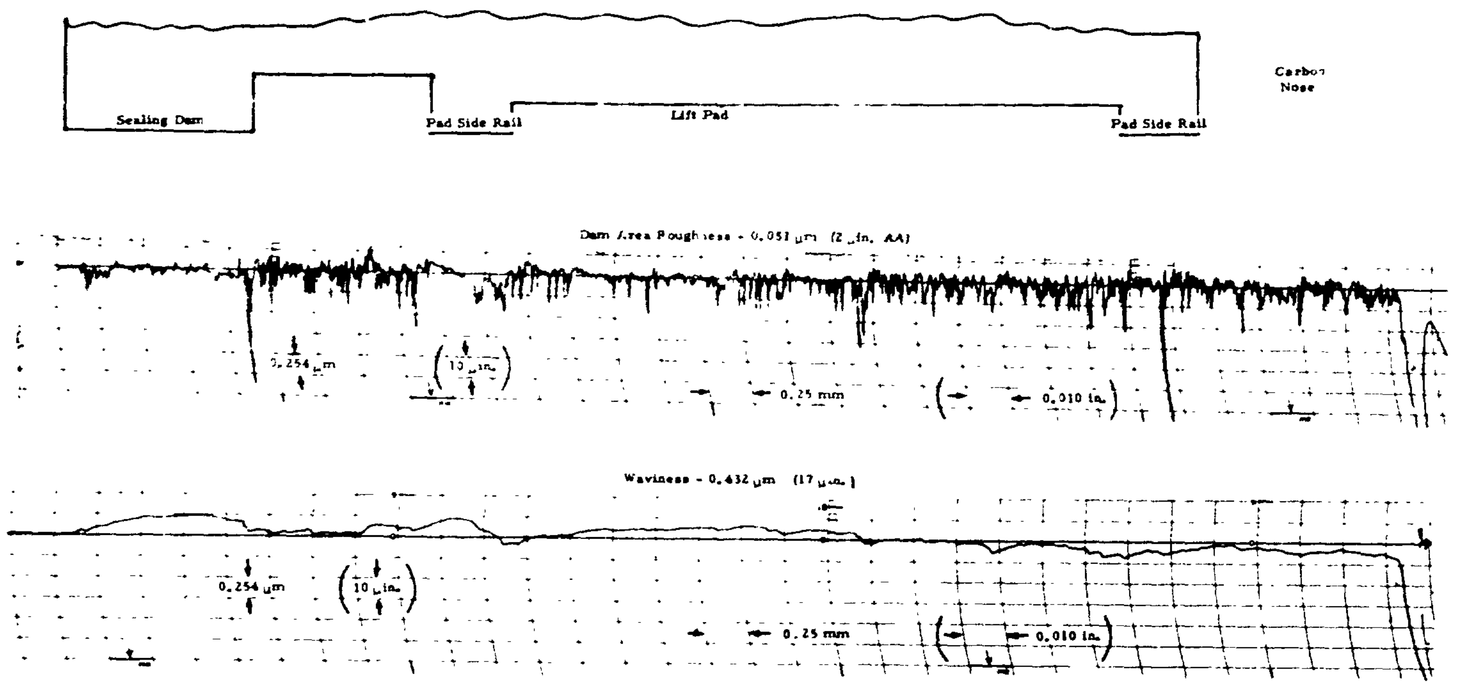


Figure 17. Trace of Aft Self-Acting Face Seal Seat After Test 7 - Taken in a Radial Direction on the Seat Face Across the Running Track.

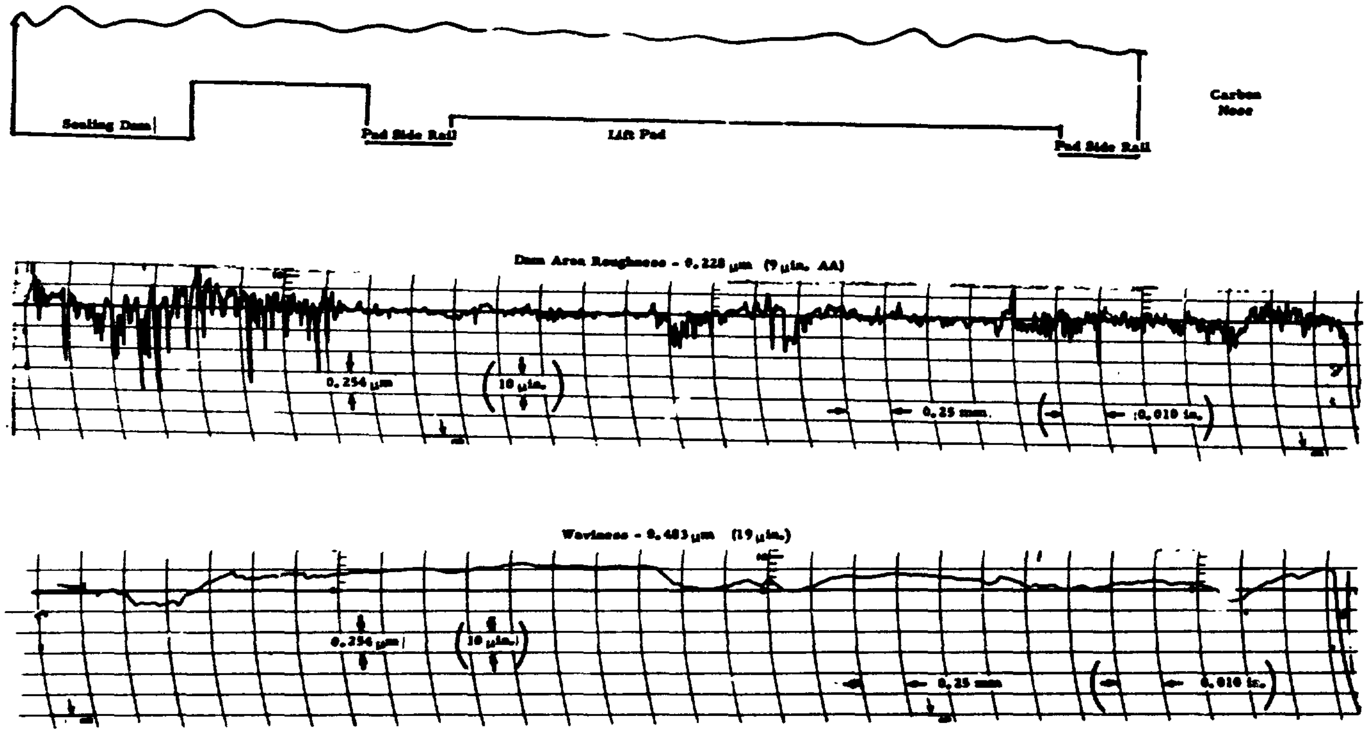


Figure 18. Trace of Aft Self-Acting Face Seal Seat After Test 8 - Taken in a Radial Direction on the Seat Face Across the Running Track.

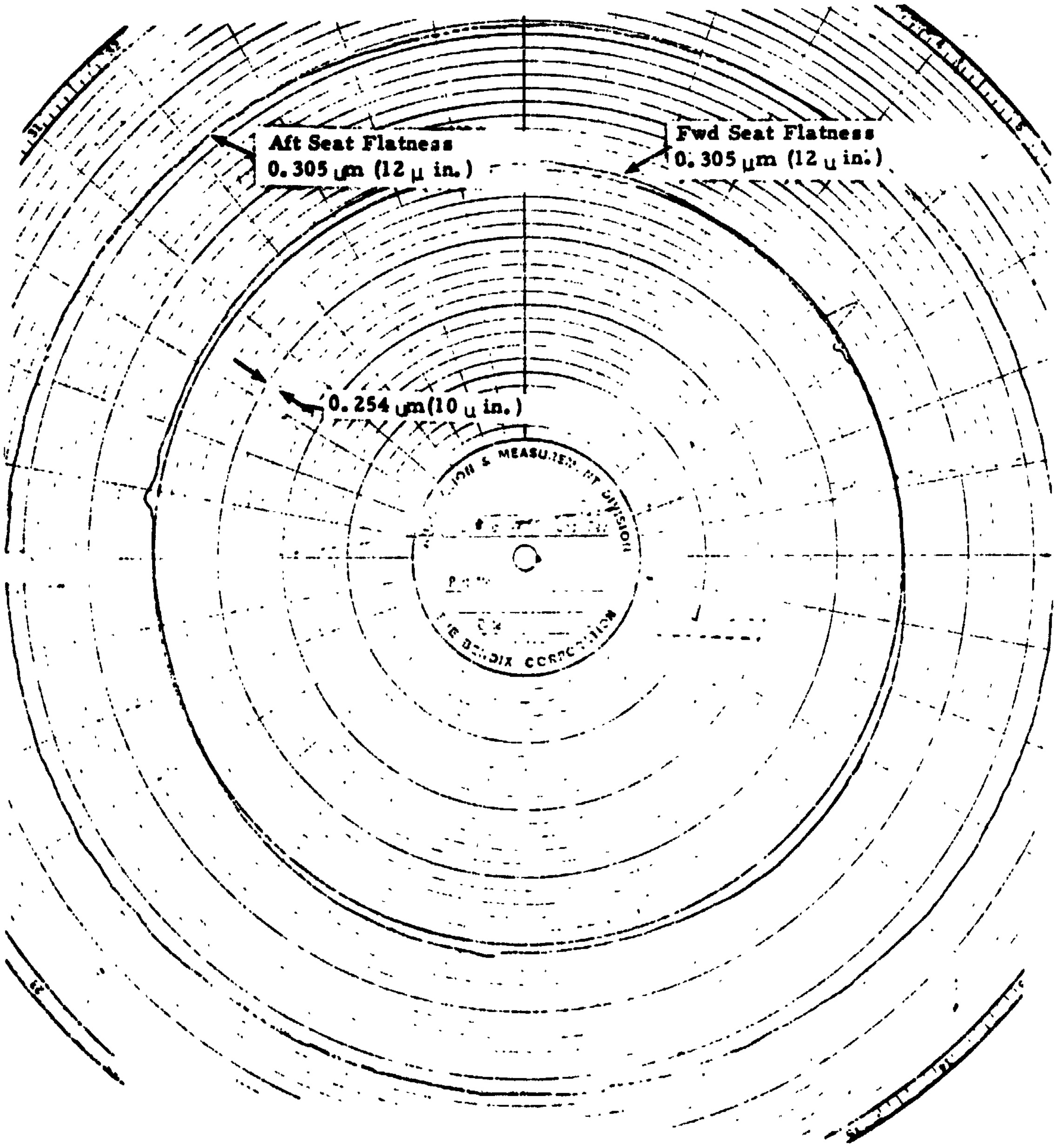


Figure 19. Self-Acting Face Seal Seat Face Flatness in the Free State Before Testing.

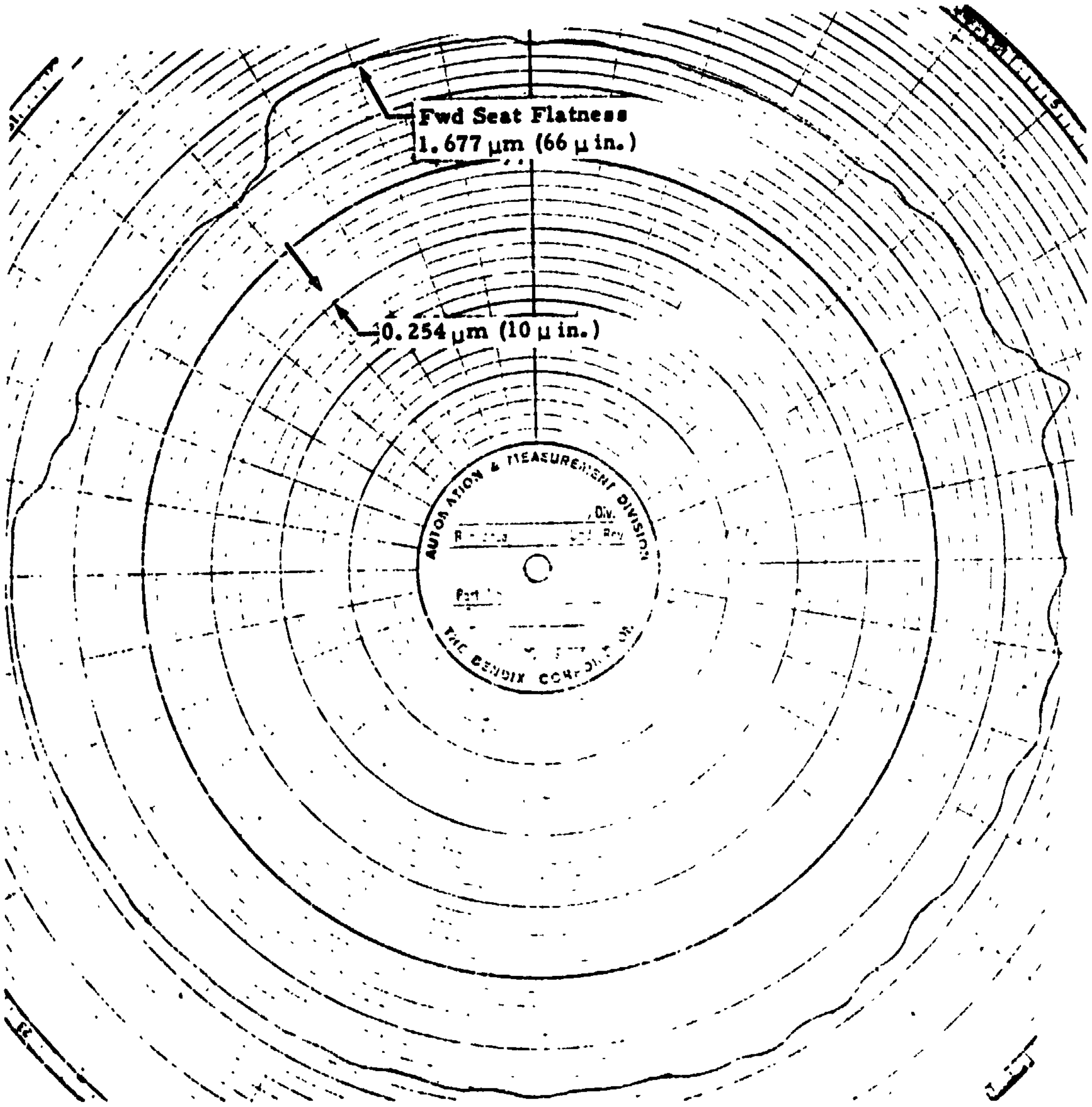


Figure 20. Self-Acting Face Seal Aft Seat Face Flatness in the Free State After Test 8.

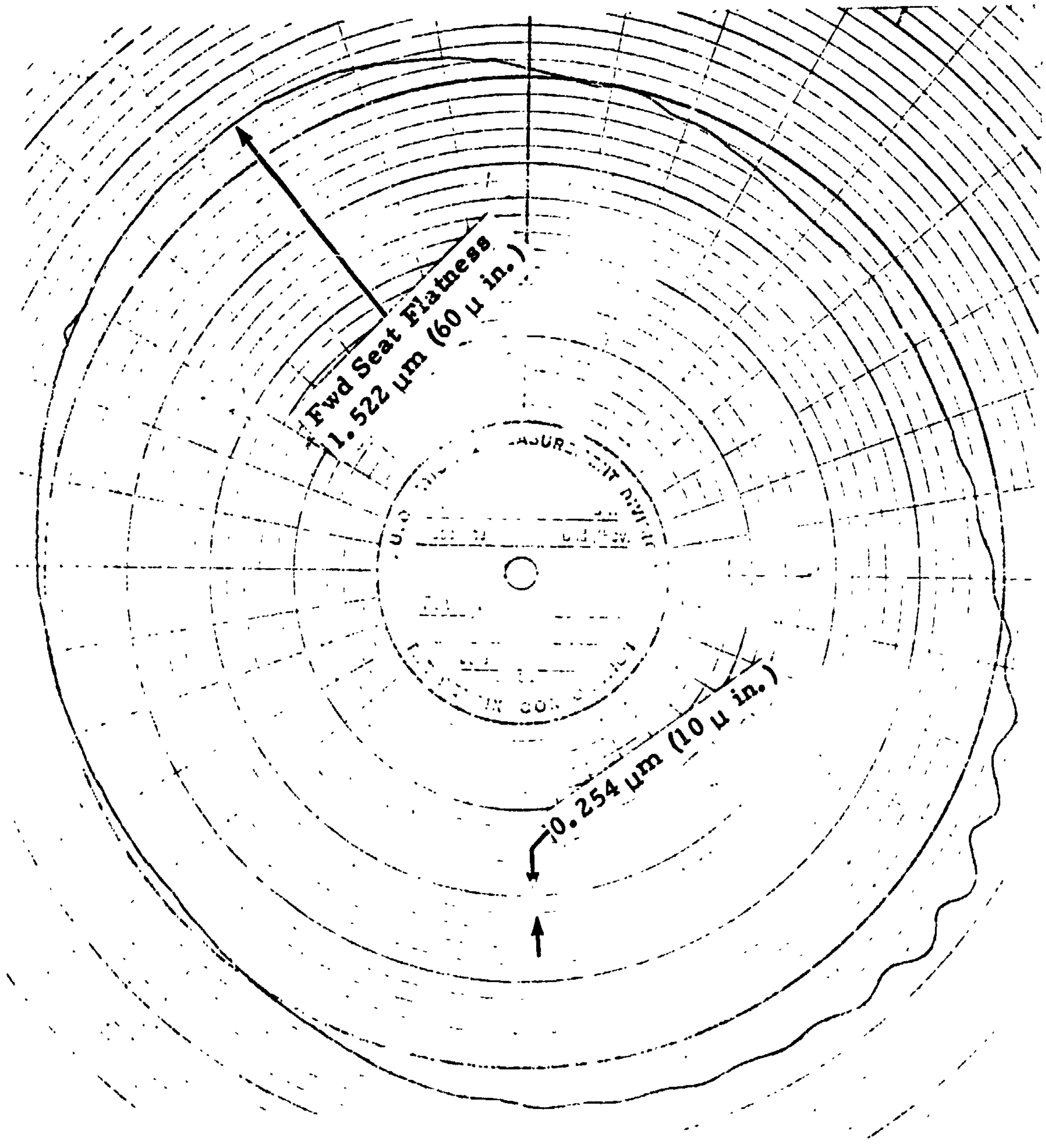


Figure 21. Self-Acting Face Seal Forward Seat Face Flatness in the Free State After Test 8.

TABLE VI. SELF-ACTING FACE SEAL - TEST 1 RESULTS

Run	Speed			Air Pressure		Cavity Pressure		Airflow (Two Seals)			Time
	(m/s)	(ft/sec)	(rpm)	(Ncm²)	(psia)	N/cm²)	(psia)	(kg/s)	(scfm)	(lb/sec)	(min)
1	91	300	27,300	44.6	64.7	11.8	17.1	0.0009	1.5	0.0019	15
2	91	300	27,300	44.6	64.7	11.9	17.2	0.0008	1.4	0.0018	15
3	122	400	36,400	44.6	64.7	11.9	17.3	0.0010	1.7	0.0022	15
4	122	400	36,400	44.6	64.7	12.1	17.5	0.0009	1.6	0.0020	15
5	91	300	27,300	79	114.7	12.9	18.5	0.0016	2.7	0.0034	15
6	91	300	27,300	79	114.7	13.2	19.1	0.0017	3.0	0.0038	15
7	122	400	36,400	79	114.7	13.3	19.3	0.0018	3.1	0.0040	15
8	122	400	36,400	79	114.7	13.3	19.3	0.0018	3.2	0.0041	15
					Shutdown						
9	91	300	27,300	113.5	164.7	13.9	20.2	0.0030	5.2	0.0066	15
10	91	300	27,300	113.5	164.7	14.1	20.5	0.0035	6.1	0.0078	15
11	122	400	36,400	113.5	164.7	14.1	20.5	0.0040	7.0	0.0089	15
12	122	400	36,400	113.5	164.7	14.9	21.7	0.0042	7.2	0.0092	15
13	91	300	27,300	147.9	214.7	15.7	22.7	0.0049	8.4	0.0107	15
14	91	300	27,300	147.9	214.7	15.5	22.5	0.0049	8.4	0.0107	15
15	122	400	36,400	147.9	214.7	16.0	23.2	0.0051	8.9	0.0113	15
16	122	400	36,400	147.9	214.7	16.2	23.5	0.0051	8.9	0.0113	15
											4 hr

TABLE VI Continued

Run	Fwd Seal Air Temp. (K)	Fwd Seal Air Temp. (°F)	Fwd Seal Temp. (K)	Fwd Seal Temp. (°F)	Aft Seal Air Temp. (K)	Aft Seal Air Temp. (°F)	Aft Seal Temp. (K)	Aft Seal Temp. (°F)
1	328	130	329	132	322	120	364	196
2	364	196	329	132	326	126	367	200
3	366	198	333	140	328	130	367	200
4	372	210	336	144	331	136	374	214
5	369	204	339	150	334	142	370	206
6	358	184	339	150	338	148	359	186
7	373	212	340	152	340	152	373	212
8	376	216	340	152	343	158	377	218
			Shutdown					
9	354	178	311	100	309	96	---	176
10	358	184	312	102	313	104	357	182
11	370	206	328	130	320	116	366	198
12	366	198	333	140	323	122	362	192
13	358	184	322	120	326	126	366	180
14	359	136	333	140	324	124	354	178
15	376	216	344	160	330	134	267	200
16	373	212	344	160	332	138	314	196

TABLE VII. SELF-ACTING FACE SEAL - TEST 2 RESULTS

Run	Speed			Air Pressure		Cavity Pressure		Airflow (Two Seals)			Time
	(m/s)	(ft/sec)	(rpm)	(N/cm^2)	(psia)	(N/cm^2	(psia)	(kg/s)	(scfm)	(lb/sec)	(min)
1	91	300	27,300	79.0	114.7	14.4	20.9	.0023	4.3	.0051	15
2	91	300	27,300	79.0	114.7	14.5	21	.0022	4.1	.0051	15
3	122	400	36,400	79.0	114.7	14.8	21.5	.0026	4.5	.0057	15
4	122	400	36,400	79.0	114.7	14.8	21.5	.0027	4.7	.0060	15
5	152	500	45,500	79.0	114.7	15.2	22.1	.0030	5.2	.0066	15
6	152	500	45,500	79.0	114.7	15.2	22.1	.0030	5.2	.0066	15
7	91	300	27,300	113.5	164.7	15.8	22.9	.0040	7.0	.0089	15
8	91	300	27,300	113.5	164.7	16.1	23.3	.0042	7.2	.0092	15
9	122	400	36,400	113.5	164.7	16.3	23.7	.0046	7.9	.0099	15
10	122	400	36,400	113.5	164.7	16.6	24.1	.0050	8.6	.0110	15
					Shutdown						
11	152	500	45,500	113.5	164.7	16.5	23.9	.0054	9.3	.0118	15
12	152	500	45,500	113.5	164.7	17.0	24.7	.0053	9.1	.0116	15
13	91	300	27,300	147.9	214.7	17.7	25.7	.0060	10.3	.0131	15
14	91	300	27,300	147.9	214.7	18.0	26.1	.0061	10.5	.0134	15
15	122	400	36,400	147.9	214.7	18.8	27.3	.0066	11.4	.0145	15
16	122	400	36,400	147.9	214.7	19.1	27.7	.0066	11.4	.0145	15
17	152	500	45,500	147.9	214.7	20.0	29.1	.0069	11.9	.0152	15
18	152	500	45,500	147.9	214.7	20.0	29.1	.0071	12.2	.0155	15
											4-1/2hr

TABLE VII - Continued

Run	Fwd Seal Air Temp. (K)	Fwd Seal Air Temp. (°F)	Fwd Seal Temp. (K)	Fwd Seal Temp. (°F)	Aft Seal Air Temp. (K)	Aft Seal Air Temp. (°F)	Aft Seal Temp. (K)	Aft Seal Temp. (°F)
1	300	80	347	164	294	70	352	174
2	310	98	354	178	307	92	356	180
3	312	102	360	188	314	105	369	204
4	322	120	361	190	322	120	370	206
5	333	140	371	208	331	136	384	232
6	339	150	374	214	335	143	387	236
7	338	148	366	199	332	138	362	192
8	333	140	364	195	332	138	362	192
9	339	150	368	202	334	142	373	212
10	339	150	367	200	334	142	372	209
				Shutdown				
11	340	152	370	206	340	152	384	232
12	340	152	378	220	341	158	384	232
13	339	150	363	194	331	135	359	186
14	338	148	363	193	329	132	353	176
15	340	152	369	204	332	138	368	202
16	339	150	370	206	332	138	368	202
17	340	152	378	220	337	146	381	226
18	341	154	379	222	338	148	382	228

TABLE VIII. SELF-ACTING FACE SEAL - TEST 3 RESULTS

Run	Speed			Air Pressure		Cavity Pressure		Airflow (2 Seals)			Time
	(m/s	(ft/sec)	(rpm)	N/cm^2	(psia)	(N/cm^2	(psia)	(kg/s)	(scfm)	(lb/sec)	(min)
1	91	300	27, 300	79	114.7	12.1	17.5	0.0031	5.4	0.0069	15
2	122	400	36, 400	79	114.7	12.2	17.7	0.0030	5.2	0.0073	15
3	152	500	45, 500	79	114.7	12.4	18	0.0038	6.6	0.0087	15
4	183	600	54, 600	79	114.7	12.7	18.5	0.0046	7.9	0.0101	15
5	91	300	27, 300	113.5	164.7	13.3	19.3	0.0055	9.6	0.0122	15
6	122	400	36, 400	113.5	164.7	13.2	19.1	0.0053	9.1	0,0116	15
7	152	500	45, 500	113.5	164.7	13.3	19.3	0.0054	9.3	0.0118	15
					Shutdown						
8	152	500	45, 500	113.5	164.7	13	18.9	0.0058	10.1	0.0129	15
9	183	600	54, 600	113.5	164.7	14	20.3	0.0066	11.4	0.0145	15
10	91	300	27, 300	147.9	214.7	14.4	20.9	0.0076	13.1	0,0167	15
11	122	400	36, 400	147.9	214.7	14.5	21.1	0.0072	12.4	0.0158	15
12	152	500	45, 500	147.9	214.7	14.8	21.5	0.0076	13.1	0.0167	15
13	183	600	54, 600	147.9	214.7	15.5	22.5	0.0098	13.1	0.0167	15

TABLE VIII - Continued

Run	Aft Seal Air Temp.		Aft Seal Temp.	
	(K)	(^{o}F)	(K)	(^{o}F)
1	324	122	357	182
2	328	130	368	202
3	336	144	377	218
4	344	158	388	238
5	336	144	357	182
6	338	148	368	202
7	342	156	379	222
	Shutdown			
8	316	110	366	198
9	327	128	379	222
10	318	112	346	166
11	322	120	361	190
12	329	132	370	206
13	338	148	384	232

Test 4

This was a 25-hour endurance test with a maximum air temperature of 433K (320 °F). Table IX list test conditions and resulting airflows, cavity pressures, and seal temperatures. Up to the 12th hour, cooling airflow was fed into the center of the shaft at the aft seal position; this was discontinued at the 12th hour. A heater malfunction in the 13th hour allowed air temperatures to rise to 522K (480 °F) in the forward area and 516 K (486 °F) in the aft area.

Inspection following the test revealed that the forward carbon had worn an average of 0.001 mm (0.00004 in.) and the aft carbon had worn an average of 0.002 mm (0.00009 in.) (Table IV). The seal seat roughness had not changed, however, waviness and flatness increased slightly (Table V). Visual inspection showed that the seats were in excellent condition.

Test 5

This was a 25-hour endurance test with a maximum air temperature of 588K (598°F). Table X lists test conditions and resulting airflows, cavity pressure, and seal temperatures.

Inspection following the test revealed no carbon wear. Seal seat surface texture did not change except for a slight increase in waviness of the forward seat.

Test 6

The seals were subjected to air pressures up to 216.8 N/cm^2 (314.7 psia) during Test 6. Table XI lists operating conditions and test results. The forward carbon did not wear and the aft carbon wore an average of 0.00032 mm (0.0000125 in.) (Table IV). Waviness and flatness of the forward seat increased slightly as did aft-seat waviness.

Test 7

During Test 7, seal speeds of 213 m/s (700 ft/sec, 63,700 rpm) were attained. Table XII lists operating conditions and test results.

Inspection following testing revealed 0.0013 mm (0.00005 in.) average wear on the forward carbon and 0.0008 mm (0.000032 in.) average wear on the aft carbon.

TABLE IX. 25-HOUR SELF-ACTING FACE SEAL ENDURANCE TEST - TEST 4

Speed = 183 m/s (600 ft/sec, 54,600 rpm)

Hour	Air Pressure		Cavity Pressure		Airflow (2 Seals)		
	(N/cm^2)	(psia)	(N/cm^2)	(psia)	(kg/s)	(scfm)	(lb/sec)
1	79	114.7	17.7	25.7	.0051	8.9	.0113
2	79	114.7	17.7	25.7	.0055	9.6	.0122
			Shutdown				
3	79	114.7	17.7	25.7	.0054	9.3	.0118
4	79	114.7	17.7	25.7	.0051	8.9	.0113
5	79	114.7	17.4	25.2	.0053	9.1	.0116
6	79	114.7	17.4	25.2	.0053	9.1	.0116
7	79	114.7	17.4	25.2	.0051	8.9	.0113
8	79	114.7	17.4	25.2	.0051	8.9	.0113
			Shutdown				
9	79	114.7	17.0	24.7	.0046	7.9	.0101
10	79	114.7	17.0	24.7	.0050	8.6	.0110
11	79	114.7	15.6	22.7	.0039	6.8	.0087
12	79	114.7	15.6	22.7	.0038	6.6	.0084
13	79	114.7	15.6	22.7	.0040	7.0	.0089
14	147,9	214.7	25.3	36.7	.0093	16.1	.0205
15	147.9	214.7	22.5	32.7	.0078	13.5	.0172
			Shutdown				
16	147.9	214.7	21.2	30.7	.0078	13.5	.0172
17	147.9	214.7	22.5	32.7	.0083	14.3	.0182
18			Shutdown				
18	147.9	214.7	22.5	32.7	.0086	14.9	.0190
19	147.9	214.7	21.8	31.7	.0080	13.8	.0176
20	147.9	214.7	22.5	32.7	.0080	13.8	.0176
21	147.9	214.7	21.8	31.7	.0081	14.0	.0178
22	147.9	214.7	21.8	31.7	.0083	14.3	.0182
23	147.9	214.7	21.8	31.7	.0081	14.0	.0173
			Shutdown				
24	147.9	214.7	22.5	32.7	.0087	15.0	.0191
25	147.9	214.7	22.5	32.7	.0087	15.0	.0191

TABLE IX - Continued

Hour	Fwd Air Temp.		Fwd Seal Temp.		Aft Air Temp.		Aft Seal Temp.	
	(K)	(°F)	(K)	(°F)	(K)	(°F)	(K)	(°F)
1	428	311	417	290	396	252	404	268
2	422	300	412	282	389	240	400	260
			Shutdown					
3	433	320	414	286	397	254	402	264
4	433	320	416	288	398	256	403	266
5	428	310	416	289	397	254	402	264
6	433	320	416	288	398	257	403	266
7	433	320	418	292	402	264	406	270
8	433	320	[illegible]9	294	402	264	404	268
			Shutdown					
9	433	320	423	302	412	282	408	274
10	433	320	426	306	417	290	410	278
11	422	300	422	300	428	310	419	295
12	422	300	423	301	427	308	419	294
13	522	480	457	360	516	468	457	362
14	422	300	437	320	430	314	426	306
15	426	306	443	338	431	316	439	330
			Shutdown					
16	439	330	442	335	443	338	431	316
17	433	320	440	330	433	319	426	306
			Shutdown					
18	433	320	442	336	433	320	428	310
19	439	330	439	336	438	328	428	310
20	433	320	439	330	433	320	426	306
21	422	300	433	320	427	308	423	302
22	431	315	438	328	429	312	426	306
23	433	320	437	326	428	310	423	302
			Shutdown					
24	422	300	433	320	420	296	421	298
25	423	302	437	326	424	304	423	302

TABLE X. 25-HOUR SELF-ACTING FACE SEAL ENDURANCE TEST - TEST 5
SPEED = 183 M/S (600 FT/SEC, 54, 600 RPM)
AIR PRESSURE = 174.9 N/cm^2 (214.7 PSIA)

Hour	Cavity Pressure		Airflow (2 Seals)			Fwd Air Temp		Fwd Seal Temp		Aft Air Temp		Aft Seal Temp	
	(N/cm^2)	(psia)	(kg/s)	(scfm)	(lb/sec	(K)	(°F)	(K)	(°F)	(K)	(°F)	(K)	(°F)
1	20	29.1	0.0069	12	0.0153	489	420	466	379	520	476	464	376
						Shutdown							
2	19.1	27.7	0.0057	9.8	0.0125	517	470	477	398	562	554	481	406
3	18.9	27.5	0.0059	10.2	0.0130	511	460	477	398	552	534	478	400
4	19.2	27.9	0.0057	9.8	0.0125	528	490	486	414	577	578	488	418
5	19.4	28.1	0.0060	10.3	0.0131	533	500	484	412	579	582	490	422
6	19.1	27.1	0.0057	9.8	0.0125	533	500	486	414	581	586	490	422
						Shutdown							
7	22	31.9	0.0087	15	0.0191	506	450	477	398	541	514	473	392
8	21.2	30.7	0.0075	13	0.0166	539	510	493	428	580	584	491	424
9	20.7	30.1	0.0075	13	0.0166	539	510	492	426	573	572	489	420
10	20.5	29.7	0.0075	13	0.0166	536	505	493	428	574	574	488	418
11	21	30.5	0.0072	12.5	0.0159	533	500	490	422	571	568	487	416
12	21	30.5	0.0075	13	0.0166	533	500	494	430	572	570	491	424
13	21.4	31.1	0.0075	13	0.0166	533	500	489	420	567	560	486	414
						Shutdown							
14	19.9	28.9	0.0069	12	0.0153	550	530	508	454	588	598	506	450
15	20.3	29.5	0.0069	12	0.0153	539	510	496	432	575	575	493	428
16	20.8	30.2	0.0075	13	0.0165	531	495	491	423	563	554	487	417
17	20.5	29.7	0.0069	12	0.0153	533	500	493	428	566	558	489	420
18	20.3	29.5	0.0069	12	0.0153	533	500	496	432	572	570	492	426
19	20.5	29.7	0.0069	12	0.0153	536	505	494	430	569	565	491	423
20	19.1	27.7	0.0061	10.5	0.0134	489	420	449	348	520	476	433	320
21	19.9	28.9	0.0062	10.8	0.0138	533	500	490	422	579	582	489	420
						Shutdown							

TABLE XI. SELF-ACTING FACE SEAL - TEST 6 RESULTS

Run	Speed			Air Pressure		Cavity Pressure		Airflow (2 Seals)			Time
	(m/s)	(ft/sec)	(rpm)	(N/cm²)	(psia)	(N/cm²)	(psia)	(kg/s)	(scfm)	(lb/sec)	(min)
1	122	400	36,400	147.9	214.7	22.7	32.9	0.0087	15	0.0191	15
2	152	500	45,500	147.9	214.7	22.9	33.2	0.0092	16	0.0204	15
3	183	600	54,600	147.9	214.7	25.7	37.3	0.0104	18	0.0229	15
4	183	600	54,600	147.9	214.7	25.6	37.1	0.0101	17.5	0.0223	15
5	183	600	54,600	147.9	214.7	25.4	36.9	0.0098	17	0.0217	15
6	183	600	54,600	147.9	214.7	25.6	37.1	0.0098	17	0.0217	15
7	91	300	27,300	182.4	264.7	27.4	39.7	0.0121	21	0.0268	15
8	122	400	36,400	182.4	264.7	26.8	38.9	0.0116	20	0.0255	15
9	152	500	45,500	182.4	264.7	27.4	39.7	0.0116	20	0.0255	15
10	183	600	54,600	182.4	264.7	29.8	43.2	0.0133	23	0.0292	15
11	183	600	54,600	182.4	264.7	29.4	42.7	0.0133	23	0.0292	15
12	183	600	54,600	182.4	264.7	29.8	43.2	0.0133	23	0.0292	15
13	183	600	54,600	182.4	264.7	29.4	42.7	0.0133	23	0.0292	15
14	183	600	54,600	182.4	264.7	29.8	43.2	0.0133	23	0.0292	15
15	183	600	54,600	182.4	264.7	30.2	43.9	0.0127	22	0.0280	15
						SHUTDOWN					
16	91	300	27,300	216.8	314.7	28.7	41.7	0.0124	21.5	0.0274	15
17	122	400	36,400	216.8	314.7	29.4	42.7	0.0133	23	0.0292	15
18	152	500	45,500	216.8	314.7	30.8	44.7	0.0145	25	0.0318	15
19	183	600	54,600	216.8	314.7	32.2	46.7	0.0150	26	0.0331	15
						SHUTDOWN					
20	183	600	54,600	216.8	314.7	32.9	47.7	0.0147	25.5	0.0325	15
21	183	600	54,600	216.8	314.7	33.6	48.7	0.0153	26.5	0.0338	15
										Total	5.25 Hr

TABLE XI Continued

Run	Fwd Seal Air Temp (K)	Fwd Seal Air Temp (°F)	Fwd Seal Temp (K)	Fwd Seal Temp (°F)	Aft Seal Air Temp (K)	Aft Seal Air Temp (°F)	Aft Seal Temp (K)	Aft Seal Temp (°F)
1	328	130	364	195	308	94	354	178
2	339	150	381	226	312	102	364	195
3	356	180	401	360	318	112	377	219
4	356	180	402	262	318	112	377	218
5	356	180	403	265	319	115	378	220
6	356	180	404	266	319	115	378	220
7	317	110	346	162	303	86	339	150
8	317	110	358	184	306	90	349	168
9	328	130	377	218	309	96	361	190
10	328	130	395	251	316	108	372	210
11	350	170	401	260	317	110	374	213
12	350	170	401	260	317	110	373	211
13	350	170	401	260	317	110	372	210
14	353	175	401	260	317	110	373	211
15	353	175	401	260	317	110	372	210
SHUTDOWN								
16	311	100	345	161	301	82	336	145
17	317	110	358	184	304	88	347	165
18	328	130	375	215	309	96	356	180
19	350	170	402	263	316	109	372	210
SHUTDOWN								
20	353	175	401	260	314	105	372	209
21	344	160	397	254	314	106	372	209

TABLE XII. SELF-ACTING FACE SEAL - TEST 7 RESULTS

Run	Speed			Air Pressure		Cavity Pressure		Air Flow (2 Seals)			Time
	(m/s)	(ft/sec)	(rpm)	(N/cm²)	(psia)	(N/cm²)	(psia)	(kg/s)	(scfm)	(lb/sec)	(min.)
1	91	300	27,300	113.5	164.7	20.8	30.2	0.0075	13	0.0166	15
2	122	400	36,400	113.5	164.7	20.8	30.2	0.0069	12	0.0153	15
3	152	500	45,500	113.5	164.7	21.2	30.7	0.0069	12	0.0153	15
4	183	600	54,600	113.5	164.7	21.8	31.7	0.0075	13	0.0166	15
5	202	660	60,000	113.5	164.7	22.5	32.7	0.0087	15	0.0191	15
6	91	300	27.300	147.9	214.7	23.9	34.7	0.0092	16	0.0204	15
7	122	400	36,400	147.9	214.7	24.6	35.7	0.0092	16	0.0204	15
8	152	500	45,500	147.9	214.7	23.9	34.7	0.0098	17	0.0217	15
9	183	600	54,600	147.9	214.7	26	37.7	0.0107	18.5	0.0236	15
10	195	638	58,000	147.9	214.7	26.7	38.7	0.0113	19.5	0.0248	15
						SHUTDOWN					
11	91	300	27,300	182.4	264.7	30.1	43.7	0.0142	24.5	0.0312	15
12	122	400	36,400	182.4	264.7	29.4	42.7	0.0142	24.5	0.0312	15
13	152	500	45,500	182.4	264.7	27.4	39.7	0.0116	20	0.0255	15
14	183	600	54,600	182.4	264.7	29.4	42.7	0.0124	21.5	0.0274	15
						SHUTDOWN					
15	213	700	63,700	182.4	264.7	30.1	43.7	0.0127	22	0.0280	15
16	213	700	63,700	182.4	264.7	30.1	43.7	0.0130	22.5	0.0287	15
						SHUTDOWN					
17	76	249	22,700	34.2	49.7	13.6	19.7	0.0012	2	0.0025	15
18	87	285	25,900	34.2	49.7	13.6	19.7	0.0012	2	0.0025	15
19	134	440	40,000	44.6	64.7	13.9	20.2	0.0019	3.3	0.0042	15
20	134	440	40,000	44.6	64.7	14.3	20.7	0.0019	3.3	0.0042	15
21	177	582	53,000	44.6	64.7	15	21.7	0.0021	3.7	0.0047	15
22	213	700	63,700	44.6	64.7	18.4	26.7	0.0043	7.5	0.0096	15
23	213	700	63,700	79	114.7	19.4	28.2	0.0055	9.5	0.0121	15
24	213	700	63,700	113.5	164.7	22.5	32.7	0.0081	14	0.0178	15
25	213	700	63,700	147.9	214.7	25.3	36.7	0.0107	18.5	0.0236	15

TABLE XII - Continued

Run	Fwd Seal Air Temp (K)	Fwd Seal Air Temp (°F)	Fwd Seal Temp (K)	Fwd Seal Temp (°F)	Aft Seal Air Temp (K)	Aft Seal Air Temp (°F)	Aft Seal Temp (K)	Aft Seal Temp (°F)
1	311	100	344	160	303	86	347	164
2	317	110	358	184	309	96	362	191
3	325	125	366	198	312	102	368	202
4	336	145	382	228	318	112	382	227
5	347	165	398	256	324	124	392	246
6	319	115	346	162	311	100	344	160
7	322	120	356	180	313	103	355	179
8	328	130	369	205	313	104	369	204
9	342	155	386	235	318	113	380	224
10	358	185	394	250	322	120	384	232
				SHUTDOWN				
11		99	338	148	303	85	336	145
12	314	105	349	168	306	91	348	166
13	364	195	397	255	331	136	378	220
14	382	245	418	292	343	158	389	240
				SHUTDOWN				
15	422	300	450	350	356	180	410	278
16	461	370	461	3[illegible]	366	193	416	289
				SHUTDOWN				
17	317	110	344	160	311	100	346	162
18	322	120	352	174	317	110	356	180
19	322	120	367	200	327	128	373	212
20	332	138	372	210	329	132	379	222
21	350	170	386	234	337	146	390	242
22	356	180	400	260	346	162	407	272
23	367	200	404	268	357	182	410	278
24	392	245	423	301	362	192	411	280
25	392	245	429	312	362	191	413	234

Figures 22 and 23 illustrate the condition of the carbons and seats after testing. The aft seat shows heavier contact.

Inspection of the seats revealed that the flatness and waviness of the forward and aft seat increased (Table V). Roughness at the dam areas decreased because of the carbon deposited.

Test 8

This was an endurance test with the following maximum operating conditions:

Speed	197 m/s (650 ft/sec, 59,150 rpm)
Air Temperature	687 K (778 °F)
Air Pressure	147.9 N/cm^2 (214.7 psia)

The seals operated for 7 hours at the maximum speed and pressure conditions with temperatures ranging from 588 to 687 K (600 to 778°F). Table XIII lists test conditions and resulting airflows cavity pressures, and seal temperatures for the full 19.25-hour test.

Operation was terminated because of increasing airflow into the bearing cavity. Disassembly revealed that the aft piston ring was cracked in several places and appeared to be soft. The carbon material used has a hardness of 90 on the Shore 'C" scale. Hardness readings on the wall of the aft piston ring were 20, indicating that the piston ring had oxidized. The forward piston ring and the forward and aft carbons were checked for hardness and found to be Shore "C" 90.

It can be seen from Table XIII that the highest forward air temperature was 650 K (710°F), while the highest aft air temperature was 687 K (778°F) with 5 hours of operation at over 650 K (710°F). Apparently the threshold oxidation temperature of the carbon material is very close to 650 K (710°F).

Inspection revealed no wear on the forward seal carbon and an average of 0.0046 mm (0.000181 in.) wear on the aft (Table V). The forward seat flatness increased and the aft seat roughness, waviness and flatness increased (Table V). Figures 24 and 25 show carbon and seat conditions after testing.

Figure 26 shows the back sides of the carbon nose, which contacts the piston ring, revealing some coking and varnish.

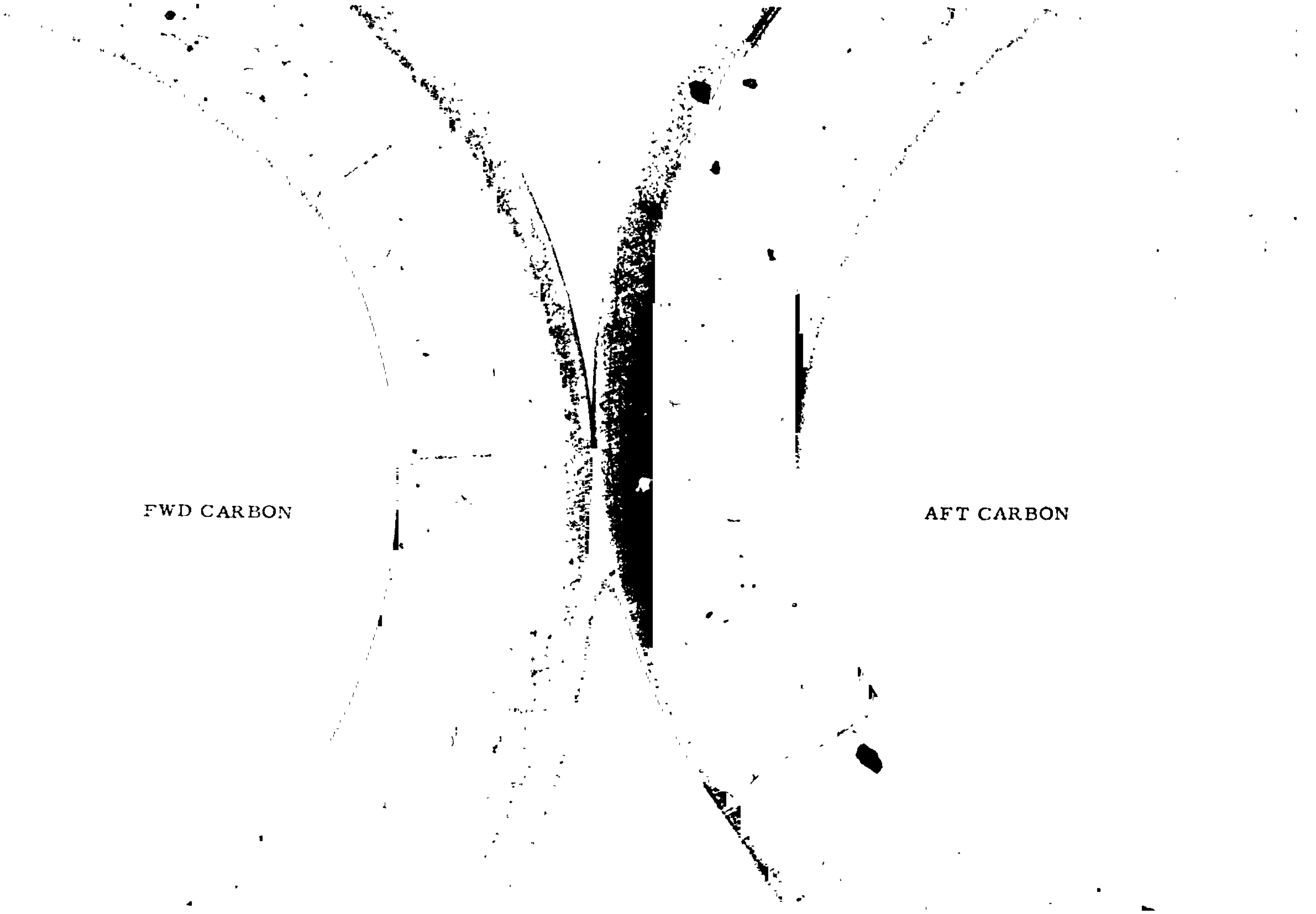


Figure 22. Self-Acting Face Seal, Carbon Nose Condition After Test 7.

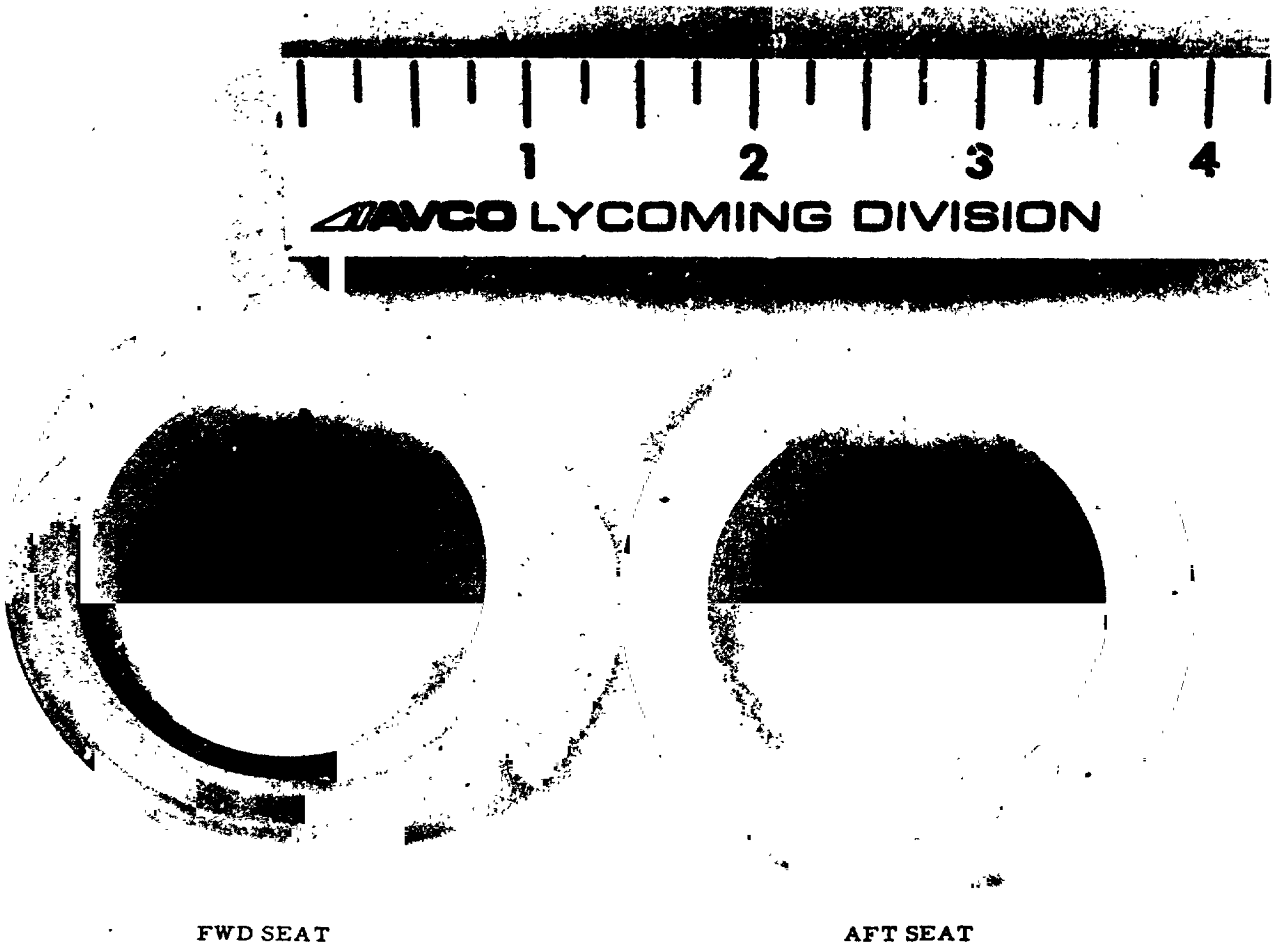


Figure 23. Self-Acting Face Seal, Seal Seat Condition After Test 7.

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TABLE XIII. 19.25-HOUR SELF-ACTING FACE SEAL ENDURANCE TEST - TEST 8

Run	Speed (m/s)	Speed (ft/sec)	Speed (rpm)	Air Pressure (N/cm^2)	Air Pressure (psia)	Cavity Pressure (N/cm^2)	Cavity Pressure (psia)	Air Flow (2 Seals) (kg/s)	Air Flow (2 Seals) (scfm)	Air Flow (2 Seals) (lb/sec)	Time (min.)
1	91	300	27,300	34.3	49.7	13.9	20.2	0.0013	2.2	0.0028	15
2	122	400	36,400	34.3	49.7	13.9	20.2	0.0014	2.4	0.0031	15
3	152	500	45,500	34.3	49.7	13.9	20.2	0.0014	2.5	0.0036	15
4	183	600	54,600	34.3	49.7	14.3	20.7	0.0016	2.8	0.0036	15
5	183	600	54,600	79	114.7	18.4	26.7	0.0045	7.7	0.0098	15
6	183	600	54,600	113.5	164.7	21.5	31.2	0.0075	13.0	0.0166	15
7	183	600	54,600	147.7	214.7	24.2	35.2	0.0098	17.0	0.0216	15
8	183	600	54,600	147.7	214.7	24.2	35.2	0.0095	16.5	0.0210	15
					SHUTDOWN						
9	183	600	54,600	147.7	214.7	27.4	39.7	0.0092	16.0	0.0204	15
10	183	600	54,600	147.7	214.7	26.6	38.7	0.0090	15.5	0.0198	15
11	183	600	54,600	147.7	214.7	26.6	38.7	0.0092	16.0	0.0204	15
12	183	600	54,600	147.7	214.7	26.6	38.7	0.0092	16.0	0.0204	15
13	183	600	54,600	147.7	214.7	27.4	39.7	0.0095	16.5	0.0408	15
14	183	600	54,600	147.7	214.7	28	40.7	0.0095	16.5	0.0408	15
15	198	650	59,150	147.7	214.7	28.8	41.7	0.0098	17	0.0216	15
16	198	650	59,150	147.7	214.7	29.4	42.7	0.0098	17	0.0216	15
17	198	650	59,150	147.7	214.7	29.4	42.7	0.0104	18	0.0242	15
					SHUTDOWN						
18	91	300	27,300	44.6	64.7	18.4	26.7	0.0034	5.9	0.0075	15
19	122	400	36,400	44.6	64.7	18.4	26.7	0.0037	6.4	0.0082	15
20	152	300	36,400	44.6	64.7	18.4	26.7	0.0042	7.2	0.0092	15
21	183	600	54,600	44.6	64.7	19.1	27.7	0.0042	7.3	0.0093	15
22	183	600	54,600	79	114.7	24.6	35.7	0.0078	13.5	0.0172	15
23	183	600	54,600	113.5	164.7	30.8	44.7	0.0119	20.5	0.0261	15
24	183	600	54,600	147.9	214.7	36.3	52.7	0.0144	25.0	0.0318	15
25	198	650	59,150	147.9	214.7	36.3	52.7	0.0144	25.0	0.0318	15
26	198	650	59,150	147.9	214.7	35.6	51.7	0.0142	24.5	0.0312	15

TABLE XIII - Continued

	Speed			Air Pressure		Cavity Pressure		Airflow (2 Seals)			Time
Run	(m/s)	(ft/sec)	(rpm)	(N/cm^2)	(psia)	(N/cm^2)	(psia)	(kg/s)	(scfm)	(lb/sec)	(min)
						SHUTDOWN					
27	198	650	59,150	147.9	214.7	37	53.7	0.0142	24.5	0.0312	15
28	198	650	59,150	147.9	214.7	35.6	51.7	0.0139	24.0	0.0306	15
29	198	650	59,150	147.9	214.7	34.3	49.7	0.0130	22.5	0.0286	15
30	198	650	59,150	147.9	214.7	33.6	48.7	0.0127	22.0	0.0280	15
31	198	650	59.150	147.9	214.7	33.6	48.7	0.0127	22.0	0.0280	15
32	198	650	59,150	147.9	214.7	35.6	51.7	0.0133	23.0	0.0293	15
33	198	650	59,150	147.9	214.7	34.3	49.7	0.0130	22.5	0.0286	15
34	198	650	59,150	147.9	214.7	33.6	48.7	0.0130	22.5	0.0286	15
35	198	650	59,150	147.9	214.7	33.6	48.7	0.0130	22.5	0.0286	15
						SHUTDOWN					
36	91	300	27,300	79	114.7	28.8	41.7	0.0092	16	0.0204	15
37	122	400	36,400	79	114.7	28.8	41.7	0.0098	16	0.0204	15
38	152	500	45,500	79	114.7	28.8	41.7	0.0090	15.5	0.0198	15
39	152	500	45,500	79	114.7	28	40.7	0.0092	16	0.0204	15
40	152	500	45,000	79	114.7	28.8	41.7	0.0092	16	0.0204	15
41	152	500	45,500	79	114.7	27.8	40.2	0.0087	15	0.0191	15
42	152	500	45,500	79	114.7	26.6	38.7	0.0081	14	0.0178	15
43	152	500	45,500	79	114.7	26	37.7	0.0078	13.5	0.0172	15
44	152	500	45,500	79	114.7	26	37.7	0.0078	13.5	0.0172	15
45	152	500	45,500	79	114.7	26	37.7	0.0075	13	0.0166	15
46	152	500	45,500	79	114.7	37.1	39.2	0.0084	14.5	0.0185	15
47	183	600	54,600	79	114.7	26	37.7	0.0078	13.5	0.0172	15
48	183	600	54,600	113.5	164.7	32.3	46.7	0.0116	20	0.0255	15
49	183	600	54,600	147.9	214.7	37	53.7	0.0150	26	0.0331	15
50	183	600	54,600	147.9	214.7	37.8	54.7	0.0133	23	0.0293	15
51	198	650	59,150	147.9	214.7	38.5	55.1	0.0144	25	0.0318	15
52	198	650	59,150	147.9	214.7	39.2	56.7	0.0150	26	0.0331	15
53	198	650	59,150	147.9	214.7	37.8	54.7	0.0150	26	0.0331	15
54	198	650	59,150	147.9	214.7	37.8	54.7	0.0150	26	0.0331	15

TABLE XIII - Continued

	Speed			Air Pressure		Cavity Pressure		Airflow (2 Seals)			Time
Run	(m/s)	(ft/sec)	(rpm)	(N/cm^2)	(psia)	(N/cm^2)	(psia)	(kg/s)	(scfm)	(lb/sec)	(min)
55	198	650	59,150	147.9	214.7	37.8	54.7	0.0150	26	0.0331	15
56	198	650	59,150	147.9	214.7	37.8	54.7	0.0150	26	0.0331	15
57	198	650	59,150	147.9	214.7	36.4	52.7	0.0147	25.5	0.0325	15
58	198	650	59,150	147.9	214.7	37	53.7	0.0144	25	0.0318	15
59	198	650	59,150	147.9	214.7	33.5	55.7	0.0147	25.5	0.0325	15
60	198	650	59,150	147.9	214.7	33.5	55.7	0.0150	26	0.0331	15
61	198	650	59,150	147.9	214.7	39.9	57.7	0.0153	26.5	0.0338	15
62	198	650	59,150	147.9	214.7	40.6	58.7	0.0153	26.5	0.0338	15
63	198	650	59,150	147.9	214.7	39.9	57.7	0.0156	27	0.0344	15
					SHUTDOWN						
64	91	300	27,300	34.2	49.7	19.1	27.7	0.0042	7.3	0.0093	15
65	122	400	36,400	34.2	49.7	19.1	27.7	0.0040	7	0.0089	15
66	152	500	45,500	34.3	49.7	20.5	29.7	0.0047	8.2	0.0104	15
67	183	600	54,600	34.3	49.7	22.6	32.7	0.0058	10.	0.0127	15
68	183	600	54,600	34.3	49.7	21.9	31.7	0.0053	9.2	0.0117	15
69	183	600	54,600	34.3	49.7	23.3	33.7	0.0059	10.2	0.0130	15
70	183	600	54,600	34.3	49.7	23.3	33.7	0.0069	12	0.0153	15
71	183	600	54,600	34.3	49.7	24.6	35.7	0.0075	13	0.0166	15
72	183	600	54,600	34.3	49.7	23.3	33.7	0.0058	10	0.0127	15
73	183	600	54,600	34.3	49.7	21.9	31.7	0.0048	8.5	0.0108	15
74	183	600	54,600	34.3	49.7	24.6	35.7	0.0072	12.5	0.0159	15
75	183	600	54,600	34.3	49.7	24.6	35.7	0.0075	13	0.0166	15
76	183	600	54,600	44.6	64.7	27.4	39.7	0.0090	15.5	0.0198	15
77	183	600	54,600	79	114.7	27.4	39.7	0.0133	23	0.0293	15

TABLE XIII - Continued

	Fwd Air Temp		Fwd Seal Temp		Aft Air Temp		Aft Seal Temp	
Run	(K)	(°F)	(K)	(°F)	(K)	(°F)	(K)	(°F)
1	439	330	391.5	245	426.5	309	386.6	236
2	452.5	335	402	264	451	352	393	248
3	447	345	412	282	447	345	407.4	274
4	439	330	422	300	431.8	328	420.2	297
5	430	315	424	304	440	332	422	300
6	427	310	427	310	426	308	422	300
7	427	310	439	330	436	325	427	310
8	461	370	440.5	333	440	332	430	315
			SHUTDOWN					
9	505	450	480.6	406	527	490	472	390
10	530	495	495.8	423	547	525	483	410
11	561	550	502	454	589	600	516	470
12	583	590	516	470	608	635	524.5	485
13	597	615	527	490	626	668	536	505
14	622	660	539	510	650	710	556	530
15	630	675	555	540	662	732	572	570
16	633	680	558	545	666	740	574	574
17	639	690	562	552	669	745	575	576
18	444	340	405	270	444	340	394	250
19	439	330	410.4	279	439	330	404	268
20	422	300	408.6	276	418.4	294	407.4	274
21	416	290	418.4	294	417.2	292	419.6	296
22	458	365	443	338	463	374	439	330
23	461	370	452.5	355	472	390	445.8	343
24	477	400	464	376	488.4	419	455	360
25	505	450	484.2	412	514	466	477	400
26	533	500	508	455	559.8	548	508	455
			SHUTDOWN					

TABLE XIII - Continued

Run	Fwd Air Temp (K)	Fwd Air Temp (°F)	Fwd Seal Temp (K)	Fwd Seal Temp (°F)	Aft Air Temp (K)	Aft Air Temp (°F)	Aft Seal Temp (K)	Aft Seal Temp (°F)
27	522	480	497	435	544	520	497.6	436
28	533	500	516	470	594	610	534.8	503
29	589	600	534.2	502	625	666	557.4	544
30	644	700	560.4	549	672	750	594	610
31	650	710	566	560	685.4	774	611	640
32	636	685	557.4	544	672	750	604	628
33	644	700	563	554	681.8	768	608.6	636
34	647	705	566	560	686	775	612	642
35	627	705	567.2	562	687.8	778	614	646
			SHUTDOWN					
36	394	250	390	242	422	300	378.8	223
37	439	330	414	286	466	380	402.5	265
38	450	350	426	308	444.6	341	413	284
39	450	350	425	306	447.6	346	413	284
40	483	410	433	320	455	360	420.8	298
41	489	420	442	336	491	424	431.8	318
42	530	495	466	380	550	530	459.2	367
43	552.5	535	474	394	577	580	477.6	401
44	591.5	605	484.2	412	598.8	618	497.6	436
45	616	650	472	426	611	640	506.2	452
46	647	705	504	448	607.4	684	522	480
47	652.5	715	511	460	644	700	528.2	492
48	633	680	527	490	627	670	544	520
49	600	620	527	490	628.8	673	547.6	526
50	589	600	516	470	631.2	677	554	538
51	627	690	552	534	673	752	589	600
52	622	660	544	520	664.5	737	579.4	584
53	630	675	553	536	674	754	606.8	633

TABLE XIII - Continued

Run	Fwd Air Temp (K)	Fwd Air Temp (°F)	Fwd Seal Temp (K)	Fwd Seal Temp (°F)	Aft Air Temp (K)	Aft Air Temp (°F)	Aft Seal Temp (K)	Aft Seal Temp (°F)
54	630	675	554	538	673.5	753	607.4	634
55	627	670	551	532	672	750	605	630
56	627	670	551	532	669.6	746	603	626
57	627	670	552	534	673	752	604	628
58	630	675	551.5	533	675	756	603.5	627
59	624.5	665	542.5	517	666	740	594	610
60	611	640	595.2	512	653	716	509	600
61	577	580	516	470	605	630	536.6	506
62	539	510	497	435	555	540	503	446
63	461	370	446.4	344	451	352	433	320
64	405	270	385.4	234	405.6	271	384.2	232
65	416	290	389.5	241	404	268	392	246
66	427	310	405	270	425	306	406.2	272
67	427	310	413.5	285	425	306	415	288
68	439	330	415	288	425	306	416	280
69	455	360	420.7	297	451	352	425	306
70	494	430	439	330	491	424	448.2	347
71	524.5	485	450	350	531.2	497	492	426
72	536	555	458.6	366	561	550	481.8	408
73	589	600	473	392	589	600	494	430
74	613.5	645	470.2	387	611	640	528.8	493
75	635	685	475	396	627	670	543	518
76	644	700	496.4	434	644.6	701	547	525
77	650	710	516	470	647	705	562	552

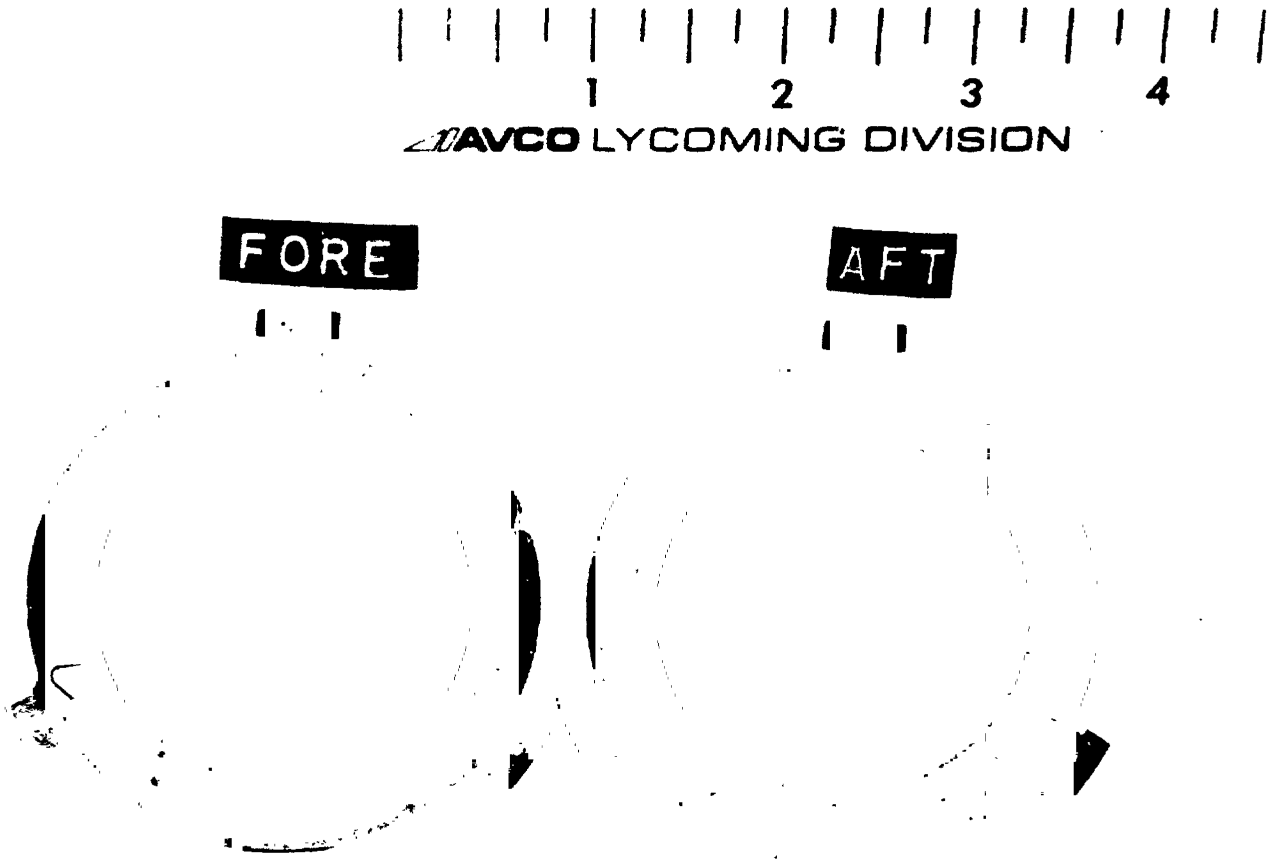

Figure 24. Self-Acting Face Seal, Carbon Nose Condition After Test 8.

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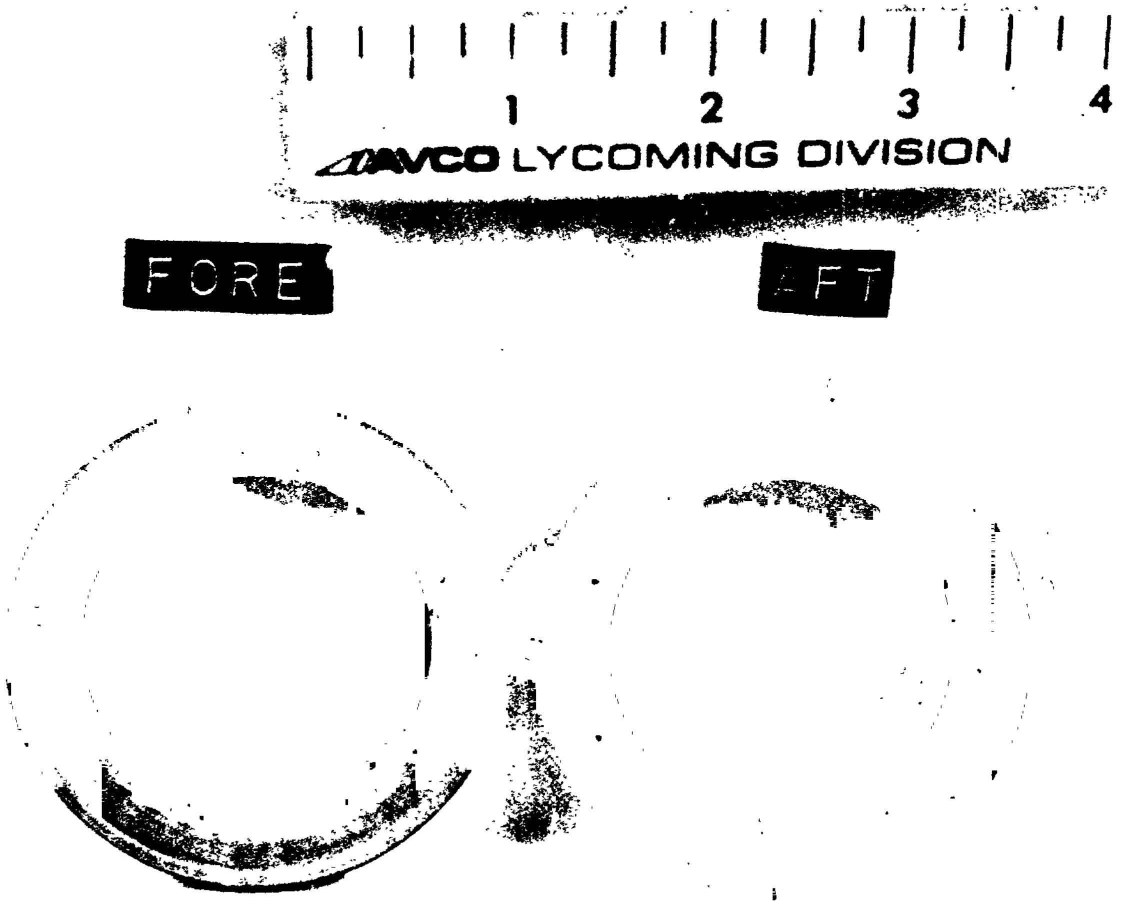


Figure 25. Self-Acting Face Seal, Seal Seat Condition After Test 8.

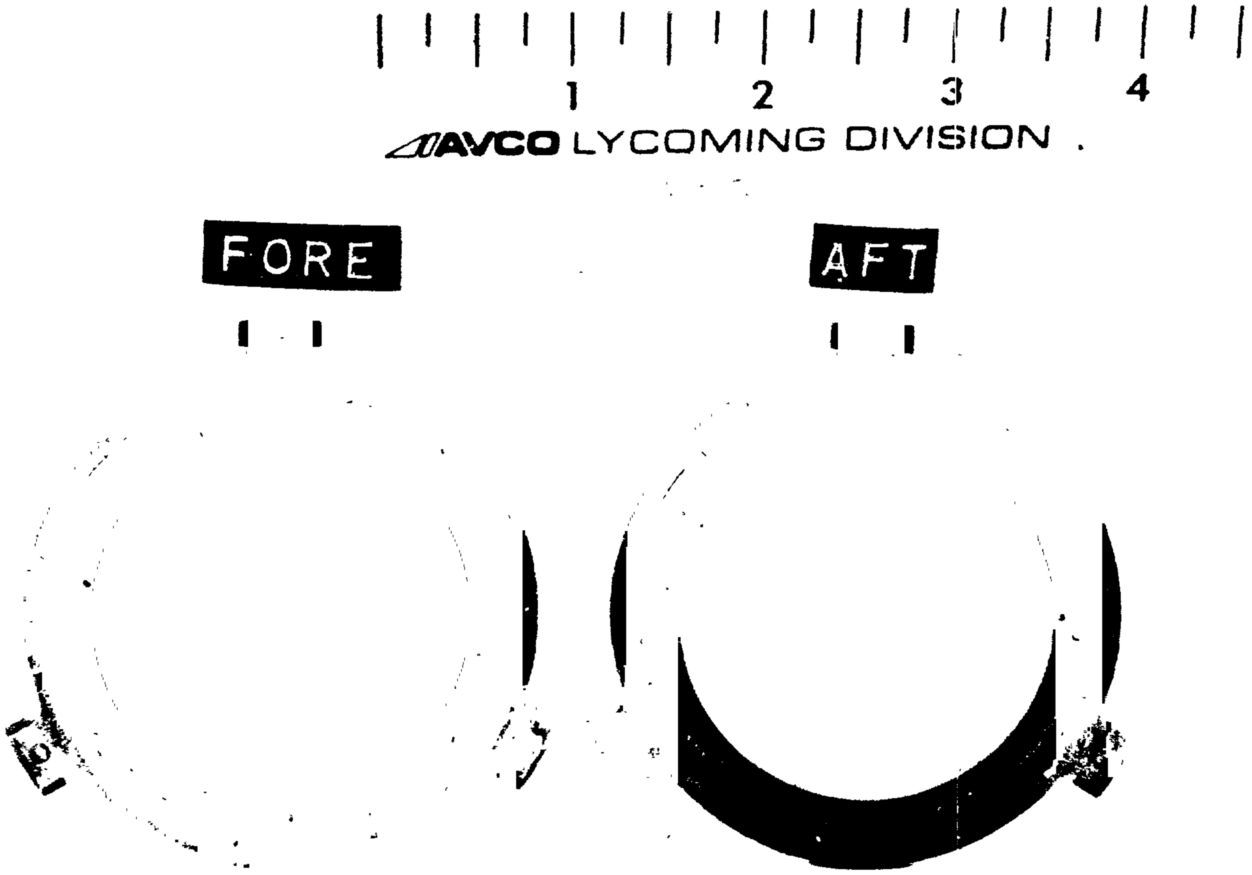


Figure 26. Self-Acting Face Seal, Backside of Carbon Nose After Test 8.

Test 9

New carbons and seats were used for Test 9. A two-hour check-out run was conducted. Table XIV lists test conditions and results.

At disassembly it was found that the aft seal had contacted the seat depositing some carbon. There was no wear on the forward carbon and an average of 0.0021 mm (0.000083 in.) on the aft (Table XV). Carbon deposits increased the aft seat waviness and flatness and the forward seat flatness (Table XVI).

Test 10

The same carbons and seats used in Test 9 were used in Test 10, a 31.50-hour endurance test. Table XVII lists test conditions and resulting airflows, cavity pressures, and seal temperatures.

Inspection following the test revealed the forward seal and seat to be in good condition (Table XV and XVI); however, the aft carbon was worn completely. Figures 27 an 28 illustrate carbon nose and seal seat condition following Test 10. The seals were coked and varnished as a result of high temperature operation. Figure 29 shows the back side of the carbon nose; Figure 30 illustrates the piston ring carrier and Figure 31 is a rear view of the seal assembly.

Conclusion

Throughout the testing of the self-acting face seal configuration,the aft seal exhibited more distress than the forward seal. In checking the flatness of the assembled seats, it was noted that the aft seat flatness generally was approximately 0.0015 mm (0.000060 in.); whereas, the forward seat flatness was approximately 0.001 mm (0.000040 in.). Prior to Tests 9 and 10, the aft seat flatness in the assembled state was found to be 0.002 mm (0.000080 in.), whereas the forward seat flatness was 0.0004 mm (0.000017 in.). The assembled flatness requirement was 0.0025 mm (0.00010 in.). Therefore, when operating at high speeds (183 m/s, 600 ft/sec) and high temperatures, flatness requirement should be a maximum of approximately 0.00125 mm (0.000050 in.).

TABLE XIV. SELF-ACTING FACE SEAL - TEST 9

Run	Speed (m/s)	Speed (ft/sec)	Speed (rpm)	Air Pressure (N/cm^2)	Air Pressure (psia)	Cavity Pressure (N/cm^2)	Cavity Pressure (psia)	Airflow (2 Seals) (kg/s)	Airflow (2 Seals) (scfm)	Airflow (2 Seals) (lb/sec)	Time (min)
1	91	300	27,300	34.3	49.7	12.9	18.7	0.0012	2.0	0.0027	15
2	122	400	36,400	34.3	49.7	12.9	18.7	0.0010	1.8	0.0023	15
3	152	500	45,500	34.3	49.7	12.9	18.7	0.0012	2.0	0.0025	15
4	183	600	54,600	34.3	49.7	18.4	26.7	0.0023	4.0	0.0051	15
5	91	300	27,300	147.9	214.7	18.4	26.7	0.0072	12.5	0.0159	15
6	122	400	36,400	147.9	214.7	20.5	29.7	0.0092	16	0.0204	15
7	152	500	45,500	147.9	214.7	21.8	31.7	0.0098	17	0.0217	15
8	183	600	54,600	147.9	214.7	22.5	32.7	0.0102	17.5	0.0223	15

Run	Fwd Seal Air Temp. (K)	Fwd Seal Air Temp. (°F)	Fwd Seal Temp. (K)	Fwd Seal Temp. (°F)	Aft Seal Air Temp. (K)	Aft Seal Air Temp. (°F)	Aft Seal Temp. (K)	Aft Seal Temp. (°F)
1	389	240	372	210	372	210	374	214
2	439	330	400	260	433	320	400	260
3	430	315	405	270	424	304	---	---
4	427	310	420	296	428	310	---	---
5	439	330	405	270	443	338	---	---
6	444	340	423	302	455	358	---	---
7	422	300	418	294	422	299	---	---
8	439	330	439	330	444	340	---	---

TABLE XV. CARBON LIFT PAD DEPTH (NEW AND TESTS 9 AND 10)

Test		New		9		10	
		(mm)	(in.)	(mm)	(in.)	(mm)	(in.)
Fwd Seal Pad	1	0.022	(0.000875)	0.022	(0.000825)	0.022	(0.000875)
	2	0.020	(0.0008)	0.020	(0.0008)	0.020	(0.0007)
	3	0.024	(0.00095)	0.024	(0.00095)	0.024	(0.00095)
	4	0.022	(0.00085)	0.022	(0.00085)	0.022	(0.00085)
Aft Seal Pad	1	0.019	(0.00075)	0.018	(0.000725)	-	-
	2	0.022	(0.00085)	0.020	(0.000775)	-	-
	3	0.016	(0.000625)	0.016	(0.000625)	-	-
	4	0.023	(0.0009)	0.019	(0.00075)	-	-

TABLE XVI. SEAL INSPECTION RESULTS (TESTS 9 AND 10)

Test		New	9	10
Fwd Seat				
Dam Area Roughness	(μm)	0.127	0.127	0.178
Waviness	(μm)	0.330	0.254	0.432
Flatness	(μm)	0.254	0.432	0.762
Aft Seat				
Dam Area Roughness	(μm)	0.127	0.152	0.635
Waviness	(μm)	0.305	0.635	10.15
Flatness	(μm)	0.279	1.397	13.98
Fwd. Seat				
Dam Area Roughness	(μin AA)	5	5	7
Waviness	(μin)	13	10	17
Flatness	(μin)	10	17	30
Aft Seat				
Dam Area Roughness	(μin AA)	5	6	25
Waviness	(μin)	12	25	400
Flatness	(μin)	11	55	500

TABLE XVII. 31.5-HOUR SELF-ACTING FACE SEAL ENDURANCE TEST - TEST 10

Run	Speed			Air Pressure		Cavity Pressure		Airflow (2 Seals)			Time
	(m/s)	(ft/sec)	(rpm)	(N/cm^2)	(psia)	(N/cm^2)	(psia)	(kg/s)	(scfm)	(lb/sec)	(min)
1	91	300	27,300	34.2	49.7	13.44	19.5	.00104	1.8	.00228	15
2	122	400	36,400	34.2	49.7	13.44	19.5	.00104	1.8	.00228	15
3	152	500	45,500	34.2	49.7	13.58	19.7	.00145	2.5	.00317	15
4	152	500	45,500	34.2	49.7	19.09	27.7	.00783	13.5	.01714	15
5	152	500	45,500	34.2	49.7	19.09	27.7	.00783	13.5	.01714	15
6	152	500	45,500	34.2	49.7	14.27	20.7	.00174	3.0	.00381	15
7	183	600	54,600	34.2	49.7	14.96	21.7	.00208	3.6	.00457	15
8	183	600	54,600	34.2	49.7	16.47	23.9	.00446	7.7	.00977	15
9	183	600	54,600	34.2	49.7	14.96	21.7	.00232	4.0	.00508	15
10	183	600	54,600	34.2	49.7	15.09	21.9	.00406	7.0	.00889	15
11	183	600	54,600	34.2	49.7	16.33	23.7	.00423	7.3	.00927	15
SHUTDOWN											
12	91	300	27,300	34.2	49.7	13.58	19.7	.00104	1.8	.00228	15
13	122	400	36,400	34.2	49.7	13.58	19.7	.00104	1.8	.00228	15
14	183	600	54,600	34.2	49.7	14.96	21.7	.00220	3.8	.00482	15
15	183	600	54,600	44.6	64.7	14.61	21.2	.00243	4.2	.00533	15
16	183	600	54,600	79.0	114.7	15.65	22.7	.00359	6.2	.00787	15
17	183	600	54,600	113.5	164.7	17.71	25.7	.00510	8.8	.01117	15
18	183	600	54,600	147.9	214.7	18.40	26.7	.00667	11.5	.01460	15
19	198	650	59,150	147.9	214.7	19.09	27.7	.00667	11.5	.01460	15
20	198	650	59,150	147.9	214.7	19.43	28.2	.00667	11.5	.01460	15
21	198	650	59,150	147.9	214.7	19.78	28.7	.00667	11.5	.01460	15
22	198	650	59,150	147.9	214.7	19.78	28.7	.00667	11.5	.01460	15
23	198	650	59,150	147.9	214.7	19.78	28.7	.00667	11.5	.01460	15
24	198	650	59,150	147.9	214.7	19.78	28.7	.00667	11.5	.01460	15
25	198	650	59,150	147.9	214.7	19.78	28.7	.00754	13	.01651	15
26	198	650	59,150	147.9	214.7	20.47	29.7	.00754	13	.01651	15
27	198	650	59,150	147.9	214.7	20.47	29.7	.00754	13	.01651	15
28	198	650	59,150	147.9	214.7	19.78	28.7	.00754	13	.01651	15
29	91	300	27,300	34.2	49.7	13.58	19.7	.00127	2.2	.00275	15
30	122	400	36,400	34,2	49.7	13.58	19.7	.00133	2.3	.00292	15

TABLE XVII - Continued

Run	Speed			Air Pressure		Cavity Pressure		Airflow (2 Seals)			Time
	(m/s)	(ft/sec)	(rpm)	(N/cm^2)	(psia)	(N/cm^2)	(psia)	(kg/s)	(scfm)	(lb/sec)	(min)
31	152	500	45,500	34.2	49.7	13.72	19.9	.00127	2.2	.00275	15
32	183	600	54,600	34.2	49.7	14.27	20.7	.00145	2.5	.00317	15
33	183	600	54,600	79.0	114.7	16.33	23.7	.00417	7.2	.00914	15
34	183	600	54,600	113.5	164.7	18.40	26.7	.00638	11.0	.01397	15
35	183	600	54,600	147.9	214.7	21.16	30.7	.00870	15	.01905	15
36	183	600	54,600	147.9	214.7	20.47	29.7	.00754	13	.01651	15
37	183	600	54,600	147.9	214.7	19.78	28.7	.00754	13	.01651	15
38	183	600	54,600	147.9	214.7	19.09	27.7	.00725	12.5	.01587	15
39	183	600	54,600	147.9	214.7	19.09	27.7	.00696	12	.01524	15
40	183	600	54,600	147.9	214.7	19.09	27.7	.00696	12	.01524	15
SHUTDOWN											
41	91	300	27,300	34.2	49.7	13.58	19.7	.00104	1.8	.00228	15
42	183	600	54,600	147.9	214.7	19.78	28.7	.00696	12	.01524	15
43	183	600	54,600	147.9	214.7	19.09	27.7	.00696	12	.01524	15
44	198	650	59,150	147.9	214.7	19.78	28.7	.00725	12.5	.01587	15
45	198	650	59,150	147.9	214.7	20.47	29.7	.00783	13.5	.01714	15
46	198	650	59,150	147.9	214.7	20.47	29.7	.00783	13.5	.01714	15
47	198	650	59,150	147.9	214.7	20.47	29.7	.00783	13.5	.01714	15
48	198	650	59,150	147.9	214.7	20.47	29.7	.00812	14	.01778	15
49	198	650	59,150	147.9	214.7	20.47	29.7	.00783	13.5	.01714	15
50	198	650	59,150	147.9	214.7	20.47	29.7	.00783	13.5	.01714	15
51	198	650	59,150	147.9	214.7	20.47	29.7	.00783	13.5	.01714	15
52	198	650	59,150	147.9	214.7	20.47	29.7	.00783	13.5	.01714	15
53	198	650	59,150	147.9	214.7	20.47	29.7	.00783	13.5	.01714	15
54	198	650	59,150	147.9	214.7	20.47	29.7	.00783	13.5	.01714	15
55	198	650	59,150	147.9	214.7	20.47	29.7	.00783	13.5	.01714	15
56	198	650	59,150	147.9	214.7	20.47	29.7	.00783	13.5	.01714	15
57	198	650	59,150	147.9	214.7	20.82	30.2	.00817	14	.01778	15
58	91	300	27,300	44.6	64.7	14.27	20.7	.00185	3.2	.00406	15
59	122	400	36,400	44.6	64.7	14.27	20.7	.00174	3	.00381	15
60	152	500	45,500	44.6	64.7	14.61	21.2	.00208	3.6	.00457	15
61	183	600	54,600	44.6	64.7	14.91	21.7	.00232	4	.00508	15

TABLE XVII - Continued

Run	Speed			Air Pressure		Cavity Pressure		Airflow (2 Seals)			Time
	(m/s)	(ft/sec)	(rpm)	(N/cm^2)	(psia)	(N/cm^2)	(psia)	(kg/s)	(scfm)	(lb/sec)	(min)
62	183	600	54,600	79.0	114.7	16.33	23.7	.00417	7.2	.00914	15
63	183	600	54,600	113.5	164.7	18.40	26.7	.00667	11.5	.01460	15
64	183	600	54,600	147.9	214.7	21.16	30.7	.00841	14.5	.01841	15
65	198	650	59,150	147.9	214.7	20.82	30.2	.00841	14.5	.01841	15
66	198	650	59,150	147.9	214.7	21.16	30.7	.00870	15	.01905	15
67	198	650	59,150	147.9	214.7	20.47	29.7	.00812	14	.01778	15
68	198	650	59,150	147.9	214.7	19.78	28.7	.01102	13	.02413	15
69	198	650	59,150	147.9	214.7	20.47	29.7	.01102	13	.02413	15
					SHUTDOWN						
70	91	300	27,300	34.2	49.7	14.27	20.7	.00162	2.8	.00355	15
71	91	300	27,300	34.2	49.7	13.92	20.2	.00162	2.8	.00355	15
72	152	500	45,500	113.5	49.7	13.92	20.2	.00174	3.0	.00381	15
73	198	650	59,150	147.9	164.7	13.92	[illegible]	.00580	10.0	.01270	15
74	198	650	59,150	147.9	214.7	18.40	[illegible]	.00754	13.0	.01651	15
75	198	650	59,150	147.9	214.7	20.47	29.7	.00754	13.0	.01651	15
76	198	650	59,150	147.9	214.7	20.47	29.7	.00783	13.5	.01714	15
77	198	650	59,150	147.9	214.7	20.47	29.7	.00783	13.5	.01714	15
78	198	650	59,150	147.9	214.7	20.47	29.7	.00783	13.5	.01714	15
79	198	650	59,150	147.9	[illegible]	20.47	29.7	.00783	13.5	.01714	15
80	198	650	59,150	147.9	[illegible]	20.47	29.7	.00754	13.0	.01651	15
81	198	650	59,150	147.9	214.7	20.47	29.7	.00754	13.0	.01651	15
82	198	650	59,150	147.9	214.7	20.47	29.7	.00754	13.0	.01651	15
83	198	650	59,150	147.9	214.7	20.47	29.7	.00754	13.0	.01651	15
84	198	650	59,150	147.9	214.7	20.47	29.7	.00754	13.0	.01651	15
85	198	650	59,150	147.9	214.7	20.47	29.7	.00812	14.0	.01778	15
86	198	650	59,150	147.9	214.7	20.47	29.7	.00754	13.0	.01651	15
87		650	59,150	147.9	214.7	20.47	29.7	.00783	13.5	.01714	15
88	91	300	27,300	79.0	114.7	15.65	29.7	.00365	6.3	.00800	15
89	122	400	36,400	79.0	114.7	15.65	22.7	.00365	6.3	.00800	15
90	152	500	45,500	79.0	114.7	15.99	22.7	.00377	6.5	.00825	15
91	152	500	45,500	79.0	114.7	15.99	23.2	.00365	6.3	.00800	15
92	152	500	45,500	79.0	114.7	15.99	23.2	.00348	6.0	.00762	15

TABLE XVII - Continued

	Speed			Air Pressure		Cavity Pressure		Airflow (2 Seals)			Time
Run	(m/s)	(ft/sec)	(rpm)	(N/cm^2)	(psia)	(N/cm^2)	(psia)	(kg/s)	(scfm)	(lb/sec)	(min)
93	152	500	45,500	79.0	114.7	15.99	23.2	.00348	6.0	.00762	15
94	152	500	45,500	79.0	114.7	15.99	23.2	.00324	5.6	.00711	15
95	152	500	45,500	79.0	114.7	15.99	23.2	.00330	5.7	.00723	15
96	152	500	45,500	79.0	114.7	15.99	23.2	.00348	6.0	.00762	15
97	152	500	45,500	79.0	114.7	15.99	23.2	.00348	6.0	.00762	15
98	91	300	27,300	34.2	49.7	13.58	19.7	.00145	2.5	.00717	15
99	152	500	45,500	34.2	49.7	13.58	19.7	.00138	2.4	.00304	15
100	152	500	45,500	79.0	114.7	15.65	22.7	.00348	6.0	.00762	15
101	152	500	45,500	79.0	114.7	15.30	22.2	.00348	6.0	.00762	15
102	183	600	54,600	79.0	114.7	15.65	22.7	.00377	6.5	.00825	15
103	183	600	54,600	113.5	164.7	17.71	25.7	.00551	9.5	.01206	15
104	183	600	54,600	147.9	214.7	21.16	30.7	.00812	14.0	.01718	15
105	198	650	59,150	147.9	214.7	21.16	30.7	.00812	14.0	.01778	15
106	198	650	59,150	147.9	214.7	20.47	29.7	.00783	13.5	.01714	15
107	198	650	59,150	147.9	214.7	20.82	30.2	.00812	14.0	.01778	15
108	198	650	59,150	147.9	214.7	21.16	30.7	.00841	14.5	.01841	15
109	198	650	59,150	147.9	214.7	21.16	30.7	.00841	14.5	.01841	15
110	198	650	59,150	147.9	214.7	21.16	30.7	.00841	14.5	.01841	15
111	198	650	59,150	147.9	214.7	21.85	31.7	.00841	14.5	.01841	15
112	198	650	59,150	147.9	214.7	22.54	32.7	.00841	14.5	.01841	15
113	198	650	59,150	147.9	214.7	22.54	32.7	.00870	15.0	.01905	15
114	198	650	59,150	147.9	214.7	22.54	32.7	.00928	16.0	.02032	15
115	198	650	59,150	147.9	214.7	23.23	33.7	.00957	16.5	.02095	15
116	198	650	59,150	147.9	214.7	23.23	33.7	.00957	16.5	.02095	15
117	91	300	27,300	34.2	49.7	13.58	19.7	.00116	2.0	.00254	15
118	122	400	36,400	34.2	49.7	13.58	19.7	.00116	2.0	.00254	15
119	152	500	45,500	34.2	49.7	13.58	19.7	.00121	2.1	.00266	15
120	183	600	54,600	34.2	49.7	13.58	19.7	.00116	2.0	.00254	15
121	183	600	54,600	34.2	49.7	13.58	19.7	.00134	2.4	.00304	15

TABLE XVII - Continued

	Speed			Air Pressure		Cavity Pressure		Airflow (2 Seals)			Time
Run	(m/s)	(ft/sec)	(rpm)	(N/cm^2)	(psia)	(N/cm^2)	(psia)	(kg/s)	(scfm)	(lb/sec)	(min)
122	183	600	54,600	34.2	49.7	13.58	19.7	.00139	2.4	.00304	15
123	183	600	54,600	34.2	49.7	13.92	20.2	.00139	2.4	.00304	15
124	183	600	54,600	34.2	49.7	13.92	20.2	.00145	2.5	.00317	15
125	183	600	54,600	34.2	49.7	13.92	20.2	.00145	2.5	.00317	15
126	183	600	54,600	34.2	49.7	13.92	20.2	.00145	2.5	.00317	15

	Fwd Air Temp		Fwd Seal Temp		Aft Air Temp		Aft Seal Temp	
Run	(K)	(°F)	(K)	(°F)	(K)	(°F)	(K)	(°F)
1	366	200	370.8	208	358.6	186	364	196
2	386	235	379.4	224	381.8	228	372	210
3	400	260	---	---	400	260	383	230
4	400	260	396.4	254	400	260	469.6	386
5	383	230	---	---	281.8	228	462	372
6	386	235	---	---	379.4	224	400	260
7	416	290	---	---	406.2	272	426	308
8	439	330	---	---	427	310	469.4	386
9	450	350	---	---	446.4	344	474.5	395
10	455	360	---	---	452	354	487.8	418
11	466	380	---	---	462	372	528.2	492
			SHUTDOWN					
12	411	280	384.2	232	405	270	406.2	272
13	444	340	401	262	440	332	426	308
14	466	380	427	310	465	373	479.4	404
15	494	430	437.8	328	484.2	412	502	444
16	566	560	479.4	404	565	558	535.4	504
17	550	530	487.8	418	553	536	518.4	474
18	583	590	508.6	456	586.6	596	556.2	542
19	611	640	530.6	496	622	660	563	554
20	622	660	538.4	509	635.4	684	577	580
21	622	660	536.6	506	637.8	688	576	578
22	622	660	536.6	506	639.0	690	580.6	586
23	622	660	536.6	506	639.0	690	581.8	588
24	622	660	536.6	506	639.0	690	583	590
25	624.5	665	536	505	639.0	690	605	630
26	624.5	665	536	505	639.0	690	594	610
27	622	660	534.2	502	639.0	690	578.2	582
28	622	660	537.8	508	639.0	690	577	580

Table: TABLE XVII - Continued

TABLE XVII - Continued

Run	Fwd Air Temp (K)	Fwd Air Temp (°F)	Fwd Seal Temp (K)	Fwd Seal Temp (°F)	Aft Air Temp (K)	Aft Air Temp (°F)	Aft Seal Temp (K)	Aft Seal Temp (°F)
29	455	360	390	242	375	216	400	260
30	450	350	394	250	383	230	409.8	278
31	427	310	404	268	384.2	232	435.4	324
32	472	390	423	306	474	394	466	380
33	427	310	417.2	292	405	270	---	364
34	422	300	425	306	418.4	294	483	410
35	422	300	428.2	312	419.6	296	275	396
36	461	370	450	350	469.6	386	403	410
37	489	420	463	374	502	444	492	426
38	522	480	483	410	552	514	516	470
39	533	500	489	420	557.4	544	518.4	474
40	574.5	575	504	448	602	624	540.0	512
			SHUTDOWN					
41	439	330	387.8	238	430.6	316	400	260
42	527	490	485.4	414	550	530	539	510
43	594	610	506.2	452	605	630	566	560
44	616	650	530.6	496	631.8	678	611	640
45	622	660	539	510	693	698	601	622
46	644	700	544	520	657.4	724	612	642
47	644	700	540	512	661	730	600	620
48	627	670	536.6	506	648.8	708	594	610
49	644	700	544	520	656.2	722	602	624
50	644	700	544	520	659.8	728	602	624
51	639	690	546.4	524	657.4	724	601	622
52	641.5	695	547.6	526	658.6	726	597.6	616
53	641.5	695	544	520	656.8	723	594.6	611
54	639	690	543	518	658	725	592	606
55	641.5	695	543	518	658.6	726	590.5	603
56	644	700	541	516	658.6	726	592	606

TABLE XVII - Continued

Run	Fwd Air Temp (K)	Fwd Air Temp (°F)	Fwd Seal Temp (K)	Fwd Seal Temp (°F)	Aft Air Temp (K)	Aft Air Temp (°F)	Aft Seal Temp (K)	Aft Seal Temp (°F)
57	644	700	541	516	657.4	724	594	608
58	411	280	375	216	373	194	391	244
59	450	350	327.8	238	376	218	400	260
60	436	325	401	262	379.4	224	430.6	316
61	433	320	412	282	387.8	238	[illegible]	370
62	444	340	417.2	292	417.2	292	[illegible]	360
63	463.5	375	436.6	326	445.2	342	489	420
64	466	380	448.4	348	472	390	511	460
65	494	430	481.8	408	530.6	496	537.8	508
66	516	470	483	410	528.2	492	565	558
67	566	560	500	440	537	580	566	560
68	589	600	511	460	602	624	570.8	568
69	600	620	514	466	606.2	632	561	550
70	427	310	381.8	228	430.6	316	391	244
71	539	510	403	266	494	430	407.4	274
72	516	470	424	304	511	460	448.8	348
73	572	570	491.5	425	552	534	558	545
74	572	570	509.8	458	593	608	576	578
75	572	570	523	482	622	660	600	620
76	605	630	524	484	627	670	572	570
77	605	630	522	480	628.2	672	572	570
78	605	630	522	480	629.4	674	569.5	566
79	605	630	516	470	628.2	672	559.8	548
80	605	630	527	490	633	680	572	570
81	605	630	525	486	631.2	677	566	560
82	605	630	523.5	483	631.8	678	566	560

TABLE XVII - Continued

Run	Fwd Air Temp (K)	Fwd Air Temp (°F)	Fwd Seal Temp (K)	Fwd Seal Temp (°F)	Aft Air Temp (K)	Aft Air Temp (°F)	Aft Seal Temp (K)	Aft Seal Temp (°F)
83	605	630	524.5	485	631.2	678	566	560
84	605	630	524	484	631.8	678	566	560
85	605	630	525	486	632.4	679	567.2	562
86	611	640	529.4	494	634.2	682	568.4	564
87	611	640	530	495	635.4	684	568.4	564
88	461	370	392	246	383	230	408.6	276
89	444	340	327	130	376.5	219	424	304
90	427	310	390	242	377	220	431.2	318
91	433	320	401	262	414	286	433	320
92	477	400	415	288	451	352	442	336
93	505	450	429.4	314	500	440	453	356
94	550	530	436.6	326	547.6	526	467.2	383
95	563.5	555	433	320	566	560	475	396
96	589	600	---	---	596.4	614	497.6	436
97	616	650	---	---	617.2	652	506.2	452
			SHUTDOWN					
98	500	440	377	220	426	408	405	270
99	533	500	425	306	544	520	464	376
100	616	650	489	420	617.2	652	526	488
101	622	660	481.8	408	639	690	522	480
102	644	700	493	428	651	712	566	560
103	644	700	500	440	624	664	556.2	542
104	616	650	500	440	635.4	684	566	560
105	627	670	495.2	432	652	714	604	628
106	639	690	509.8	458	661	730	600	620
107	644	700	487.8	418	666	740	606.2	632
108	639	690	480.6	406	666	740	605	630
109	639	690	524	484	---	740	604	628

TABLE XVII - Continued

Run	Fwd Air Temp		Fwd Seal Temp		Aft Air Temp		Aft Seal Temp	
	(K)	(°F)	(K)	(°F)	(K)	(°F)	(K)	(°F)
110	639	690	525	486	666	740	604	628
111	627	670	519	475	655.6	721	594.6	611
112	633	680	517.2	472	661	730	598.2	617
113	633	680	483	410	662	732	600	620
114	633	680	515	468	662	732	600	620
115	633	680	522	480	662	732	600	620
116	633	680	---	---	661	730	602.5	625
117	424.5	305	357.4	184	358.6	186	407.4	274
118	422	300	357.4	184	346.4	164	419.6	296
119	611	640	---	---	363	194	422	300
120	422	300	---	---	377	220	453	356
121	447	345	380.6	226	397.6	256	457.4	364
122	461	370	389	240	450	350	464	376
123	477	400	396.4	254	457.4	364	467.2	382
124	522	480	401	262	533	500	481.8	408
125	527	490	416.8	288	534.2	502	486	415.
126	536	505	420.8	298	546.4	524	489	420

End of Test

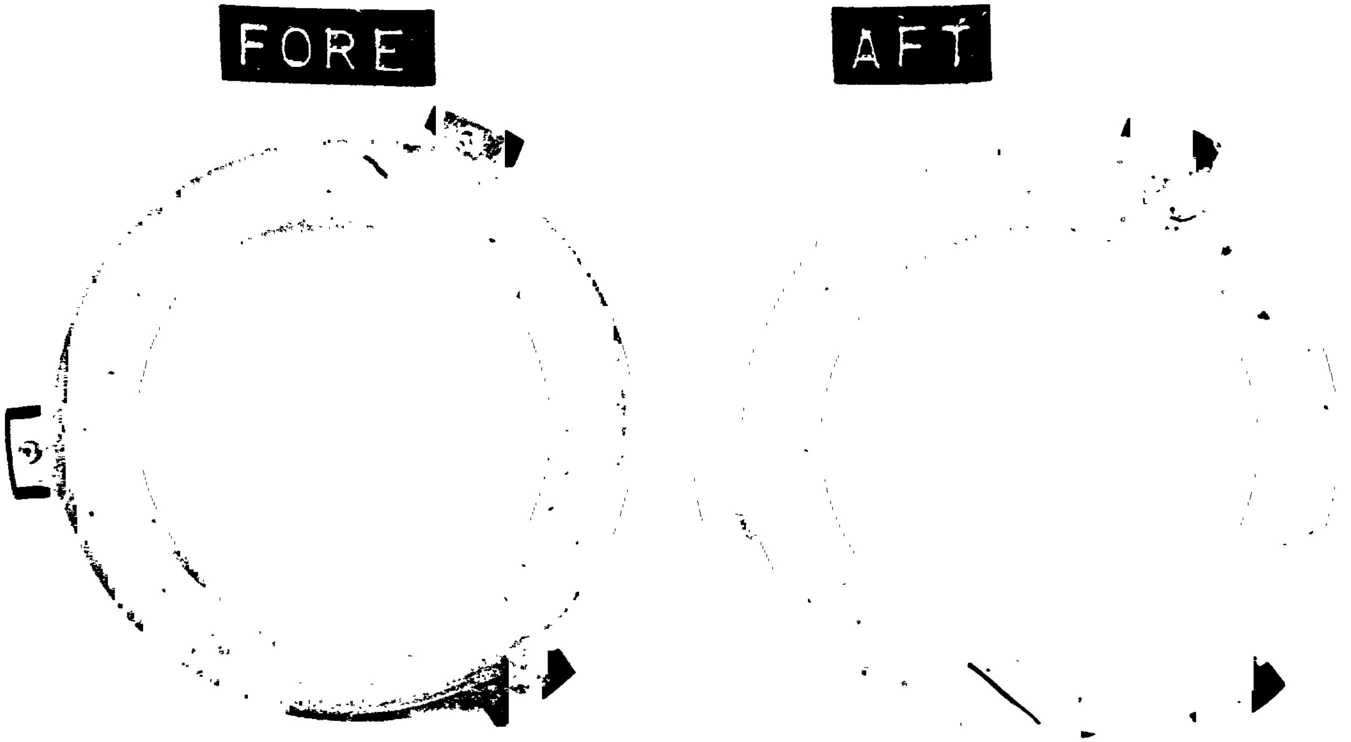


Figure 27. Self-Acting Face Seal, Carbon Nose Condition After Test 10.

Figure 28. Self-Acting Face Seal, Seat Condition After Test 10.

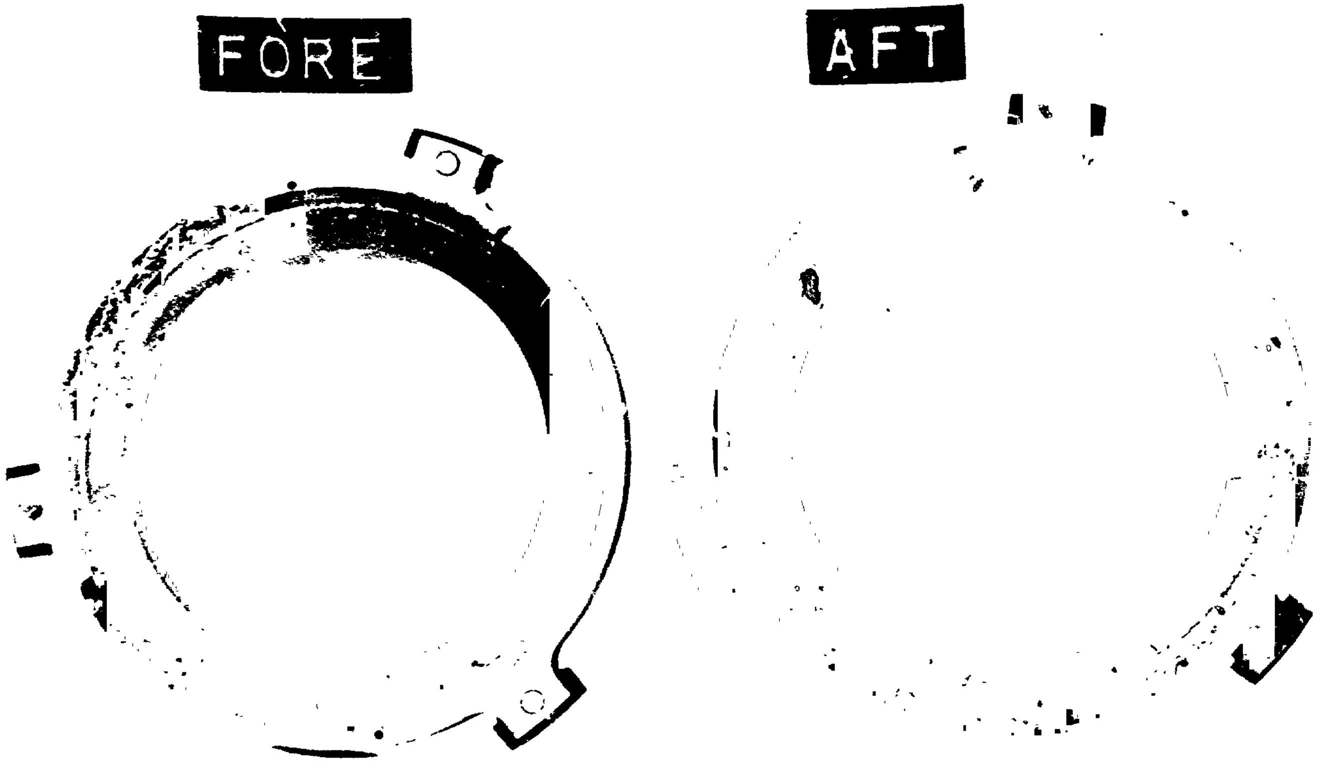


Figure 29. Self-Acting Face Seal, Backside of Carbon Nose After Test 10.

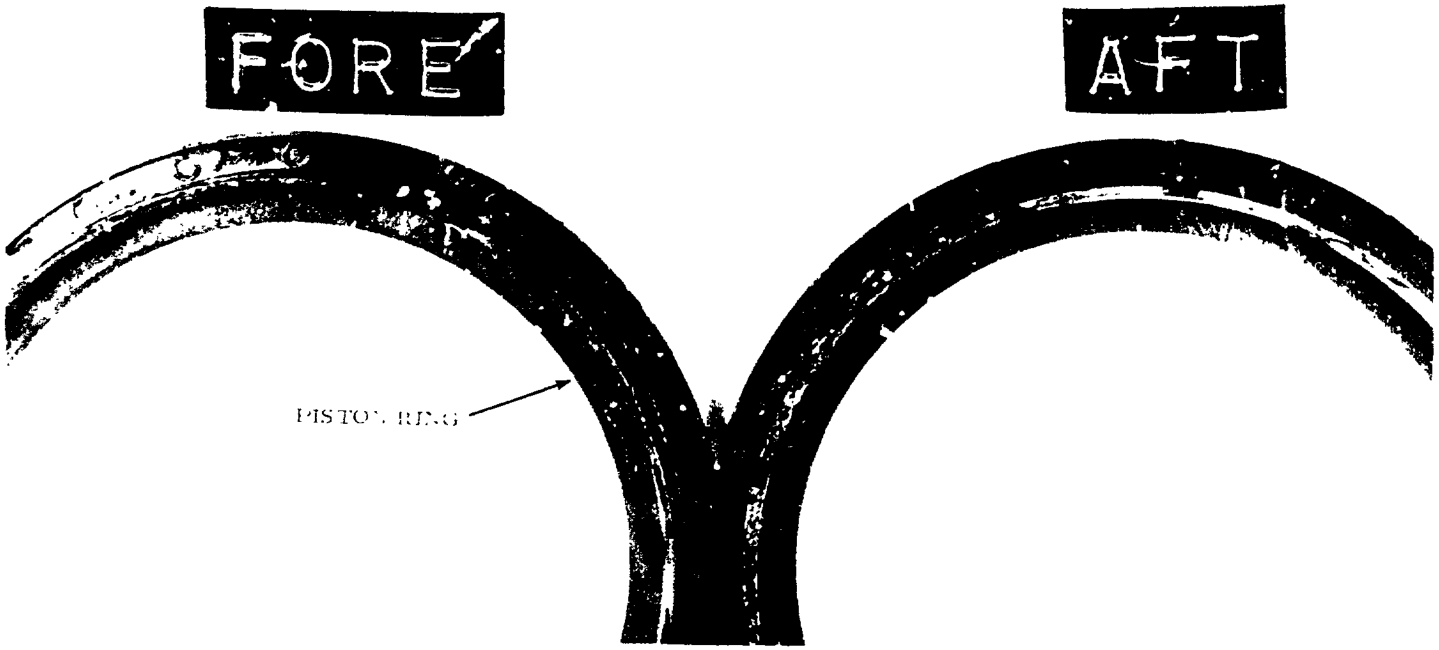


Figure 30. Self-Acting Face Seal , Piston Ring Carrier After Test 10.

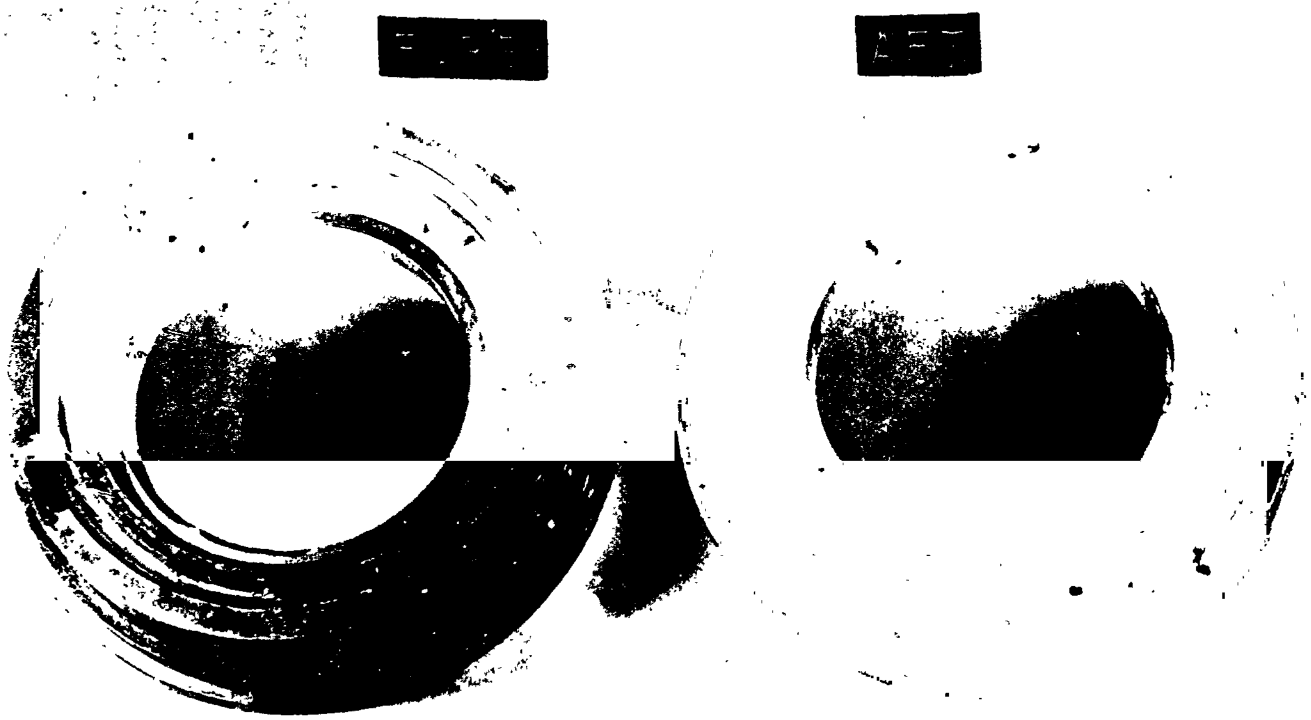


Figure 31. Self-Acting Face Seal, Rear View After Test 10.

Self-Acting Circumferential Seal Design

The self-acting circumferential seal configuration (Figure 32) is similar to a conventional circumferential seal with the addition of self-acting geometry on the carbon bore for lift augmentation. A detail of a carbon segment illustrating the self-acting geometry is shown in Figure 33.

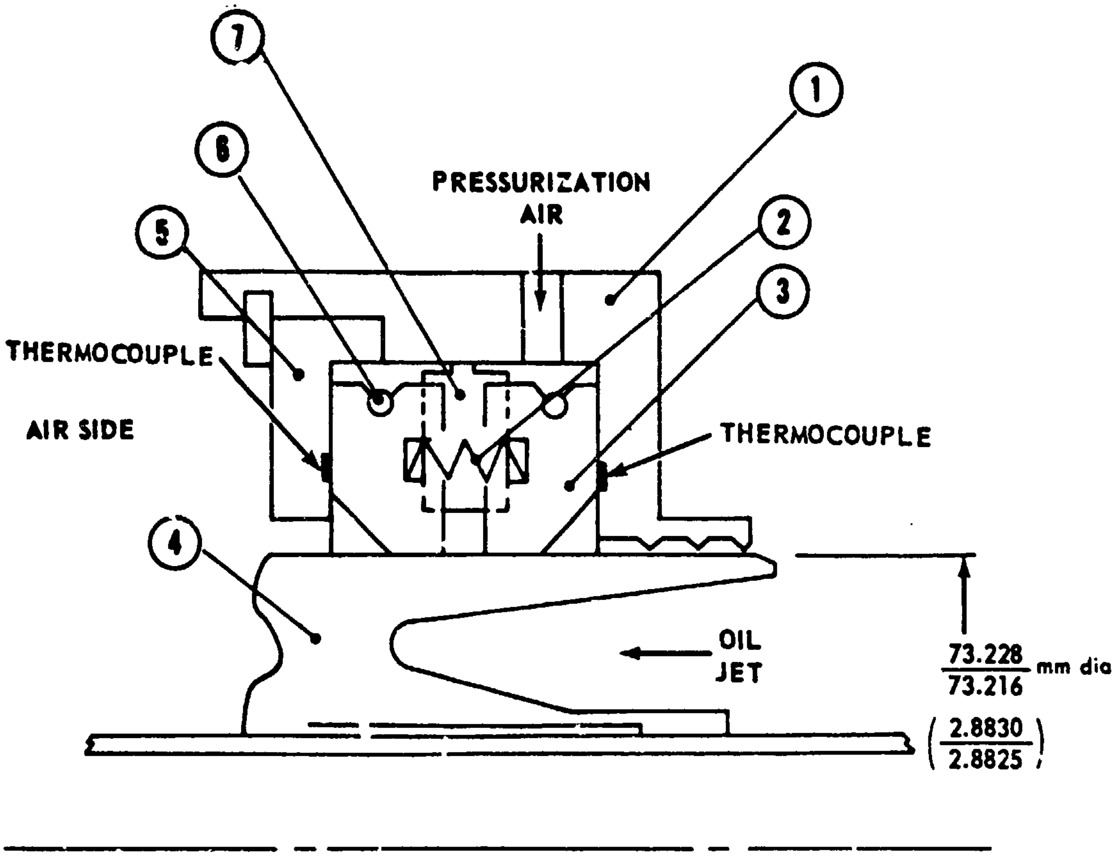
The seal is internally pressurized with two rings, made up of three carbon segments each, comprising the sealing elements. The segment joints are overlapped, and an antirotation lock in the center of the seal prevents the segments from turning with the shaft.

In a previous test program (Reference 1), it was determined that the self-acting geometry generated insufficient lift force. Figure 34 illustrates this lift pad geometry (5 pads for each segment). Design of the pad was changed to that shown in Figure 33 for the testing of the self-acting circumferential seal (4 pads for each segment). Analysis indicated that a 4-pad design produced more lift force than a 5-pad design.

Results

Initially, eight evaluation tests were conducted over a range of speeds and internal air pressures at ambient air temperatures. Test conditions and resulting airflows and carbon temperatures are listed in Table XVIII. Because the air pressure in the cavities on the air-side of the seals was 37.7 to 44.6 N/cm^2 (54.7 to 64.7 psia), the pressure drop across the oil-side carbons was greater than across the air-side carbons. This can be seen in the temperature data shown in Table XVIII where the oil-side carbons ran hotter than the air-side carbons. Figures 35 and 36 summarize the airflow and temperature data of the eight evaluation tests.

Measurements after each test consisted of Proficorder traces across a center lift pad of each carbon segment, axial carbon thickness measurements, Proficorder traces of runner roughness, and Indi-Ron traces of runner roundness. Initial lift-pad depths varied from 0.0014 to 0.019 mm (0.00055 to 0.00075 in.).



1. SEAL CASE	18-8 STAINLESS STEEL
2. COMPRESSION SPRING	INCONEL X
3. CARBON SEGMENT	HIGH-TEMPERATURE CARBON
4. RUNNER	AMS 6382 FLAME SPRAYED WITH LCIC CHROME CARBIDE
5. SEALING PLATE	18-8 STAINLESS STEEL
6. GARTER SPRING	INCONEL X .71 N (.159 lb)
7. ANTIROTATION LOCK	18-8 STAINLESS STEEL

Figure 32. Self-Acting Circumferential Seal.

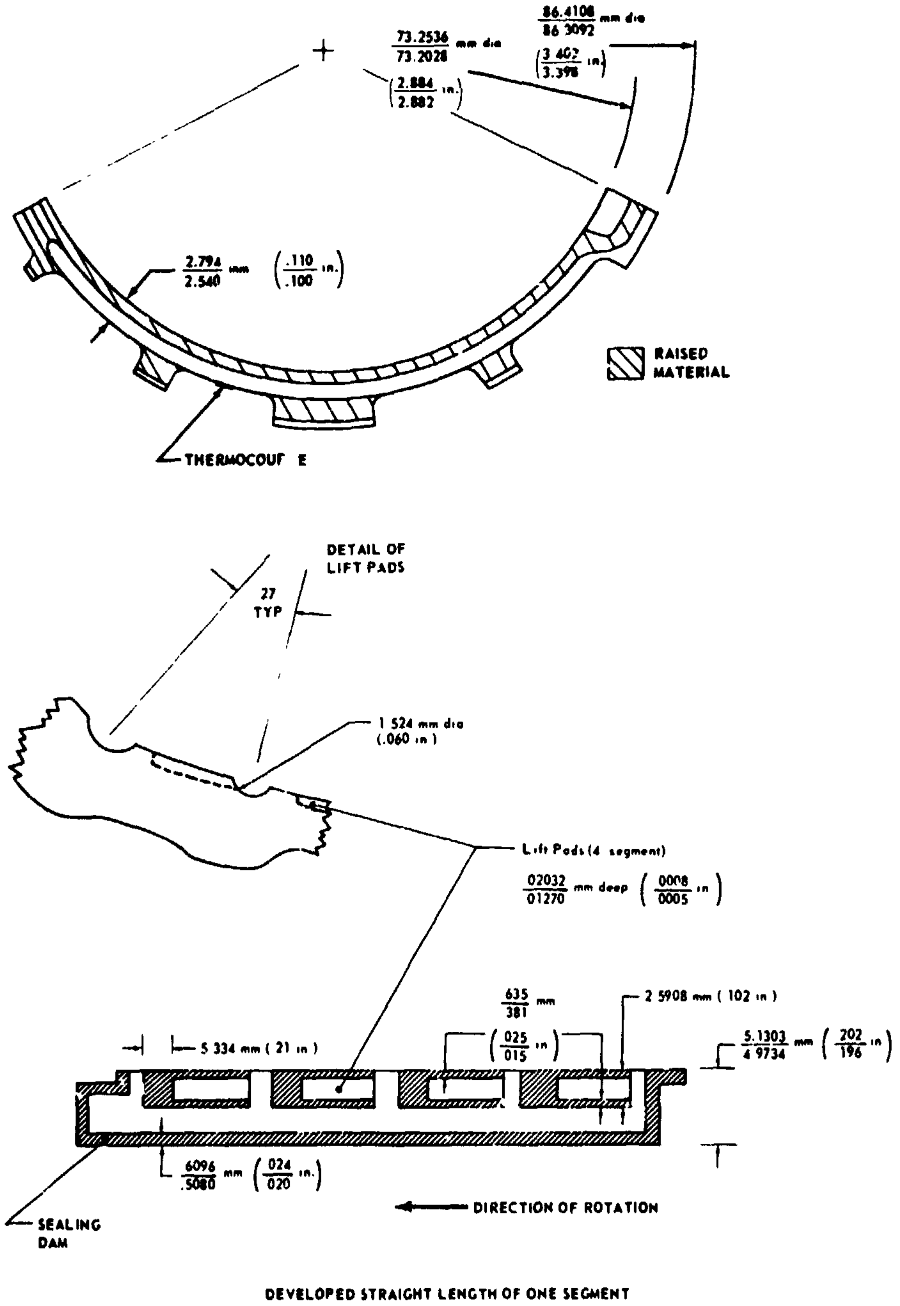


Figure 33. Self-Acting Circumferential Seal Details of Carbon Segment.

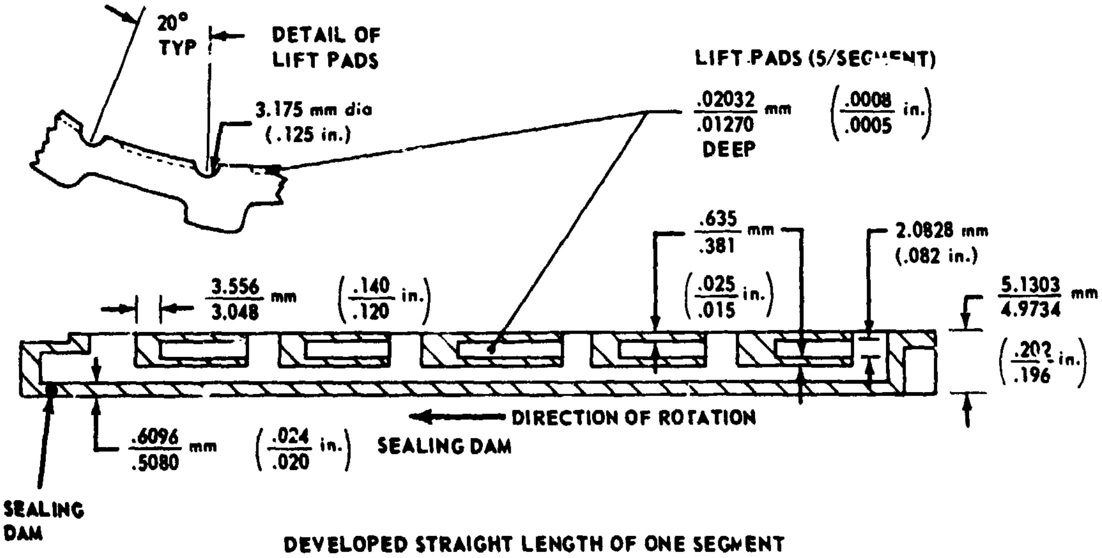


Figure 34. Previous Self-Acting Circumferential Seal Lift Pad Geometry.

TABLE XVIII. SELF-ACTING CIRCUMFERENTIAL SEAL EVALUATION TEST RESULTS

		Speed			Maximum Pressure Differential Oil side	Maximum Pressure Differential Carbons	Max. Airflow Through Two Seals		
Test	Hours	m/s	ft/sec	rpm	N/cm^2	psi	kg/s	scfm	lb/sec
1	3	91	300	23,900	34	49	0.0007	1.2	0.0015
2	1.0	91	300	23,900	34	49	0.0009	1.5	0.0019
	4.0	122	400	31,800	34	49	0.0009	1.6	0.0020
3	1.0	91	300	23,900	25	36	0.0008	1.4	0.0018
	1.0	122	400	31,800	33	48	0.0009	1.6	0.0020
	3.0	152	500	40,000	33	48	0.0010	1.7	0.0022
4	0.5	91	300	23,900	34	49	0.0007	1.2	0.0015
	0.5	122	400	31,800	34	49	0.0007	1.2	0.0015
	1	152	500	40,000	34	49	0.0008	1.3	0.0017
	1	183	600	47,700	23	34	0.0006	1.0	0.0013
	1.25	183	600	47,700	34	49	0.0008	1.3	0.0017
5	0.5	91	300	23,900	34	49	0.0007	1.2	0.0015
	4.5	91	300	23,900	50	73	0.0010	1.7	0.0022
6	0.5	91	300	23,900	34	49	------	---	------
	1.0	91	300	23,900	51	74	------	---	------
	0.5	91	300	23,900	34	49	0.0009	1.5	0.0019
	0.5	91	300	23,900	51	74	0.0012	2.0	0.0025
	4.5	122	400	31,800	50	73	0.0012	2.0	0.0025

TABLE XVIII - Continued

Test	Hours	Speed			Maximum Pressure Differential		Max. Airflow Through Two Seals		
					Oilside	Carbons			
		m/s	ft/sec	rpm	N/cm^2	psi	kg/s	scfm	lb/sec
7	0.25	91	300	23,900	34	49	0.0009	1.5	0.0019
	0.25	91	300	23,900	51	74	0.0012	2.0	0.0025
	0.50	122	400	31,800	50	73	0.0012	2.0	0.0025
	4.0	152	500	40,000	50	73	0.0012	2.1	0.0027
8	0.25	91	300	23,900	50	73	0.0010	1.8	0.0023
	0.25	122	400	31,800	50	73	0.0010	1.8	0.0023
	0.5	152	500	40,000	50	73	0.0010	1.8	0.0023
	4.0	183	600	47,700	50	72	0.0010	1.7	0.0022

TABLE XVIII - Continued

					Max. Seal Carbon Temperature							
					Fwd Seal				Aft Seal			
		Speed			Airside		Oilside		Airside		Oilside	
Test	Hours	m/s	ft/sec	rpm	K	°F	K	°F	K	°F	K	°F
1	3	91	300	23,900	---	---	---	---	---	---	---	---
2	1	91	300	23,900	388	238	422	300	377	218	396	252
	4	122	400	31,800	410	278	449	348	396	254	417	290
3	1	91	300	23,900	392	246	426	306	366	196	---	---
	1	122	400	31,800	410	278	452	354	389	240	---	---
	3	152	500	40,000	434	320	483	410	413	284	---	---
4	0.5	91	300	23,900	387	236	426	296	371	207	391	244
	0.5	122	400	31,800	396	262	438	328	386	234	406	270
	1	152	500	40,000	422	300	471	388	402	264	423	302
	1	183	600	47,700	433	318	488	418	413	284	435	322
	1.25	183	600	47,700	448	346	495	430	421	297	437	326
5	0.5	91	300	23,900	374	214	400	260	359	186	377	218
	4.5	91	300	23,900	411	280	435	322	390	242	405	268
6	0.5	91	300	23,900	378	220	399	258	372	226	384	230
	1.0	91	300	23,900	411	280	441	333	388	239	407	272
	0.5	91	300	23,900	409	276	440	332	376	216	398	256
	0.5	91	300	23,900	409	276	436	325	372	226	402	264
	4.5	122	400	31,800	445	340	485	414	396	252	415	286

TABLE XVIII - Continued

					Max. Seal Carbon Temperature							
					Fwd Seal				Aft Seal			
		Speed			Airside		Oilside		Airside		Oilside	
Test	Hours	m/s	ft/sec	rpm	K	°F	K	°F	K	°F	K	°F
7	0.25	91	300	23,900	370	205	391	244	360	188	378	220
	0.25	91	300	23,900	397	254	423	302	380	224	400	260
	0.5	122	400	31,800	422	299	465	376	392	245	412	282
	4.0	152	500	40,000	389	330	485	414	407	272	428	310
8	0.25	91	300	23,900	372	210	386	234	373	212	298	256
	0.25	122	400	31,800	396	254	418	292	386	234	408	274
	0.5	152	500	40,000	418	294	445	341	399	258	422	300
	4.0	183	600	47,700	456	360	498	416	432	317	451	351

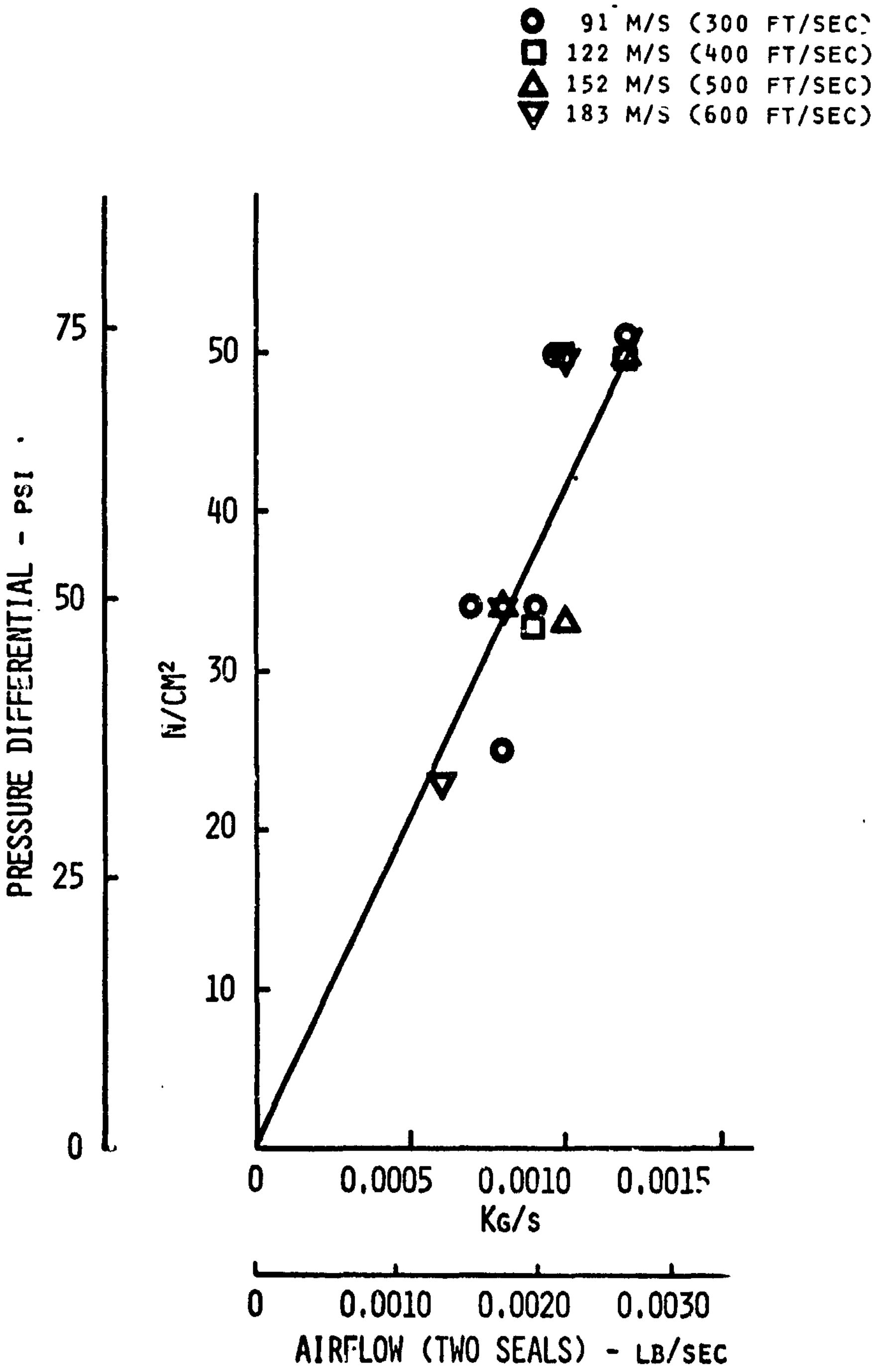


Figure 35. Airflow Through Two Self-Acting Circumferential Seals Versus Pressure Differential.

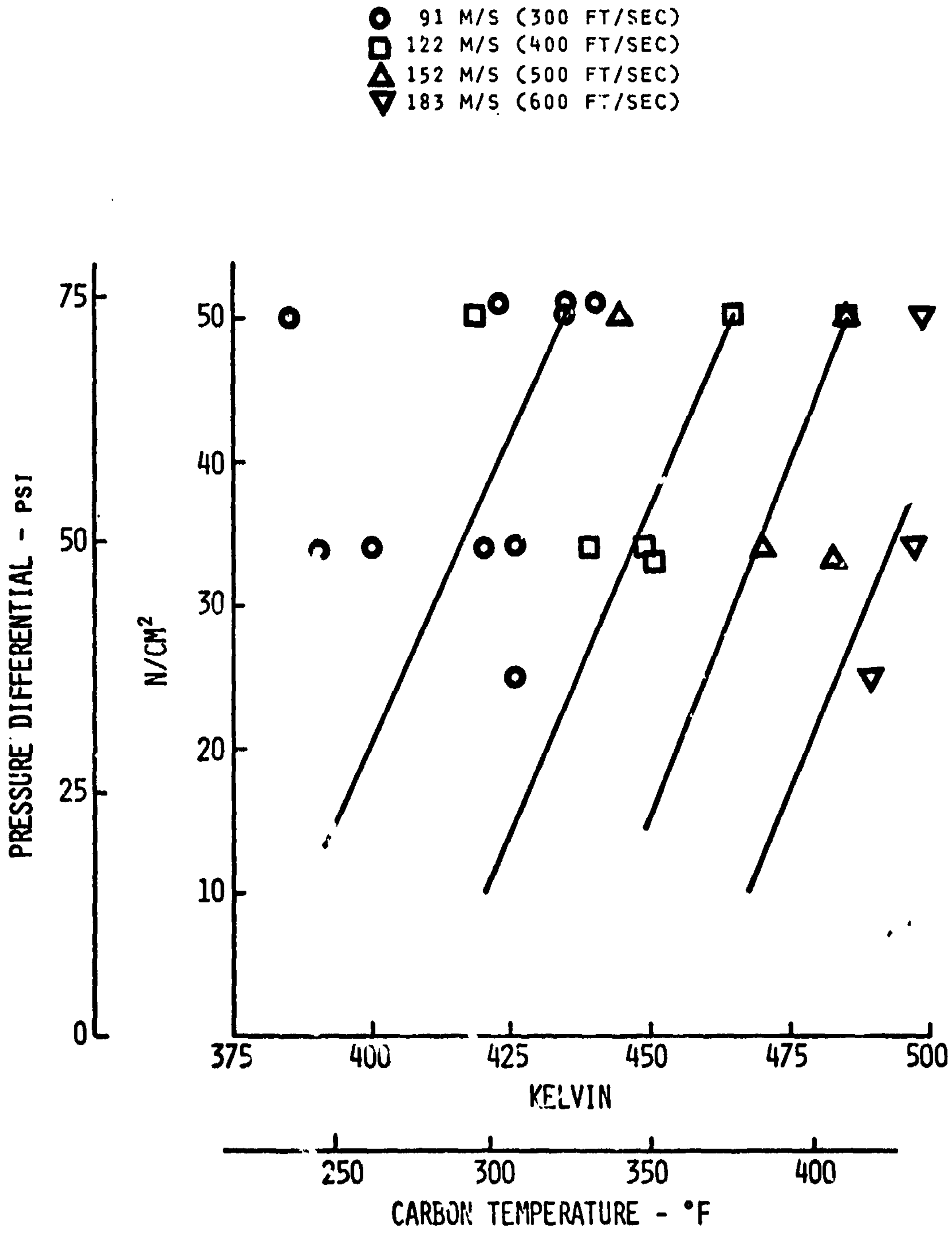


Figure 36. Self-Acting Circumferential Seal Forward Seal Oil-Side Carbon Temperature Versus Pressure Differential for Various Speeds.

Inspection following Test 1 revealed that the lift-pad depth had decreased 0.0006 mm (0.000025 in.) on the oil-side carbon segments of the aft seal. The lift-pad depth on two of the three carbon segments on the air-side of the aft seal also decreased 0.0006 mm (0.000025 in.), while the third did not wear. The forward seal carbons exhibited no wear.

There was no significant change in the surface texture of the runners during Test 1, although a thin carbon line could be seen on the [illegible]-side edge of both runners.

No further reduction of lift-pad depth was measured from Tests 2 through 8; but, visual observation revealed that the carbons had contacted the runners, particularly at the carbon leading edges.

Figure 37 illustrates the condition of the runners after Test 4 showing a carbon trace at the oil side edge. Figure 38 shows a closeup of a carbon segment after Test 8 with some evidence of carbon scuffing.

Traces of the lift pads indicated that while the depth of the pads did not change through Test 8 the sealing dams wore in the order of 0.0025 mm (0.0001 in.). Figure 39 is a lift-pad trace comparing carbon condition after Tests 1 and 8.

The runners were in good condition following Test 8. Maximum roughness was 0.127 μm (5μ in. AA), and maximum waviness was 1.52 μm (60μ in.). Maximum out- of-roundness was 1.65 μm (65 μ in.).

Test 9 was a 25-hour endurance run with the following maximum conditions:

Speed-182 m/s (600 ft/sec, 47700 rpm)
Pressurization Air Pressure - 44.6 N/cm^2 abs (64.7 psia)
Air Temperature - 478 K (400°F)
Pressure Diff. Across Air-side Carbons - 3.4 to 10.3 N/cm^2 (5 to 15 psi)
Pressure Diff. Across Oil-side Carbons - 33 N/cm^2 (48 psi)

New carbons and runners were used for Test 9.

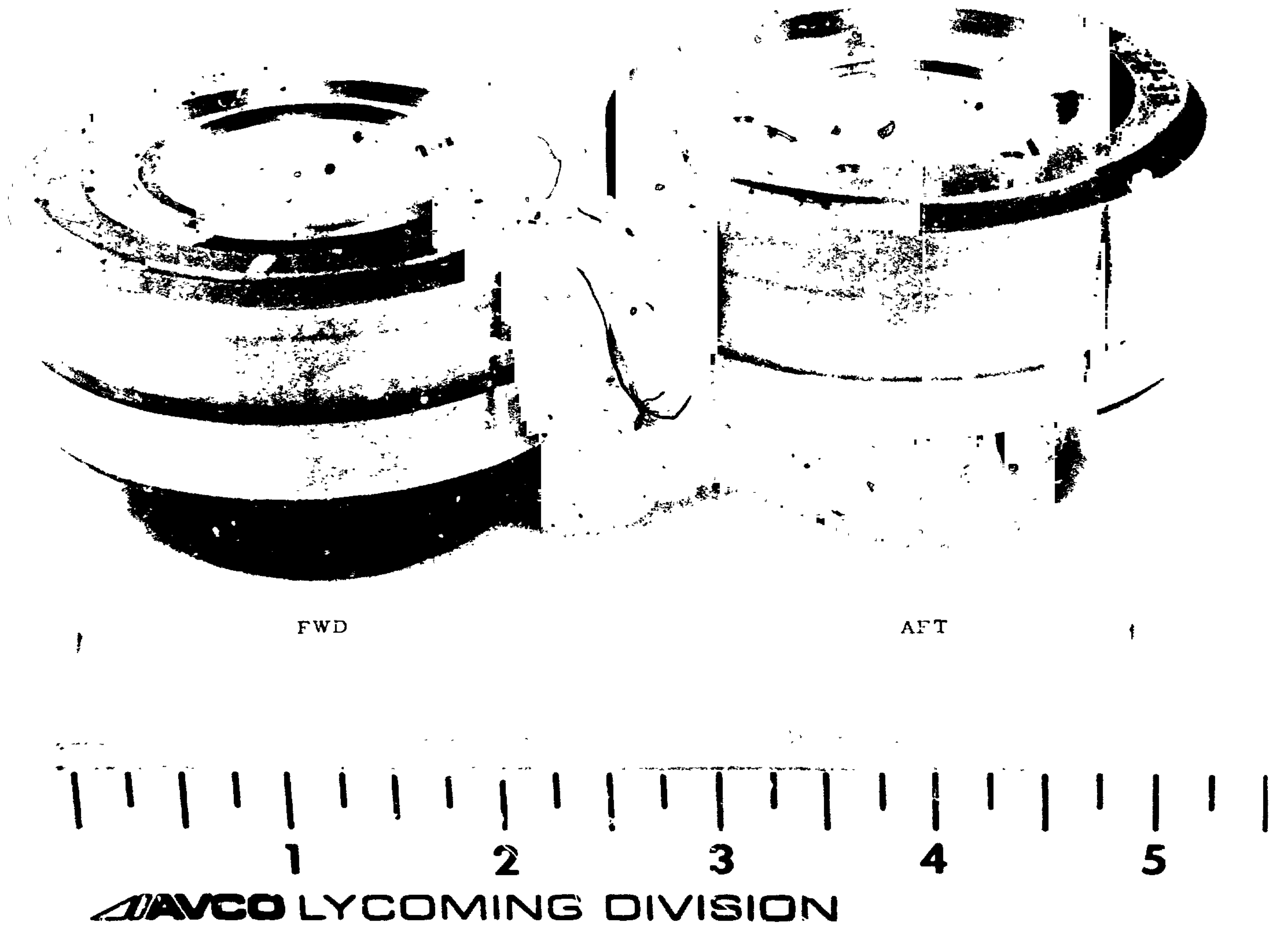


Figure 37. Self-Acting Circumferential Seal Runners After Test 4.

C-2

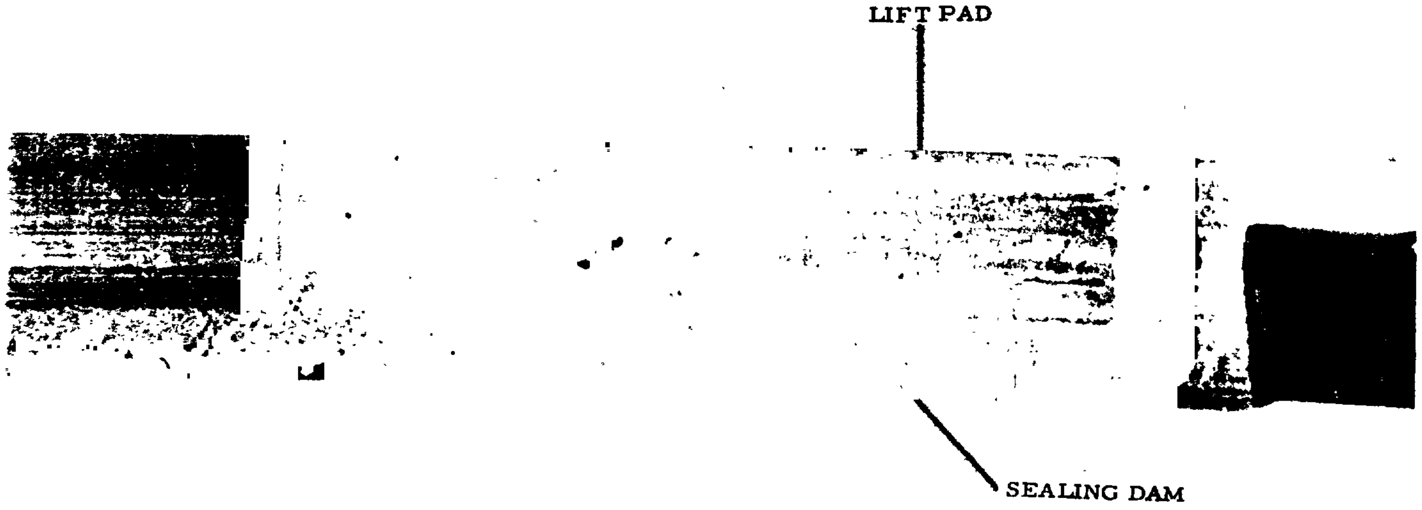


Figure 38. Self-Acting Circumferential Seal Carbon Segment After Test 4.

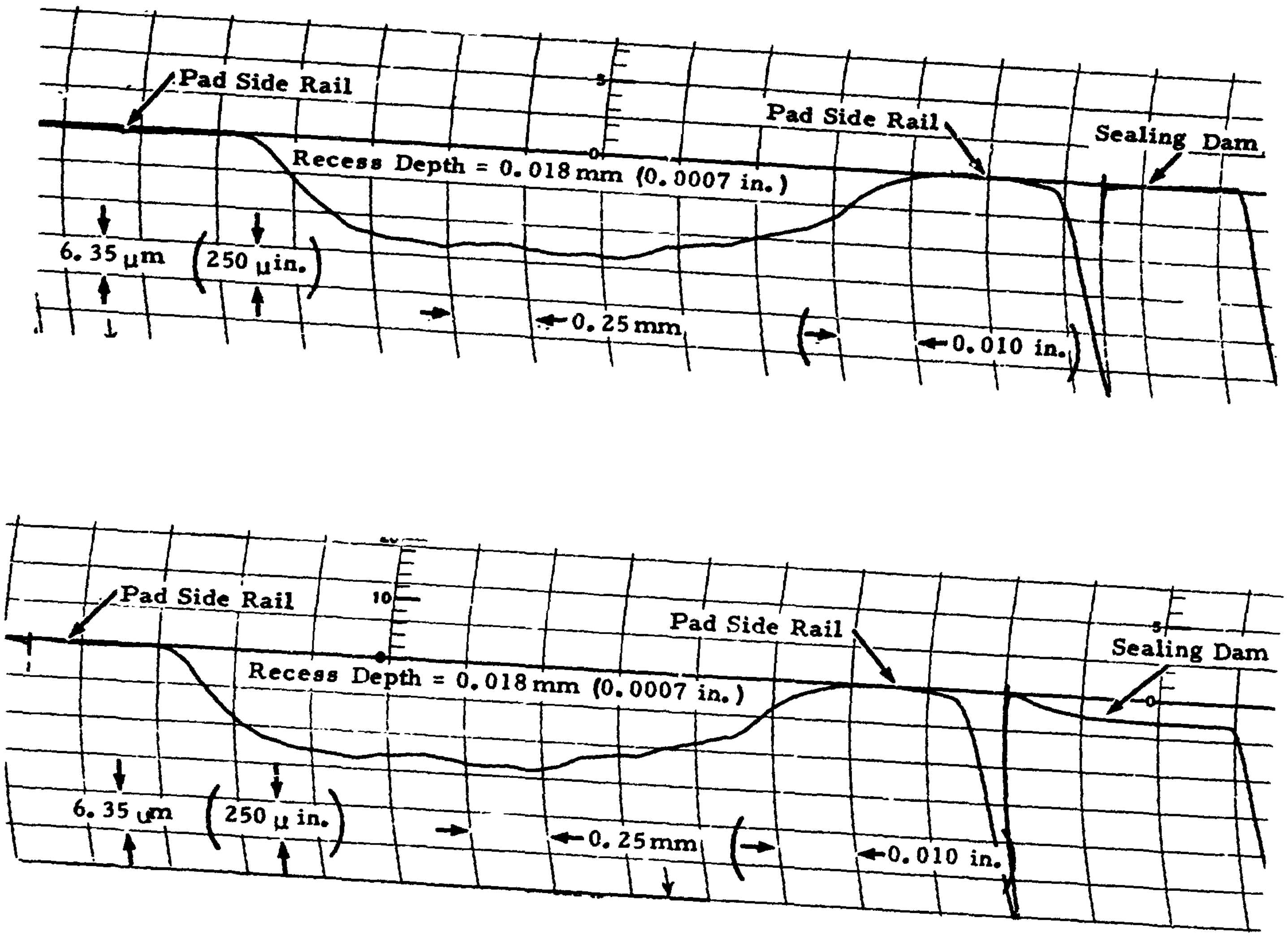


Figure 39. Self-Acting Circumferential Seal Trace of Carbon Segment Lift Pad After Tests 1 and 8.

After two-hours of operation, a rubbing sound was heard, and the rig was disassembled for inspection. The noise was caused by the forward seal carbons contacting the runners. Although there were carbon tracks on the runner, wear appeared to be insignificant, and the seals were judged acceptable for further operation. Table XIX lists the operating parameters for this two-hour run. Note the high temperatures of the forward seal carbon.

Testing continued for an additional 23 hours. Table XX lists the operating parameters and resulting airflows and temperatures.

Inspection following testing revealed that the forward seal oil-side carbon carbons were badly worn. The forward seal air-side carbons and the aft seal carbons were in relatively good condition. Figures 40 through 43 show the carbon segments following Test 9. For this test, all lift pads were traced before and after testing. Table XXI lists the average and maximum wear.

There was a 0.0023 mm (0.000092 in.) carbon buildup on the forward runner where the oil-side carbons contacted and a 0.0012 mm (0.000046 in.) carbon buildup on the aft runner where the oil side carbons contacted (Figure 44). Except for these areas, the texture of the runner surface was not affected.

Test 10 was a 23-hour endurance run with the following operating conditions

Speed-182 m/s (600 ft/sec, 47700 rpm)
Pressurization Air Pressure-23.9 N/cm^2 abs (34.7 psia)
Pressure Diff. Across Forward Air-side Carbon-10.3 N/cm^2 (15psi)
Pressure Diff. Across Forward Oil-side Carbon-12.8 N/cm^2 (18.5 psi)
Pressure Diff. Across Aft Air-side Carbon-13.1 N/cm^2 (19 psi)
Pressure Diff. Across Aft Oil-side Carbon-12.8 N/cm^2 (18.5 psi)

The carbons and runners used were the same as those used in the initial No. 8 evaluation tests.

Table XXII lists the resulting airflows, air temperatures, and carbon temperatures. The maximum air-side temperature during this test was 534 K (500 °F).

TABLE XIX. SELF-ACTING CIRCUMFERENTIAL SEAL ENDURANCE TEST - TEST 9, HOURS 1 AND 2

				Pressure Diff. Across Carbons								Airflow Through Two Seals		
				Forward Seal				Aft Seal						
	Speed			Airside		Oilside		Airside		Oilside				
Run	(m/s)	(ft/sec)	(rpm)	(N/cm^2)	(psi)	(N/cm^2)	(psi)	(N/cm^2)	(psi)	(N/cm^2)	(psi)	(kg/s)	(scfm)	(lb/sec)
1	91	300	23,900	10.3	15	33	48	6.9	10	33	48	.0009	1.5	.0019
2	122	400	31,800	10.3	15	33	48	6.9	10	33	48	.0009	1.5	.0019
							SHUTDOWN							
3	91	300	23,900	10.3	15	33	48	6.9	10	33	48	.0008	1.3	.0007
4	122	400	31,800	10.3	15	33	48	6.9	10	33	48	.0008	1.4	.0018
5	152	500	40,000	10.3	15	33	48	6.9	10	33	48	.0008	1.4	.0018
6	183	600	47,700	10.3	15	33	48	6.9	10	33	48	.0008	1.4	.0018
7	183	600	47,700	10.3	15	33	48	6.9	10	33	48	.0008	1.4	.0018
8	183	600	47,700	10.3	15	33	48	6.9	10	33	48	.0009	1.5	.0019
9	183	600	47,700	10.3	15	33	48	6.9	10	33	48	.0012	2.0	.0025

TABLE XIX - Continued

	External Air Temperature		Seal Carbon Temperature							
			Forward Seal				Aft Seal			
			Airside		Oilside		Airside		Oilside	
Run	(K)	(°F)	(K)	(°F)	(K)	(°F)	(K)	(°F)	(K)	(°F)
1	299	78	384	232	407	274	370	207	394	248
2	300	80	402	262	428	311	382	228	406	271
SHUTDOWN										
3	298	76	389	240	417	290	369	205	394	250
4	298	77	403	266	436	315	384	230	412	280
5	300	81	429	312	454	357	396	254	422	300
6	302	84	460	359	492	426	413	284	433	320
7	306	92	470	386	502	444	423	302	441	333
8	312	102	493	428	514	465	432	318	451	351
9	---	---	534	500	547	525	---	---	475	395

TABLE XX. SELF-ACTING CIRCUMFERENTIAL SEAL ENDURANCE TEST - TEST 9, HOURS 3 - 25 (Data Speed - 183 m/sec (600 ft/sec, 47, 700 rpm))

	Pressure Diff. Across Carbons								Airflow Through Two Seals		
	Forward Seal				Aft Seal						
	Airside		Oilside		Airside		Oilside				
Hour	N/cm^2	psi	N/cm^2	psi	N/cm^2	psi	N/cm^2	psi	kg/s	scfm	lb/sec
3	12. 4	18	33	48	10. 3	15	33	48	.0006	1. 0	.0013
4	13. 1	19	33	48	10. 3	15	33	48	.0006	1. 0	.0013
					SHUTDOWN						
5	12. 4	18	33	48	10. 3	15	33	48	.0006	1. 0	.0013
6	7. 6	11	33	48	3. 4	5	33	48	.0005	.9	.0011
7	6. 9	10	33	48	3. 4	5	33	48	.0005	.8	.0010
8	6. 9	10	33	48	3. 4	5	33	48	.0005	.8	.0010
9	6. 9	10	33	48	3. 4	5	33	48	.0005	.8	.0010
10	6. 9	10	33	48	3. 4	5	33	48	.0005	.8	.0010
					SHUTDOWN						
11	6. 9	10	33	48	3. 4	5	33	48	.0003	.6	.0008
12	8. 3	12	33	48	3. 4	5	33	48	.0003	.6	.0008
13	8. 3	12	33	48	3. 4	5	33	48	.0003	.6	.0008
14	7. 6	11	33	48	3. 4	5	33	48	.0003	.5	.0006
15	8. 3	12	33	48	3. 4	5	33	48	.0003	.5	.0006
16	7. 6	11	33	48	3. 4	5	33	48	.0003	.5	.0006
17	8. 3	12	33	48	3. 4	5	33	48	.0003	.5	.0006
					SHUTDOWN						
18	8. 3	12	33	48	3. 4	5	33	48	.0005	.9	.0011
19	8. 3	12	33	48	3. 4	5	33	48	.0005	.8	.0010
20	8. 3	12	33	48	3. 4	5	33	48	.0004	.7	.0009
21	6. 9	10	33	48	3. 4	5	33	48	.0003	.6	.0008
22	6. 9	10	33	48	3. 4	5	33	48	.0003	.6	.0008
23	6. 9	10	33	48	3. 4	5	33	48	.0003	.6	.0008
24	6. 9	10	33	48	3. 4	5	33	48	.0003	.6	.0008
25	6. 9	10	33	48	3. 4	5	33	48	.0003	.6	.0008

TABLE XX - Continued

TEST NO. 9

	External Air Temp.				Seal Carbon Temperature					
					Forward Seal				Aft Seal Oilside	
	Forward		Aft		Airside		Oilside			
Hour	K	°F	K	°F	K	°F	K	°F	K	°F
3	363	193	355	179	459	366	493	428	433	319
4	425	305	440	331	519	474	537	506	469	384
				SHUTDOWN						
5	341	153	337	147	403	266	428	310	398	256
6	434	320	448	346	535	502	---	---	476	396
7	467	380	470	386	537	506	---	---	485	412
8	465	377	471	388	535	503		---	492	426
9	470	385	471	387	537	507		---	490	421
10	477	398	478	401	542	516		---	489	420
				SHUTDOWN						
11	---	---	460	368	530	494		---	489	420
12	---	---	471	387	538	508		---	494	430
13	---	---	472	390	545	521		---	495	431
14	---	---	474	392	551	532		---	495	432
15	---	---	473	391	557	543		---	494	429
16	---	---	470	386	550	530		---	492	426
17	---	---	468	382	549	528		---	493	427
				SHUTDOWN						
18	---	---	329	132	---	---		---	---	---
19	---	---	467	380	537	507		---	493	428
20	---	---	474	392	545	521		---	500	440
21	---	---	469	384	541	514		---	494	430
22	---	---	471	387	548	526		---	499	438
23	---	---	472	389	544	519		---	493	428
24	---	---	470	386	542	516		---	494	430
25	---	---	470	386	543	518		---	493	427

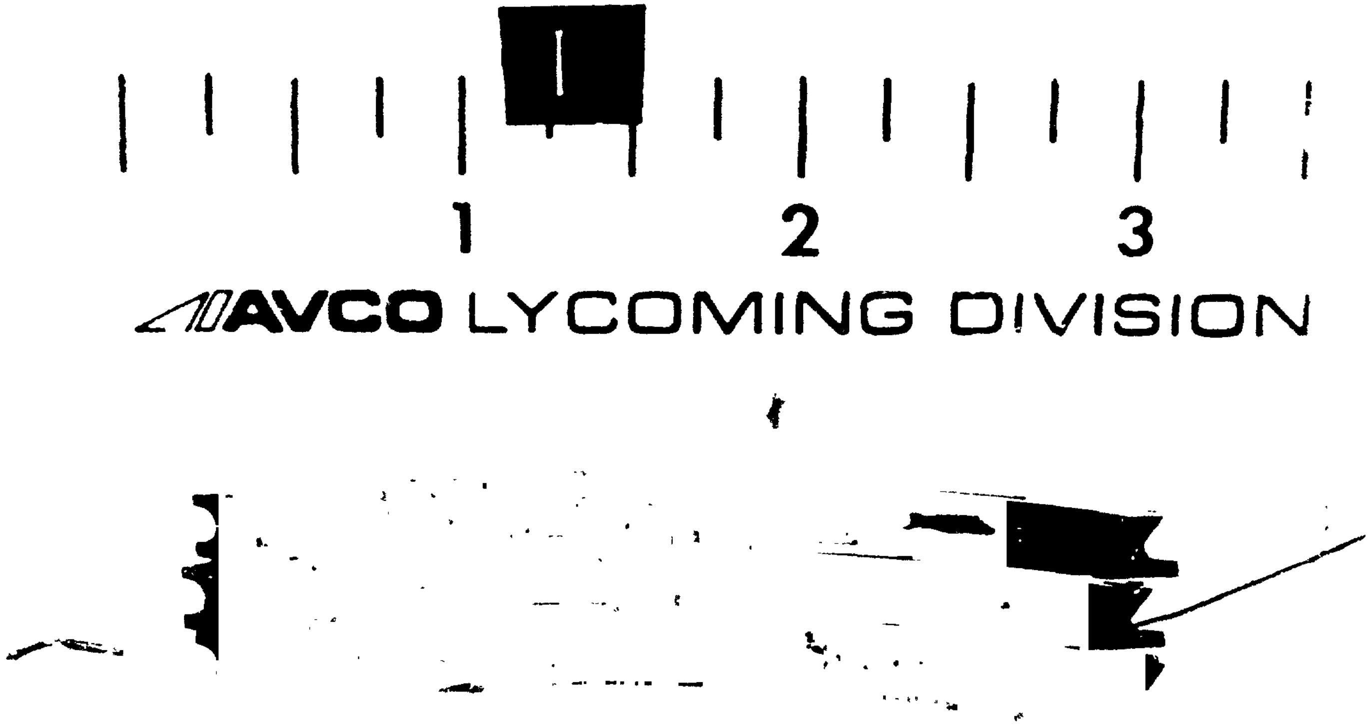


Figure 40. Self-Acting Circumferential Seal Forward Air-Side Segments After Test 9.

Figure 41. Self-Acting Circumferential Seal Forward Oil-Side Segments After Test 9.

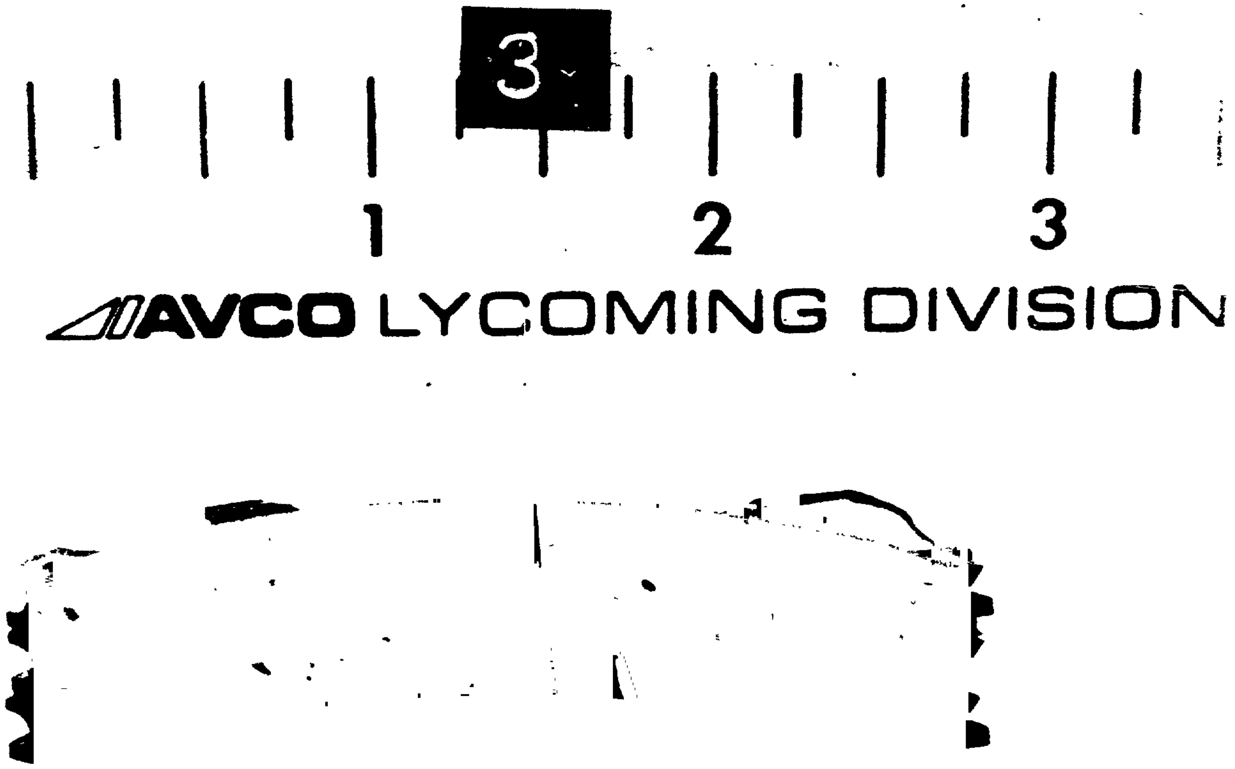


Figure 42. Self-Acting Circumferential Seal Aft Air-Side Segments After Test 9.

Figure 43. Self-Acting Circumferential Seal Aft Oil-Side Segments After Test 9.

TABLE XXI. CARBON SEGMENT INSPECTION RESULTS AFTER TEST 9

	AVG. REDUCTION IN LIFT-PAD DEPTH		MAX. REDUCTION IN LIFT-PAD DEPTH	
	(μm)	(μin)	(μm)	(μin)
FWD. SEAL OIL-SIDE CARBON	6.35	250	13.32	525
FWD. SEAL AIR-SIDE CARBON	0.64	25	1.90	75
AFT SEAL OIL-SIDE CARBON	1.22	48	5.08	200
AFT SEAL AIR-SIDE CARBON	0.20	8	1.27	50

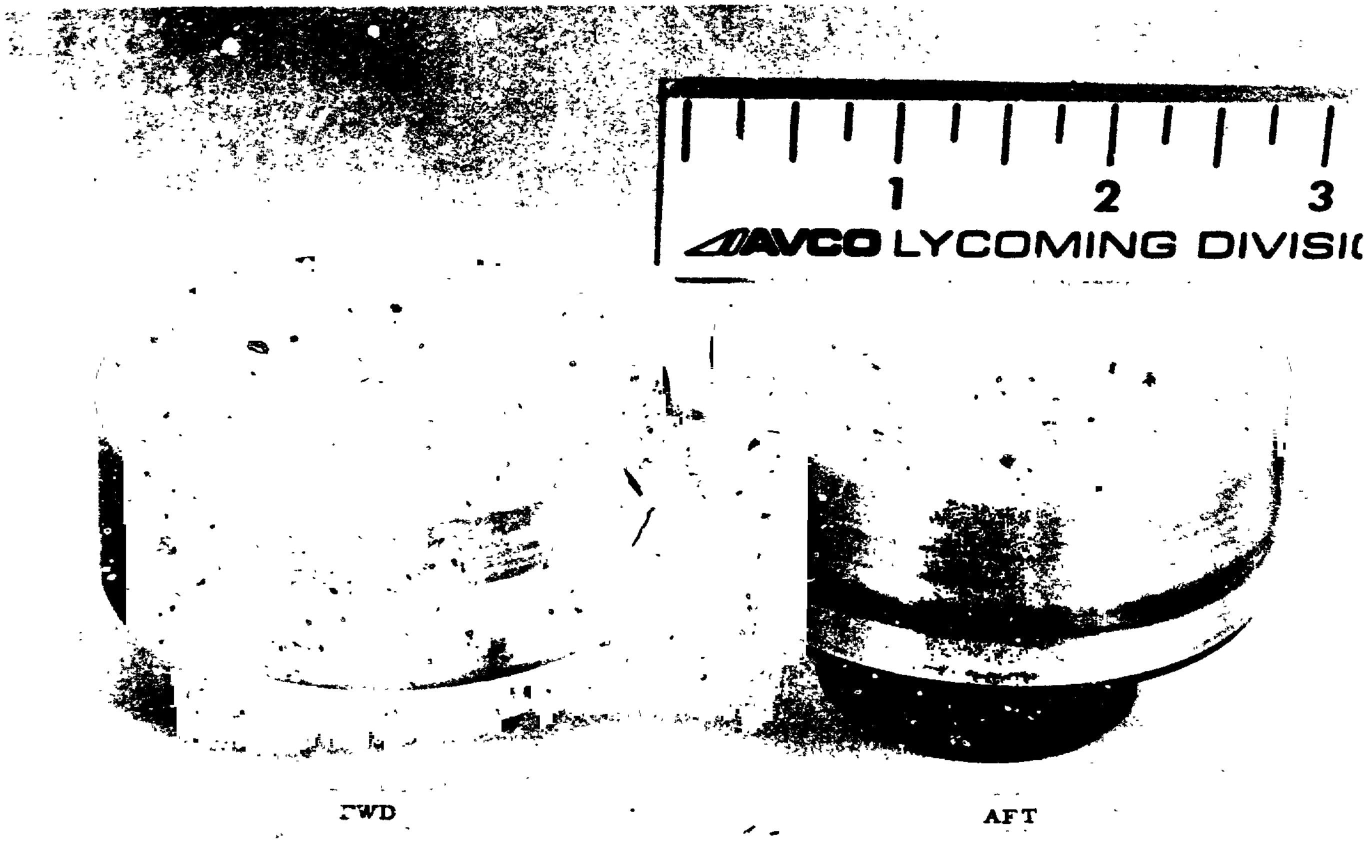


Figure 44. Condition of Runner After Test 9.

TABLE XXII. SELF-ACTING CIRCUMFERENTIAL SEAL ENDURANCE TEST - TEST 10

Hour	AIRFLOW THROUGH TWO SEALS			EXTERNAL AM TEMP. FWD		EXTERNAL AM TEMP. AFT		FWD SEAL TEMP. AIRSIDE		AFT SEAL TEMP. OILSIDE	
	Kg/s	scfm	lb/sec.	K	°F	K	°F	K	°F	K	°F
1	0.0006	1	0.0013	346.4	344	300	80	461	370	436.6	326
			SHUTDOWN								
2	0.0005	.8	0.0010	419.6	296	456.2	362	485.4	414	443	338
3	0.0005	.8	0.0010	426	308	466	380	493	428	446.4	344
4	0.0005	.8	0.0010	426	308	469.6	386	497.6	436	450	350
			SHUTDOWN								
5	0.0004	.75	0.0010		-	417.2	292	466	380	434.2	325
6	0.0004	.75	0.0010		-	451	352	486.6	416	442	336
7	0.0004	.70	0.0009		-	465	378	494	430	449.4	349
8	0.0004	.70	0.0009		-	466	380	495.2	432	450	350
9	0.0004	.70	0.0009		-	464	376	493	428	448.8	348
10	0.0004	.70	0.0009		-	474	394	501	442	451	352
11	0.0004	.70	0.0009		-	468.4	384	498.8	438	454	358
			SHUTDOWN								
12	0.0004	.70	0.0009		-	455	360	490	422	445.2	342
13	0.0004	.65	0.0008		-	464	376	497	435	448.8	348
14	0.0004	.65	0.0008		-	465	378	498.8	438	449.4	349
15	0.0004	.65	0.0008		-	466	380	497.6	436	450	350
16	0.0004	65	0.0008		-	470.8	388	515	468	456.2	362
17	0.0004	.65	0.0008		-	477	400	503.6	456	455	360
			SHUTDOWN								
18	0.0004	.70	0.0009		-	423.2	312	487.2	417	458.6	366
19	0.0004	.65	0.0008		-	487.8	418	519.6	476	461.5	371
20	0.0004	.65	0.0008		-	483	410	513	464	465.5	379
21	0.0004	.65	0.0008		-	474	394	515	468	468.4	384
22	0.0003	.60	0.0008		-	476	398	517.2	472	468.4	384
23	0.0003	.60	0.0008		-	480	405	515	468	468.4	384

Inspection following Test 10 revealed no carbon wear except for the leading edge pad on each of the forward seal oil-side carbons. Figure 45 illustrates the conditions of this lift pad. The runners were in good condition following the test.

Test 11 was a 24-hour endurance test using the same carbons and runners as used in Test 10 except for the aft seal oil-side segments. These segments were replaced with a new set because a segment had been broken in handling. Test conditions were as follows:

Speed-182 m/s (600 ft/sec, 47700 rpm)
Pressurization Air Pressure-30.8 N/cm^2 abs (44.7 psia)
Pressure Diff. Across Forward Air-side Carbon-15.2 N/cm^2 (22 psi)
Pressure Diff. Across Forward Oil-side Carbon-19.4 N/cm^2 (28.2 psi)
Pressure Diff. Aft Air-side Carbon-19.7 N/cm^2 (28.5 psi)
Pressure Diff. Aft Oil-side Carbon-19.8 N/cm^2 (28.7 psi)

Table XXIII lists the resulting airflows, air temperatures and carbon temperatures. The maximum air-side temperature during this test was 588 K (600 °F).

Inspection following testing revealed that several of the forward and aft oil-side carbon lift pads were partially worn. Wear on the air-side segment was negligible, and the seal runners were in good condition.

Test 12 was a 27-hour endurance run using new carbon segments. The runners were the same as those used in Test 9; but, they were axially positioned so that the carbons were not operating on the previous tracks. Test Conditions were as follows:

Speed-182 m/s (600 ft/sec, 47700 rpm)
Pressurization Air Pressure-34.2 N/cm^2 abs (49.7 psia)
Pressure Diff. Across Forward Air-side Carbon-17.2 N/cm^2 (25 psi)
Pressure Diff. Across Forward Oil-side Carbon-22.8 N/cm^2 (33 psi)
Pressure Diff. Across Aft Air-side Carbon - 23.4 N/cm^2 (34 psi)
Pressure Diff. Across Aft Oil-side Carbon-22.8 N/cm^2 33 psi)

Table XXIV lists the resulting airflows, air temperatures, and carbon temperatures. The maximum air temperature of the forward seal was 710 K (820 °F), while the maximum air temperature of the aft seal was 622 K (660 °F).

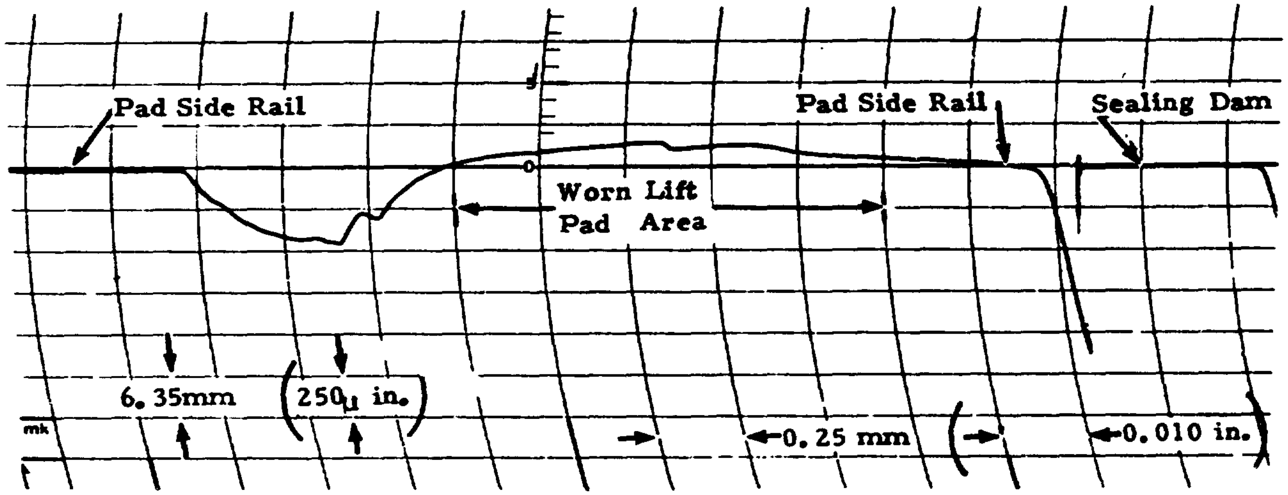


Figure 45. Self-Acting Circumferential Seal Trace of Carbon Segment Lift Pad After Test 10.

TABLE XXIII. SELF-ACTING CIRCUMFERENTIAL SEAL ENDURANCE TEST - TEST 11

Hour	AIRFLOW THROUGH TWO SEALS			EXTERNAL AIR TEMP. FWD		EXTERNAL AIR TEMP. AFT		FWD. SEAL TEMP. AIRSIDE	
	Kg/s	scfm	lb/sec.	K	°F	K	°F	K	°F
1	0.0009	1.5	0.0019	-	-	416	290	490	422
2	0.0007	1.2	0.0015	-	-	502.5	445	546.4	524
3	0.0007	1.2	0.0015	-	-	511	460	540.5	513
			SHUTDOWN						
4	0.0005	0.85	0.0011	-	-	500	440	539	510
5	0.0005	0.8	0.0010	-	-	516	470	550.5	531
6	0.0005	0.8	0.0010	572	570	523	482	-	-
7	0.0005	0.8	0.0010	572	570	522.5	481	548.8	528
8	0.0004	0.75	0.0010	569	565	519	475		-
9	0.0004	0.75	0.0010	578.2	582	489	488		-
10	0.0004	0.75	0.0010	569	565	523	482		-
			SHUTDOWN						
11	0.0004	0.7	0.0009	574.5	575	492	426		-
12	0.0004	0.7	0.0009	533	500	494	430		-
13	0.0004	0.7	0.0009	569	565	512.5	463		-
14	0.0004	0.7	0.0009	589	600	533	500		
15	0.0004	0.7	0.0009	589	600	536.6	506		-
16	0.0005	0.8	0.0010	589	600	537.8	508		-
17	0.0005	0.8	0.0010	589	600	537.8	508		-
			SHUTDOWN						
18	0.0004	0.7	0.0009	583	590	528.8	493		
19	0.0004	0.65	0.0008	589	600	535.4	504		
20	0.0004	0.7	0.0009	589	600	537.2	507		
21	0.0004	0.7	0.0009	589	600	538.4	509		
22	0.0004	0.7	0.0009	589	600	536.6	506		
23	0.0004	0.8	0.0010	589	600	541.0	514		
24	0.0004	0.8	0.0010	589	600	539	510		

TABLE XXIV. SELF-ACTING CIRCUMFERENTIAL SEAL ENDURANCE TEST - TEST 12

	AIRFLOW THROUGH TWO SEALS			EXTERNAL AM TEMP FWD		AFT		FWD SEAL TE AIRSIDE				AFT SEAL TEMP. OILSIDE			
Hour	Kg/s	Scfm	lb/sec.	K	°F	K	°F	K	°F	K	°F	K	°F	K	°F
1	0.0008	1.35	0.0017	597	615	533	500	590	602	568.4	564	503	446	500	440
2	0.0008	1.3	0.0017	630	675	559.8	548	608	635	580.6	586	511	460	509.2	457
3	0.0007	1.25	0.0016	644	700	570.8	568	612	642	581.8	588	515.5	469	516	470
			SHUTDOWN												
4	0.0006	0.95	0.0012	589	600	509.8	458	559.2	547	542.5	517	498.2	437	497	435
5	0.0006	0.95	0.0012	630	675	568.4	564	594	610	573	572	519.6	476	520.8	478
6	0.0005	0.9	0.0011	647	705	587.2	597	617.2	652	595.8	603	523	482	519.6	476
7	0.0005	0.9	0.0011	650	710	590	602	619.6	656	596.4	614	522	480	519.6	476
8	0.0006	0.95	0.0012	650	710	587.8	598	612	642	594	610	525	486	524.5	485
9	0.0006	0.95	0.0012	658	725	[illegible]	613	614	646	594.6	611	531.8	498	531.8	498
10	0.0006	0.95	0.0012	583	590	555	540	584.2	592	573.5	573	526	488	531.8	498
			SHUTDOWN												
11	0.0005	0.8	0.0010	639	690	557.4	544	602	622	-	-	516	470	520.8	478
12	0.0005	0.9	0.0011	689	780	592.5	607	619.6	656	-	-	530.6	496	531.8	498
13	0.0005	0.9	0.0011	658	725	583	590	590	602	-	-	525.5	487	528.2	492
14	0.0005	0.85	0.0011	639	690	572	570	583.6	591	-	-	519.6	476	522	480
15	0.0005	0.85	0.0011	639	690	623	662	583	590			520.2	477	522	480
			SHUTDOWN												
16	0.0005	0.85	0.0011	652.5	715	572	570	597	615			523	482	522	480
17	0.0005	0.85	0.0011	697	775	593	608	615	648			533	500	531.2	497
18	0.0005	0.85	0.0011	700	800	611	640	619.6	656			535.4	504	534.2	502
19	0.0005	0.9	0.0011	702.5	805	611	640	622	660			535.4	504	536.6	506
20	0.0005	0.9	0.0011	702.5	805	612.5	643	633	680			536.6	506	536.6	506
21	0.0005	0.85	0.0011	702.5	805	612.5	643	635.4	684			537.8	508	539	510
			SHUTDOWN												
22	0.0005	0.9	0.0011	663.5	735	575	576	629.4	674			526.5	489	527	490
23	0.0006	1.0	0.0013	702.5	805	614.5	647	636.6	686			534.8	503	531.8	498
24	0.0006	1.0	0.0013	705	810	617.8	653	651	712			540	512	536	505
25	0.0006	1.1	0.0014	708	815	620.2	657	655	720			537.2	507	533	500
26	0.0006	1.1	0.0014	711	820	622	660	672	750			539.5	511	534.2	502
27	0.0006	1.05	0.0013	711	820	622	660	655	720			534.2	502	528.2	492

The maximum air temperature of the forward seal was 710 K (820 °F), while the maximum air temperature of the aft seal was 622 K (660°F).

Inspection following testing revealed that the forward seal air-side carbon lift pads were completely worn. The first two lift pads on the leading edge of the oil-side carbon segments were also worn an average of 0.008 mm (0.00032 in). The aft air-side carbons did not wear. Two lift pads wore on the aft oil-side carbons, one 0.011 mm (0.00045 in.) and the other 0.002 mm (0.000075 in.).

Figure 46 shows the condition of the seal following Test 12. Note the coking on the aft seal case. Because the forward seal experienced higher temperatures, the coke deposits had burned off.

The runners were in good condition following Test 12. Maximum roughness and waviness were 0.18 μm (7μ in. AA) and 2.54 μm (100 μ in.). Maximum out-of-roundness was 2.97 μm (117 μ in.).

Conclusion

In previous testing (Reference 1), the self-acting circumferential seal was found to be limited to speeds of 122 m/s (400 ft/sec, 31800 rpm) and pressure differentials of 79 N/cm^2 (115 psi). The modified lift pad geometry did not demonstrate any improvement over these values. At speeds of 182 m/s (600 ft/sec, 47700 rpm), the pressure differential capability appears to be approximately 20.7 N/cm^2 (30 psi).

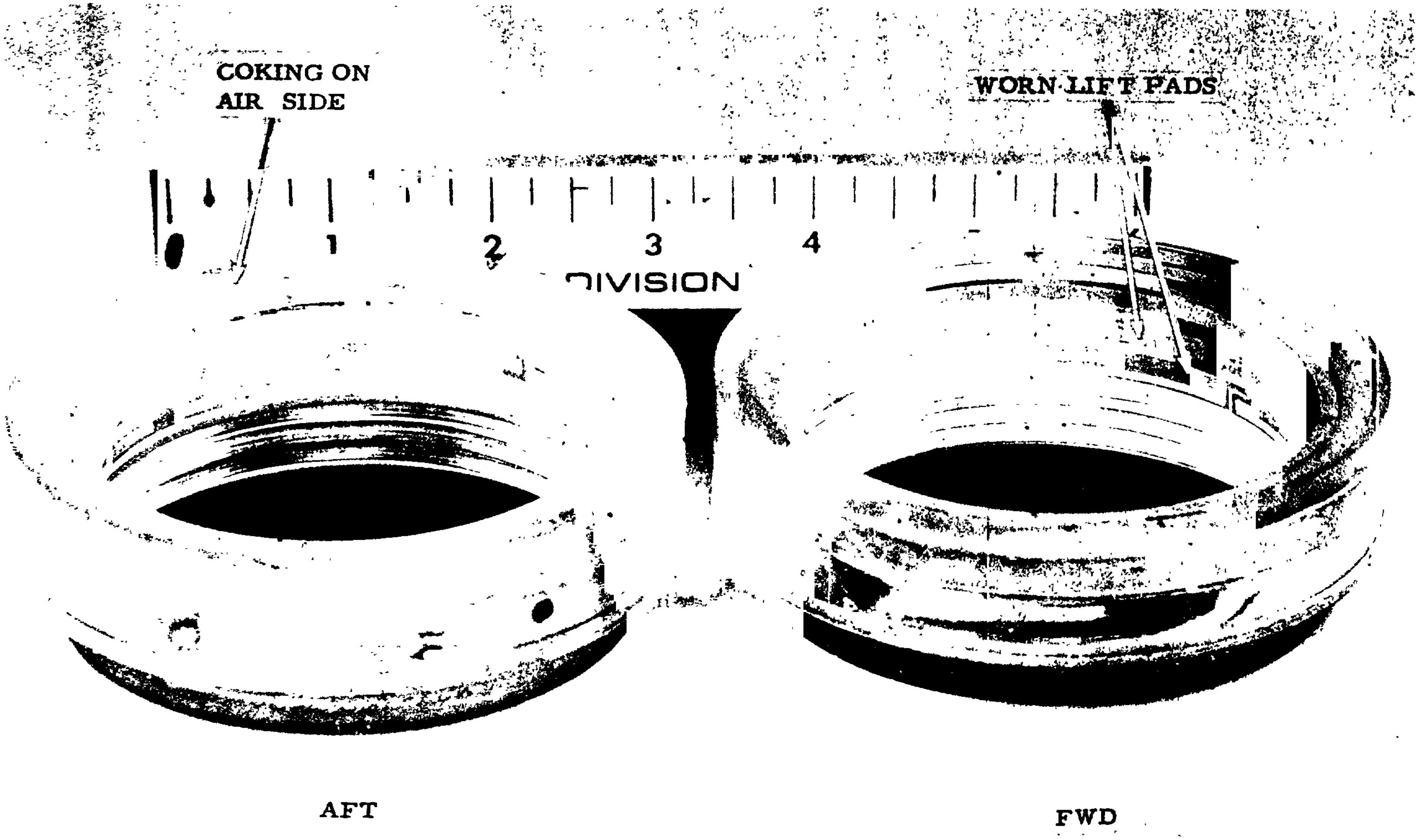


Figure 46. Condition of Self-Acting Circumferential Seal After Test 12.

CONCLUSIONS AND RECOMMENDATIONS

The self-acting face seal and circumferential seal configurations were subjected to 264 hours of testing during this program.

The self-acting face seal was shown to be capable of operating at conditions more severe than experienced in present gas turbine mainshaft applications. Air pressures of 216.8 N/cm^2 abs. (314.7 psia) were successfully sealed and speeds of 214 m/s (700 ft/sec, 63800 rpm) were attained. There appears to be no limitation to ambient pressure; however, at speeds of 198 m/s (650 ft/sec, 59150 rpm) and above carbon wear occurred. This was attributed to distortion of the seal seat. It appears that assembled seal seat flatness may be a limiting factor to high-speed operation.

The TZM seal seat extended the speed and temperature capabilities of the self-acting face seal by reducing distortion caused by temperature. Also, the result of carbon-seal seat contact was not as catastrophic as experienced in the previous test program (Reference 1) with a 4340 seal seat.

The self-acting circumferential seal performance was not improved by modification of the lift pad geometry. Previous testing found this seal to be limited to speeds of 122 m/s (400 ft/sec, 31800 rpm) and pressure differentials of 79 N/cm^2 (115 psi). Additional development is required on this seal for use in advanced gas turbine engines.

The operating air temperature during the test program was limited to 687K (778°F) because of carbon oxidation. Seals should be tested incorporating higher temperature carbons.

REFERENCES

1. Lynwander, P. : "Development of Helicopter Engine Seals" Avco Lycoming Report LYC 73-48, NASA CR-13467, 1973.

2. Lynwander P. : "Development of Self-Acting Seals For Helicopter Engines" Avco Lycoming Report LYC 74-55, NASA CR-134739, 1974.

3. Ludwig, L. P. , and Johnson, R. L. : "Design Study of Shaft Face Seal with Self-Acting Augmentation. III - Mechanical Components, NASA TN D-6164, 1971.

4. Ludwig, L. P., Zuk, J., and Johnson, R. L. : "Design Study of Shaft Face Seal with Self-Acting Lift Augmentation IV - Force Balance, "NASA TN D-6568, 1972.

5. Zuk, J., Ludwig, P., and Johnson, R. L. : "Quasi-One-Dimensional Compressible Flow Across Face Seals and Narrow Slots. I - Analysis, "NASA TN D-6668, 1972.

6. Zuk, J., and Ludwig, L. P. : "Investigation of Isothermal, Compressible Flow Across a Rotating Sealing Dam I - Analysis, "NASA TN D-5344, 1969.

7. Zuk, J., and Smith, P. J. : "Computer Program for Viscous Isothermal Compressible Flow Across a Sealing Dam with Small Tilt Angle, "NASA TN D-5373, 1969.

8. Zuk, J., Ludwig, L. P., and Johnson, R. L. : "Design Study of Shaft Face Seal with Self-Acting Lift Augmentation. I - Self-Acting Pad Geometry, "NASA TN D-5744, 1970.

9. Colsher, R., and Shapiro, W. : "Steady State and Dynamic Performance of Gas- Lubricated Seals, "NASA CR - 121093, 1972.