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MINI-BRU/BIPS FOIL BEARING DEVELOPMENT

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16. Abstract

This report covers the development testing of the Mini-BRU Teflon coated foil journal bearings conducted in support of the DoE Brayton Isotope Power System (BIPS) Phase I program. This work was an extension of the basic Mini-BRU engine development program reported in NASA CR-159441.

Tests conducted with the Mini-BRU in the BIPS Workhorse Loop (WHL) during November and December, 1977 revealed serious deterioration of the compressor end foil bearing in relatively short test times.

Detailed analysis and/or tests were conducted to examine coating temperature effects, foreign particles, electrical or magnetic effects, low speed motoring, starvation, stagnation, distortion, WHL gas environment, bearing minimum film (design versus actual), bearing loads, mechanical design and control and bearing power loss.

The analysis revealed the failure agent to be a combination of poor teflon coating adhesion, a decrease in bearing sway space and, possibly, lack of flushing flow through the bearing.

A change in Teflon coating vendors provided substantially improved coating quality and surface finish. The sway space was increased and the cooling bleed flow was adjusted to flush the bearing.

These changes were included in a test conducted in the WHL from 6 April to 22 May 1978 which resulted in the completion of 1006.9 hours of operation at temperature and load. Post-test inspection revealed the bearings to be in excellent condition and capable of completing a much longer test.

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SUMMARY

Tests conducted with the Mini-Brayton Unit (Mini-BRU) in the DOE Brayton Isotope Power System (BIPS) Workhorse Loop (WHL) during November and December, 1977 revealed serious deterioration of the compressor end foil bearing in relatively short test times.

An exhaustive investigation was conducted to examine every possible type of bearing failure and determine if it contributed to the failures.

Detailed analysis and/or tests were conducted to examine coating temperature effects, foreign particles, electrical or magnetic effects, starvation, stagnation, distortion, low speed motoring, WHL gas environment, bearing minimum film (design versus actual), bearing loads, mechanical design and control and bearing power loss.

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INTRODUCTION

In April, 1977, the first Mini-Brayton Rotating Unit, shown in cutaway in Figure 1, was conformance tested and delivered to the DOE for installation and testing in the Brayton Isotope Power System (BIPS) Workhorse Loop (WHL). The Mini-BRU is shown installed in the loop in Figure 2. A detailed description of the program to develop the Mini-BRU is presented in Reference 1. At the time of delivery no hot testing had been performed on the unit. It was the intent of the DOE BIPS program to integrate the Mini-BRU with a recuperator, simulated isotope heat source, ducting and cooler such that a simulated flight-type system could be tested.

The basic NASA design comprised a Columbium (C-103) turbine plenum/nozzle assembly with the intent of operating in a 1600°F turbine-inlet-temperature refractory system. Concerns over the integrity of the refractory components and the cleanliness of the system prompted DOE to direct the fabrication of an all superalloy system as the WHL.

This system was designed and fabricated in August, 1977, the Mini-BRU, now fitted with a Waspaloy turbine plenum was installed in the loop in preparation for system performance mapping and endurance testing.

Simultaneously with the loop preparation, testing was also being continued with the Mini-BRU Simulator Test Rig (STR). The STR is a bench test rig which simulates the dynamic characteristics of the Mini-BRU including the alternator and bearing system.

The Mini-BRU utilizes cycle gas lubricated foil bearings. The journal bearings consist of 8 cantilevered foils wrapped around the shaft and retained in a housing as shown in Figure 15. The nomenclaute used to represent the bearing is shown on Figure 50.

The STR tests revealed a possible journal bearing instability problem at high electrical loads. The problem could be accentuated by high temperature operation where it was then expected that an increase in sway space might occur. A decision was therefore made to remove the unit from the loop and replace the bearings with "stiffer" ones. This modification was accomplished, and the unit was reassembled into the loop.

Figure 1. - Mini-BRU.

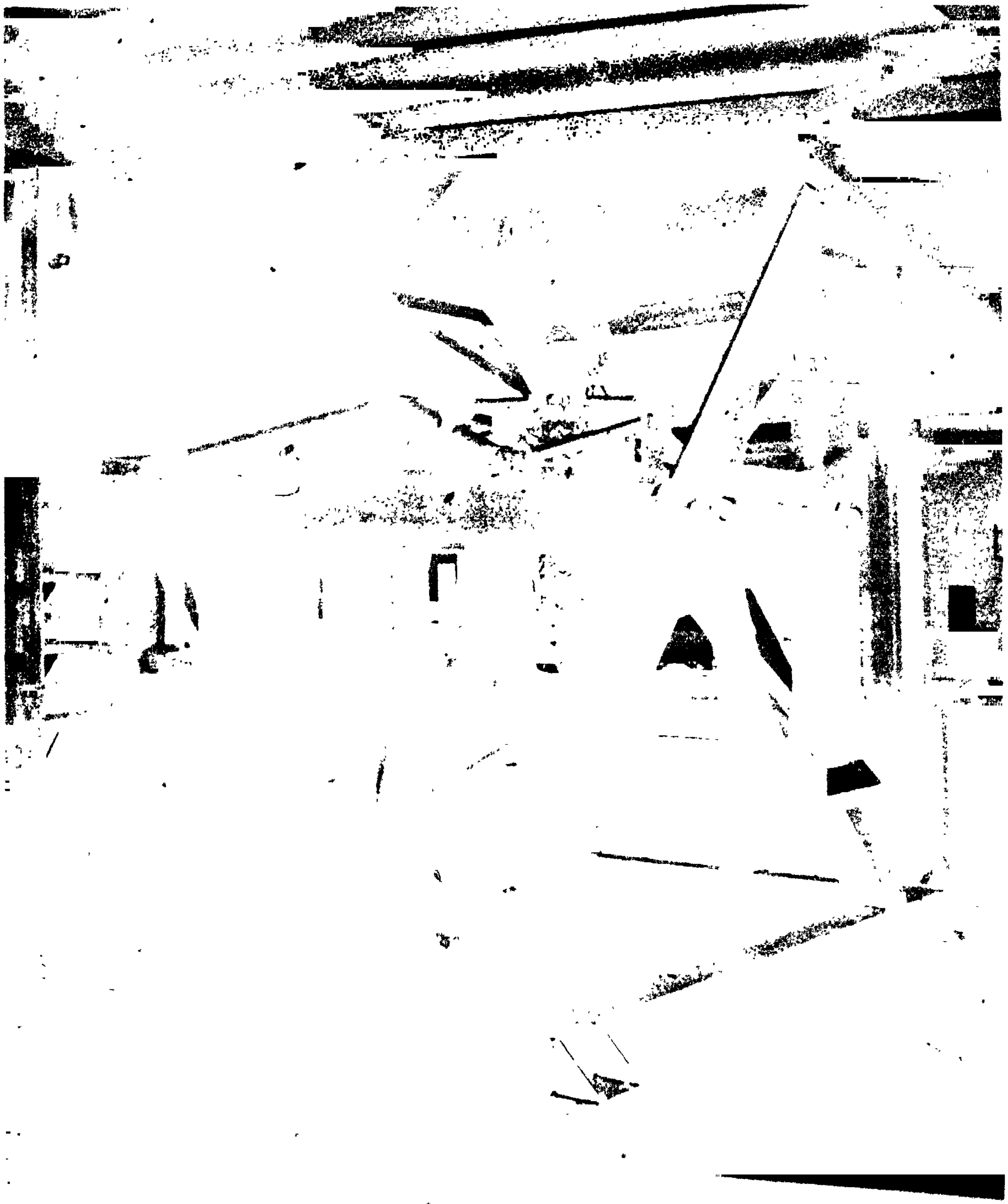

Figure 2. - Mini-BRU Installed in the Workhorse Loop.

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On November 2, 1977, WHL operation was initiated. As the system was brought up to speed the Mini-BRU was electrically motored for substantial periods at speeds in the range of 14,000 to 30,000 rpm to circulate warm gas and aid in uniform heating of the loop. The unit became self-sustaining and automatically locked on speed and load at a turbine temperature of less than 800°F. The turbine end bearing temperature was monitored by a thermocouple attached to the backside of a foil and reached a maximum of 444°F.

After 69 hours and 2 minutes of testing had been completed, the unit shutdown on November 8, 1977. Twenty-four aborted starts were conducted in attempts to bring the unit back to operating conditions; however, self-sustaining operation could not be achieved.

The unit was removed from the loop and disassembly revealed the compressor journal bearing to be severely deteriorated. A review of the trend recorder data revealed an erratic condition of unit electric power output just prior to shutdown suggesting internal power absorption.

Figure 3 shows the historical and chronological sequence of events leading up to this and the subsequent WHL tests.

Examination of the totally failed compresor bearing and the relatively unscathed turbine bearing suggested that the long periods of low-speed motoring and perhaps bearing instability had contributed to the demise of the compressor bearing. As a result of this diagnosis, tests were conducted in the STR to duplicate the low speed motoring histogram. In addition, tests and analyses were conducted on the Mini-BRU, operating cold, to determine if instability existed in the rotor/bearing system. These tests proved negative so another WHL test was attempted with higher radius of curvature bearings, closer tolerance rotor balance, and no low-speed motoring.

Figure 4 provides a listing of pertinent foil bearing parameters selected for the following several WHL tests and other builds.

Testing with these modifications was initiated in the WHL on December 21, 1977. The installation of a multifoil insulation pack between the turbine backshroud and the turbine journal bearing resulted in a reduction of that bearing temperature from 440° to 350°F. After 3 hours and 30 minutes of testing, a unit overspeed initiated a loop shutdown.

Key Tests	Results	Supporting Tests And Analysis	Resulting MODS To Mini-BRU
Mini-BRU Conformance Test 5 Hrs At Speed No Load	Bearings Look O.K.	STR Tests Indicate Instability With "Thin" Foils	Mini-BRU Journal Foils Replaced With Thicker Foils
11-8-77 WHL #1 Failure In 52 Hours	Low Speed Motoring and/ Or Rotor Stability Suspect Slot Fit	Analysis: Low Speed Motoring Tests, Start/Stop Tests Rotor Stability Evaluation Improve Inspection Techniques R_c, Skew, Spring Rate	Increase R_c, Pre-Test To Monitor Stability, Eliminate Low Speed Motoring In WHL, Better Balance
12-22-78 WHL #2 Bearing Distress in 3 Hours	Suspect Overtemperature Overload/or Change In Sway Space Causing Instability-Or-Electric Arcing-Or-Coating Deterioration. Evidence of Teflon Coating Lack of Bond	Electrical Arcing Tests in STR, Thermal Analysis, Foreign Particle, Starvation/Stagnation Design Deficiency (High Load-Low Film Min) Check Mag. Forces On Foils and Bars, Uncoated Foil Tests, Improve Fabrication and Inspection Techniques Skew, R_c, Surface Fin.	Instrument To Measure Foil, Carrier, Shaft Temperatures
2-14-78 WHL #3 Good Results in 6 Hours	High Temperature Eliminated As Suspect; Thermal Analysis Shows 0.0008 In Reduction Of Sway Space-Comp End	Unable To Simulate Failure In "Cold" Rigs, New Vendor For Tef-S Coating Evaluated, NASA Beam Analysis Indicates Good Design, Continue to Improve Fabrication and Inspection Techniques	Continuity/Ground Probe Installed, Sway Space Increased, Bleed Flow Cooling Increased, Vent Compressor Bearing Better Tef-S Surf. Finish, Composition and Closer Process Control
5-22-78 WHL #4 No Problem In 1000 Hours	Diagnosis Shown To Be Correct	Continue Tests In STR and MBTR To Simulate Failure With Tight Sway Space, Continue To Improve Fabrication And Inspection Techniques	Extended Program Needed To Verify Design Margin And Characterize Teflon Coating

Figure 3. - Bearing Development Histogram.

WHL Date	October 24, 1977	November 8, 1977	December 22, 1977	February 14, 1978	March 17, 1978 and March 27, 1978 Build	1000 Hour WHL * April 17, 1978 through May 22, 1978
Lot Number	7318	7491	7517	8569	8592	8593
Foil Material	302 S.S.	302 S.S.	302 S.S.	302 S.S.	302 S.S.	302 S.S.
Pin Material (Mag/ Non-Mag)	Mag	Mag	Non-Mag	Non-Mag	Non-Mag	Non-Mag
Material Thickness--Base/ Total	0.0048/ 0.0058	0.0052/ 0.0062	0.0052/ 0.0061	0.0050, 0.0051/ 0.006	0.0050 0.0062	0.0050 0.0060
Radius of Curvature	0.59	0.57	0.61	0.59	0.57	0.57
Surface Finish (RMS)	30-45	26-34	20-33	30-48	8	8
Spring Rate (lbs/in.)	910	3845	2380	1000	1562	1351
Foil Coating	Teflon-S	Teflon-S	Teflon-S	Teflon-S	Teflon-S	Teflon-S
Cure Temperature	650°F	650°F	650°F	650°F	570°F	630°F
Foil Length	0.770	0.775	0.770	0.770	0.765	0.775
Foil Width	0.902	0.896	0.902	0.901	0.880	0.880
Sway Space - Compressor End (cold) - Turbine End	0.0092 0.0092	0.0076 0.0076	0.0082 0.0080	0.0087 0.0086	0.0091 0.0084	0.0099 0.0092
Balance - "H" Plane Open - "V" Plane		0.0034 0.0027	0.0010 0.0012	0.0007 0.0005		0.0007 0.0005

*Successfully completed 1006.9 hours on May 22, 1978.

Figure 4. - Mini-BRU Journal Bearings Comparison: Four Workhorse Loop Tests Plus New Mini-BRU Builds.

Review of trend recorder data revealed the load shedding phenomena to have again occurred. Consequently, the unit was removed from the loop and disassembled.

Again the compressor-end bearing was found in a seriously deteriorated condition while the turbine-end bearing showed only minor wear. Fortunately, the imminent bearing failure had been caught early, and the bearing pads were in a condition amenable to mechanical and thermal analysis.

The similarities and differences between the two failures increased concern to the extent that NASA extended the Mini-BRU program to provide an extensive bearing investigation.

A summary chart showing the wide variety of topics examined and the results found is presented in Table I. That bearing program and the results and conclusions arrived at therein are the subject of this report.

During the time period following the November bearing failure, a major effort was also directed at improving the method of fabricating the bearings and, equally important, inspecting the process and the finished product. This effort resulted in a great improvement in controlling radius of curvature, edge skew, material composition and thickness, and overall dimensional control.

Investigation into electrical arcing revealed that the phenomena could occur under conditions where the bearings were totally lifted off the shaft. This investigation, however, raised another question, that is, whether the foils were completely losing contact with the shaft. Electrical continuity measurements revealed that only a seemingly random basis, was totally loss of continuity achieved.

Continuity tests were conducted on the highly successful DC-10 foil bearing machine. With the sensing circuit on low sensitivity, continuity was apparently lost; however with high sensitivity, spikes of continuity were observed. This testing led to the design, fabrication, and installation of a continuity/ground probe for the Mini-BRU.

Subsequently, further detailed thermal analysis revealed that the compressor-end sway space was reduced at operating temperature by 0.0008 inch whereas the turbine-end sway space was reduced by 0.0003 inch. This was judged to be significant since both bearing failures had involved the compressor bearing.

Based on the analysis and test results at that date, another WHL test was scheduled. The design modifications to the Mini-BRU were as follows:

TABLE I. - BEARING DEVELOPMENT PROGRAM

Possible cause		Action	Results
1. Coating	Composition and process	STR test uncoated foils	Bare, dichronite and MoS_2 coated foils tesced and judged to be suitable for alternate configurations
	Cleaning	WHL test uncoated foils	Not implemented
	Adherence	BCL microbalance tests (A)	~10 percent Teflon loss estimated for 7 year mission
	Blisters	Hot stage microscopy (D,E)	Complete - No bubbling or debonding
	Softening	Hohman wear Tester (C,D,E)	Hohman tests not implemented - no softening experienced with properly cured Teflon
2. Temperature	Coating	WHL test w/instrumentation	February 14, 1978; temperatures agree with analysis
	Distortion	Analyze results - correlate with analysis - fix	Thermal analysis checks with test
	Overloads		
3. Foreign particles		Identify TI and CR sources	Part of Teflon
		SEM, EDAX (foils ?, Shaft?)	All material identified as teflon or shaft
		BRU blow-down	Negative except for one large particle of encapsulating compound
		Loop blow-down	No particles larger than 5-10 microns found
4. Electric or Mag effects	ischarge	Measure potential analytical	Charge/discharge observe STR under certain conditions - none experience in WHL
	Mag foils Mag force	Check magnetic force	CRES 302 foils not attracted-magnetic keepers are
5. Starvation 6. Stagnation		Added pressure instrumentation on WHL	Attempted to add pressure instrumentation on WHL to measure bearing
7. Distortion		Thermal analysis	Thermal analysis indicates no excessive temperatures
		Foil surface examination	No foil distortion measured
8. Low speed motoring		Review first WHL test where bearings were changed	Prolonged motoring at N<25,000 deleted from test procedure; start/stop with Teflon-S coated not a problem; start/stop with MoS_2 coated OK for limited number of starts made to date

TABLE I. - Concluded.

	Possible cause		Action	Results	
9.	WHL tests environment gas in brg comp	Inert atmosphere	Hohman wear test in Xe-He	Not applicable	These causes eliminated by WHL tests
		Interaction			
		Lubricity	CTR tests	Not implemented	
10.	h_{MIN} Marginal-design versus actual		Hydronamic analysis	Modeling of foil deflecting zero eccentricity case complete. Gas film pressure complete	
			Compare to DC-10 bearings no measurement	Empirical comparison indicates similar design margins	
11.	Actual bearing loads		Calculate bearing loads for actual operating conditions (static)	Bearing loads found to be within acceptable limits-design has adequate load margin	
12.	Mechanical design and control		Dim analysis and review critical cards	Dimensional analysis indicates no abnormal interferences	
13.	Bearing performance	High power loss in KR at pressure	SBTR	Tests in PBTR conducted to characterize uncoated, alternate coatings and alternate configurations in air, argon, krypton and Xe-He from 0-100 psia - results factored into thermal analysis	

(1) Increased bleed flow for bearing cooling (~50% increase)

(2) Slotted retainer on compressor end journal bearing

(3) Increased sway space:

0.0099 compressor cold (0.0091 hot)

0.0092 turbine cold (0.0087 hot)

(4) Journal foils coated by Crest Coating Co.

Surface finish 8 rms

630°F cure

(5) Continuity/ground probe

(6) Bearing cavity pressure instrumentation

(7) Provision for assuring retainer is always wider than foil

This test was initiated on April 7, 1978, and was originally targeted as a 100 hour bearing verification test. The initial 100 hours were completed and indications were that the bearing was performing well: Bearing temperatures remained absolutely stable throughout the test period.

A decision was made to continue the test to 1000 hours. A total operating time of 1006.9 hours was successfully completed on May 22, 1978.

For purpose of convenience, the details of the development program in the following sections are arranged according to the type of testing or the major topic.

DETAILED TESTS, ANALYSES AND RESULTS

STR and MBTR Tests

During the period 5 January through 20 June 1978, a tests series was conducted using the Simulator Test Rig (STR) and a similar rig called the Mini-BRU Test Rig (MBTR). These rigs as well as the test techniques, objectives and results are described in the sections which follow.

Simulator test rig (STR). - The STR is shown in Figure 5. The rotating masses and inertial properties of the STR are identical to that of the Mini-BRU; thus, it provides dynamic simulation of the parent machine.

The central portion of the STR consists of a Mini-BRU alternator stator and housing. An actual Mini-BRU alternator rotor and a thrust runner are used in the rotating group. A dummy mass is substituted for the turbine wheel and an air driven turbine wheel is substituted for the compressor wheel. In the usual mode of operation, compressed air impinging upon the blades of this turbine wheel drives the rotating group. The rotor is supported by a complete bearing system consisting of two journals and a thrust bearing. Bearings and carriers are completely interchangeable with Mini-BRU components.

The STR is also capable of being electrically motored (as is the Mini-BRU). In the motoring configuration, the turbine air drive is removed from the compressor end and a compressor wheel and diffuser is substituted. This configuration may be operated in air or in an inert gas in a sealed environmental chamber.

Available STR instrumentation permits the monitoring of rotor stability, temperatures, speed, bearing lift off, and start and stop characteristics.

The STR provides a close dynamic simulation of the Mini-BRU except for the following:

(1) A flow path for air (or other gas in which the STR operates) is provided in the STR to reach both journal bearings. In the Mini-BRU, the region surrounding the compressor journal bearing is not served by flowing gas but is dependent upon conduction for cooling.

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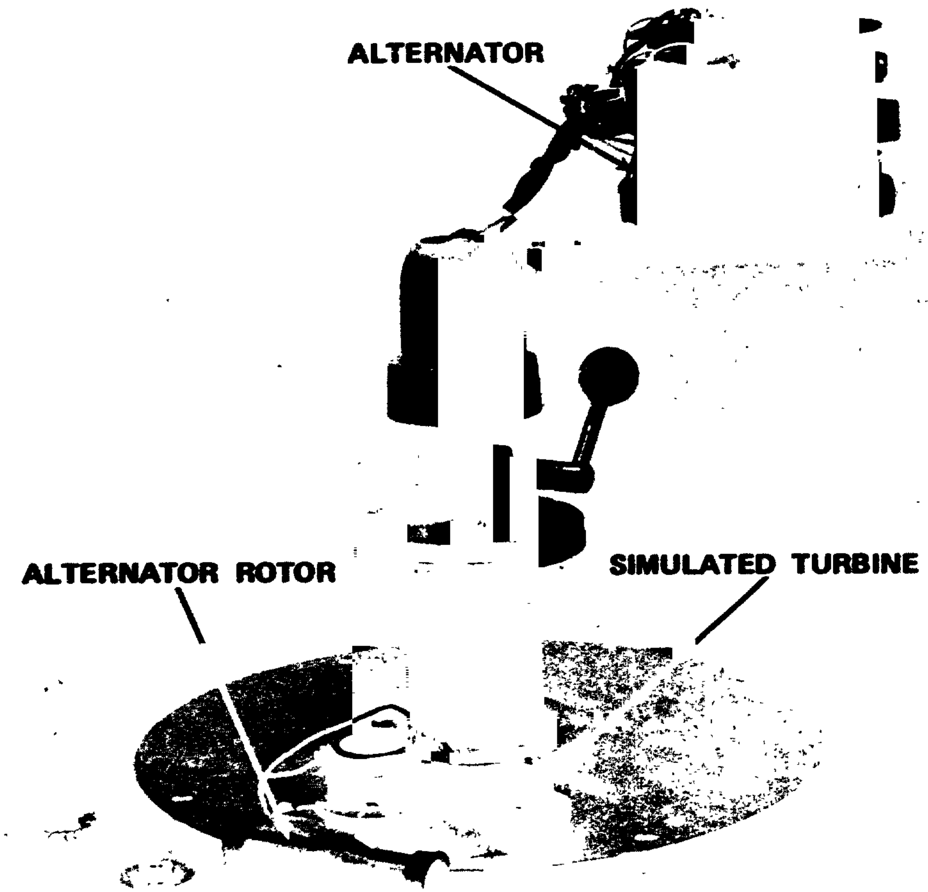


DYNAMIC SIMULATOR

FEATURES

- 3 BEARING SYSTEM
- ACTUAL ROTOR MASS AND INERTIA
- PERMITS VARIETY OF TESTS
  - STABILITY
  - START-STOP
  - ENDURANCE
  - CRITICAL SPEED

Figure 5. - Simulator Test Rig.

(2) The STR does not (nor was it ever intended to) duplicate the temperatures and pressures present during closed-loop WHL operation.

Therefore, a special configuration was used for several tests in order to more closely simulate the geometry of the Mini-BRU, thus compensating for the deficiency (1) above. This configuration was designated the Mini-BRU test rig.

Mini-BRU test rig (MBTR). - The MBTR utilized the No. 2 Mini-BRU Alternator Assembly and Housing. The STR rotor, thrust runner, and thrust bearings were used as was the STR compressor wheel (identical to the Mini-BRU compressor wheel). The compressor backface shroud and compressor diffuser with monopoles completed the build at the compressor end of the assembly. A pair of Wayne-Kerr displacement probes were installed at the turbine end. A dummy was installed in place of the turbine wheel.

To simulate motoring of the Mini-BRU with argon (as was done in the WHL), the MBTR is capable of being placed in an environmental chamber and the chamber pressurized with argon. This test configuration was used in one test series.

Motoring of the MBTR in air is limited to - 28,000 rpm (-24,000 rpm in pressurized argon). For higher speed operation, the turbine dummy mass was replaced with an actual Mini-BRU turbine wheel and the turbine test rig nozzle assembly was added. The rotating group was then driven by means of compressed air impinging upon the turbine blades.

Continuity testing. - Among the new techniques which evolved during the tests program was that of continuity testing. The objective was to detect the absence of contact (electrical continuity) between the rotor and the stator at operating speed.

The test setup is shown schematically in Figure 6. For the STR tests, a simple brush riding on the flat surface of the turbine dummy was provided contact with the moving rotor. (A more sophisticated carbon brush contact was developed for the Mini-BRU used in the 1000 hour WHL run of April-May 1978.)

With the rotor at rest, the scope indicates 0 volts if the bearing surface is conductive. If bearing surface is non-conductive, a thin (0.000020 in.) flashing of gold is added. As the resistance of the rotor/foil interface

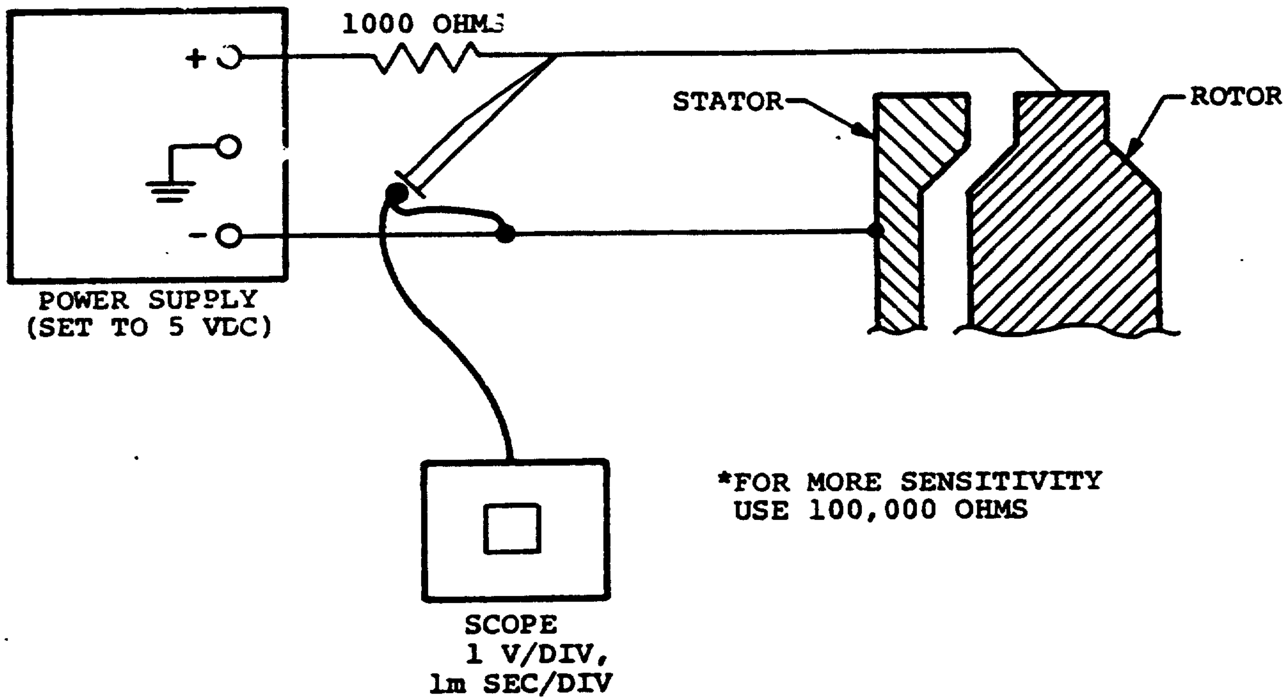


Figure 6. - Continuity Test Schematic.

becomes large compared to 1000 ohms, the scope shows 5 volts. Intermediate gas film resistances may be estimated.

Although many continuing tests were conducted using the test setup, additional refinement of the equipment is needed before repeatable results may be expected.

Charge build up testing. - A similar brush contact was used in checking for the presence of charge build up on the rotor during STR operation. The test configuration is shown schematically in Figure 7. The electrostatic voltmeter used had an internal impedance of 10^{15} ohms.

Rotor/Bearing Capacitance Test - The capacitance between the Rotor and the Bearings was measured by means of the test setup shown schematically in Figure 8a. The scope is first adjusted for the display shown in Figure 8b. The msec/division adjustment on the scope is then decreased to determine the time to (0.63) x 5 = 3.15 divisions.

Capacitance, C, is then calculated:

$$C = \frac{\text{Time}}{1 \times 10^6} \text{ farads}$$

The typical rotor/bearing capacitance was determined to be 2100 picofarads.

Trim balancing of rotating group. - Prior to 23 March 1978 it was the custom to balance the rotating group while it was removed from the Mini-BRU or the STR. After balancing, the rotating group was disassembled and then reassembled in the Mini-BRU or in the STR. Experience showed that the balance varied slightly after teardown and reassembly.

On 23 March 1978, a successful attempt was made to trim balance the rotating group while installed in the STR. The method utilized a dynamic analyzer capable of determining balance in two planes while the rotor operated at 52,000 rpm. Balance was corrected by adding small amounts of a fast setting acrylic cement to the air drive turbine and the turbine dummy mass. Typically, the Lissajous pattern (denoting shaft excursions) could be reduced from 0.0005 inch to approximately 0.0001 inch diameter on each end of the rotating group shaft.

Fixtures were fabricated for use in trim balancing the Mini-BRU and are now available for future use.

Scanning electron microscopy (SEM) and microprobe analysis. - Scanning Electron Microscopy (SEM) and Microprobe Analysis was used in support of a number of tests conducted.

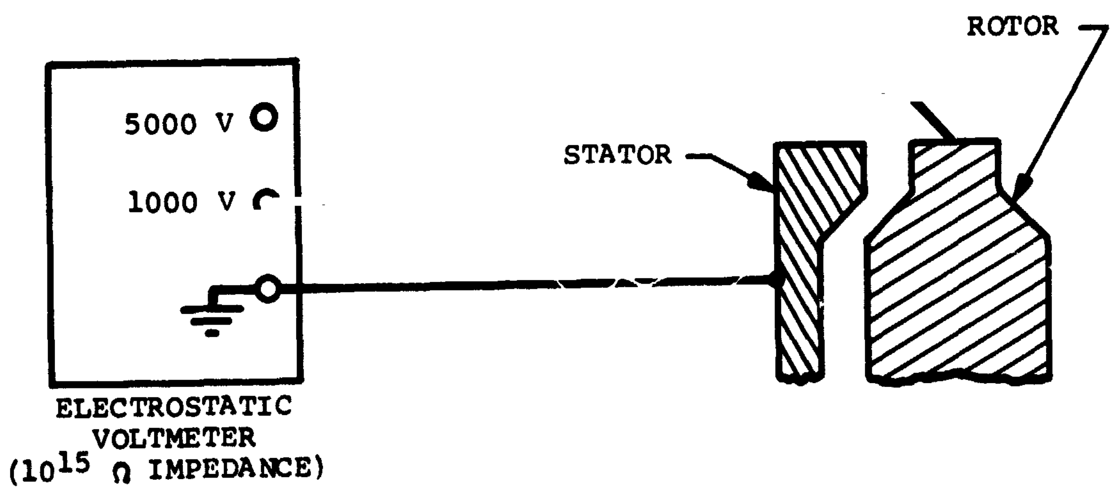


Figure 7. - Charge Buildup Test.

SEM photographs were made of selected areas of the foil bearing surfaces before and after certain tests. Microprobe analysis was used to identify foreign particles.

Examples of SEM photos and microprobe analysis made during the low speed motoring tests conducted 16-19 January 1978, are in the Figures 9, 10, and 11. Figures 12 and 13 show a spectroscopic analysis of a spot on one foil. This technique was used to identify debris and/or inclusions in the Teflon material. These two traces show the inclusion to be insatially Teflon material.

Test techniques. - Among the test techniques originated and/or used during the January - June 1978 test series were the following:

(1) Motor starts and runs in pressurized argon (simulation of WHL motoring)

(2) Test for loss of electrical continuity (rotor/bearings)

(3) Test for rotor/bearing capacitance

(4) Test for charge buildup on rotor

(5) Accelerated charge/discharge induction

(6) Flashing of foils with gold (to detect loss of electrical continuity of Teflon-coated foils)

(7) Test for open and short circuits - alternator output

(8) Trim balancing of rotating group while installed in STR

(9) Static tests for rotor/carrier and thrust runner/ thrust bearing continuity

(10) Scanning electron microscopy and microprobe analysis - examination of foils, pre- and post-test.

Principal observations. - The principal observations made during the STR and MBTR tests are:

(1) STR and MBTR simulations of 12-22-77 WHL shutdown histogram - unable to duplicate bearing damage; however, STR test of 11-12 May 1978 resulted in excessive and abnormal wear.

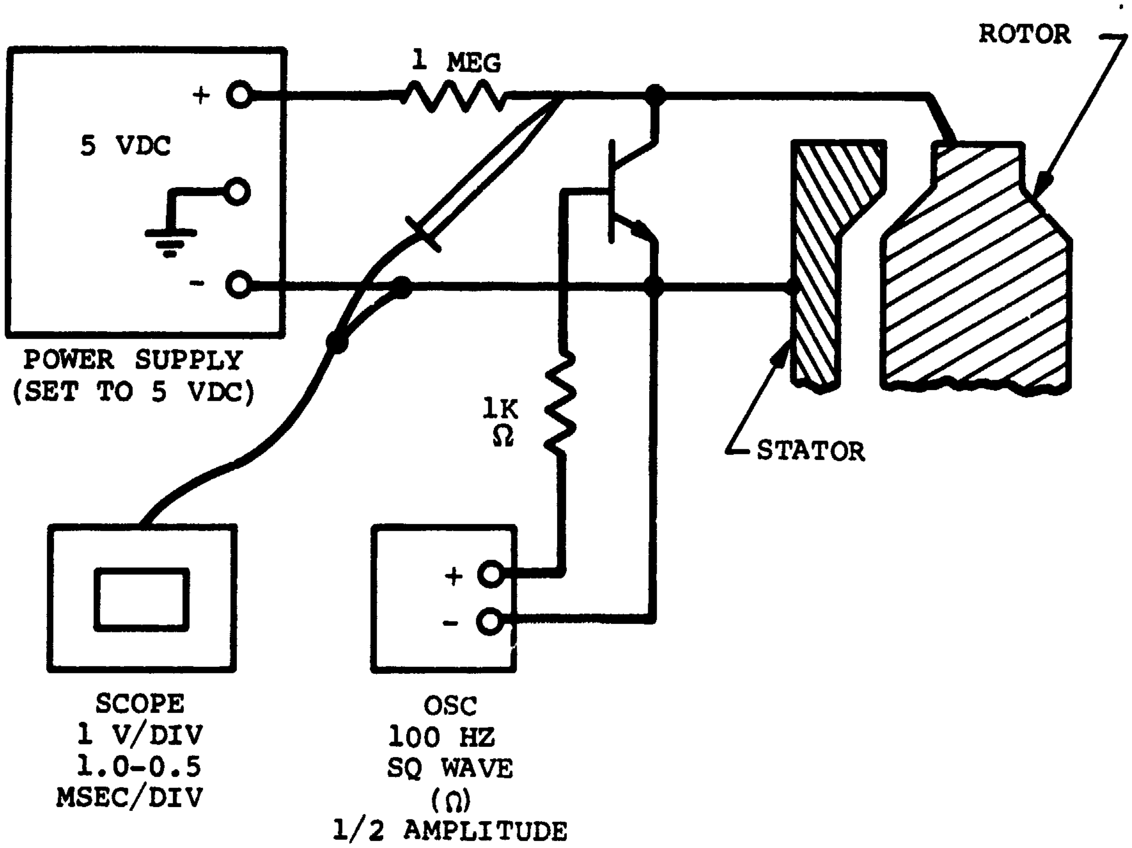


Figure 8a. - Capacitance Test Schematic.

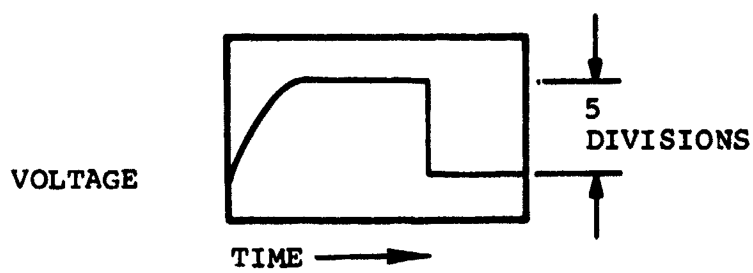
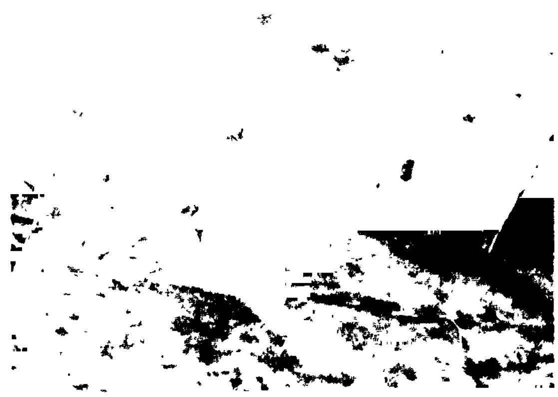


Figure 8b. - Charge Buildup Scope Display Schematic.

AREA "42" S/N 604-62X
WEAR ON TRAILING EDGE
TEFLON DEBRIS



AREA "41" S/N 604-210X
TYPICAL WEAR OF
TEFLON

Figure 9. - Post-Test Scanning Electron Microscopy.

FOIL S/N 600-17X AREA "28" - 240X AREA "28" - 510X

ANALYSIS OF SPOT IN AREA 28 SHOWED MAJOR CHROME, MINOR NICKEL.
PROBABLY POORLY MIXED BINDER OF FILLER IN TEFLON.

Figure 10. - Pre-Test Scanning Electron Microscopy (trailing edge toward top).

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FOIL S/N 610 - 17X

AREA "31" - 250X

AREA "31" - 510X

Figure 11. - Pre-Test Scanning Electron Microscopy.

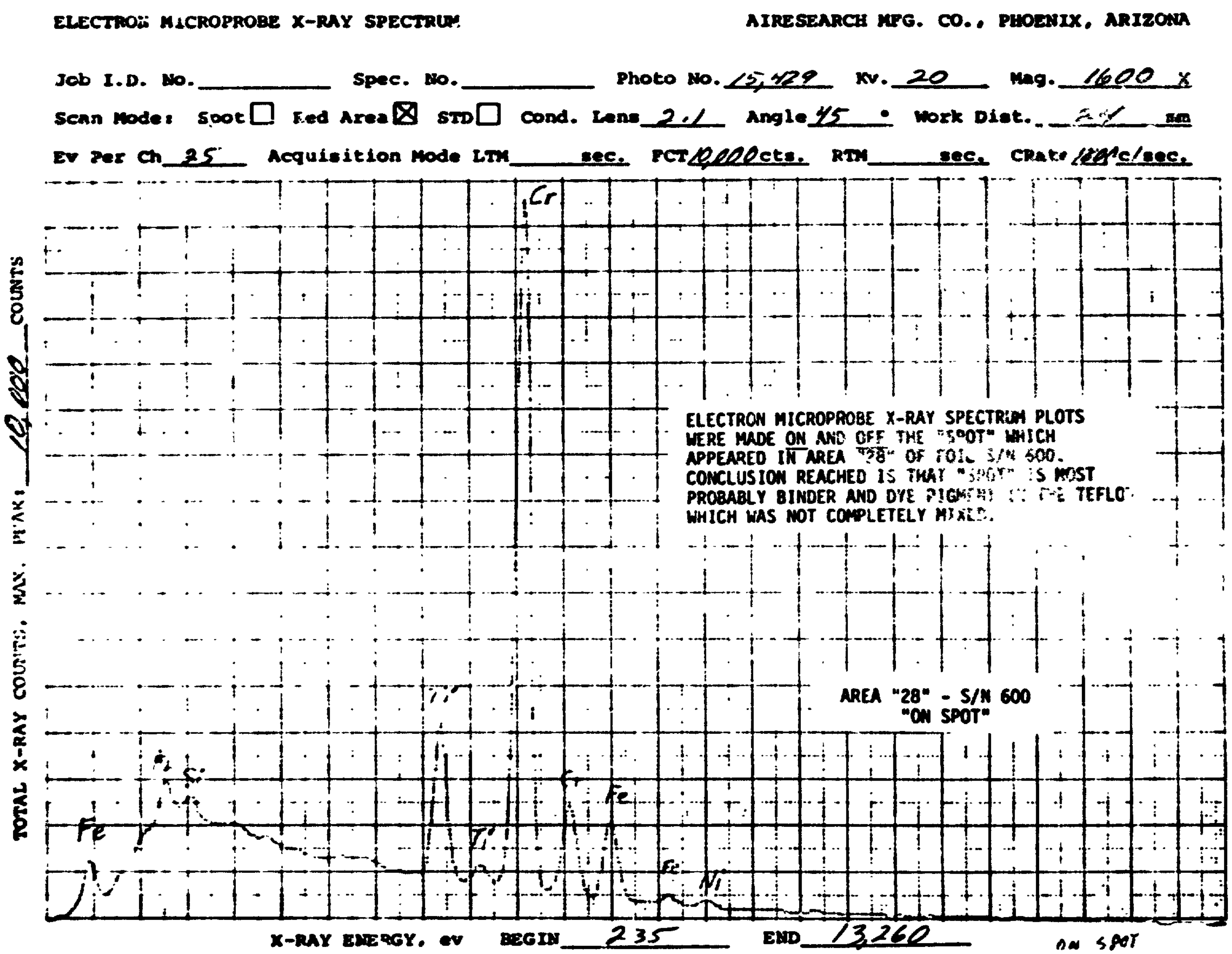


Figure 12. - Electron Microprobe X-Ray Spectrum.

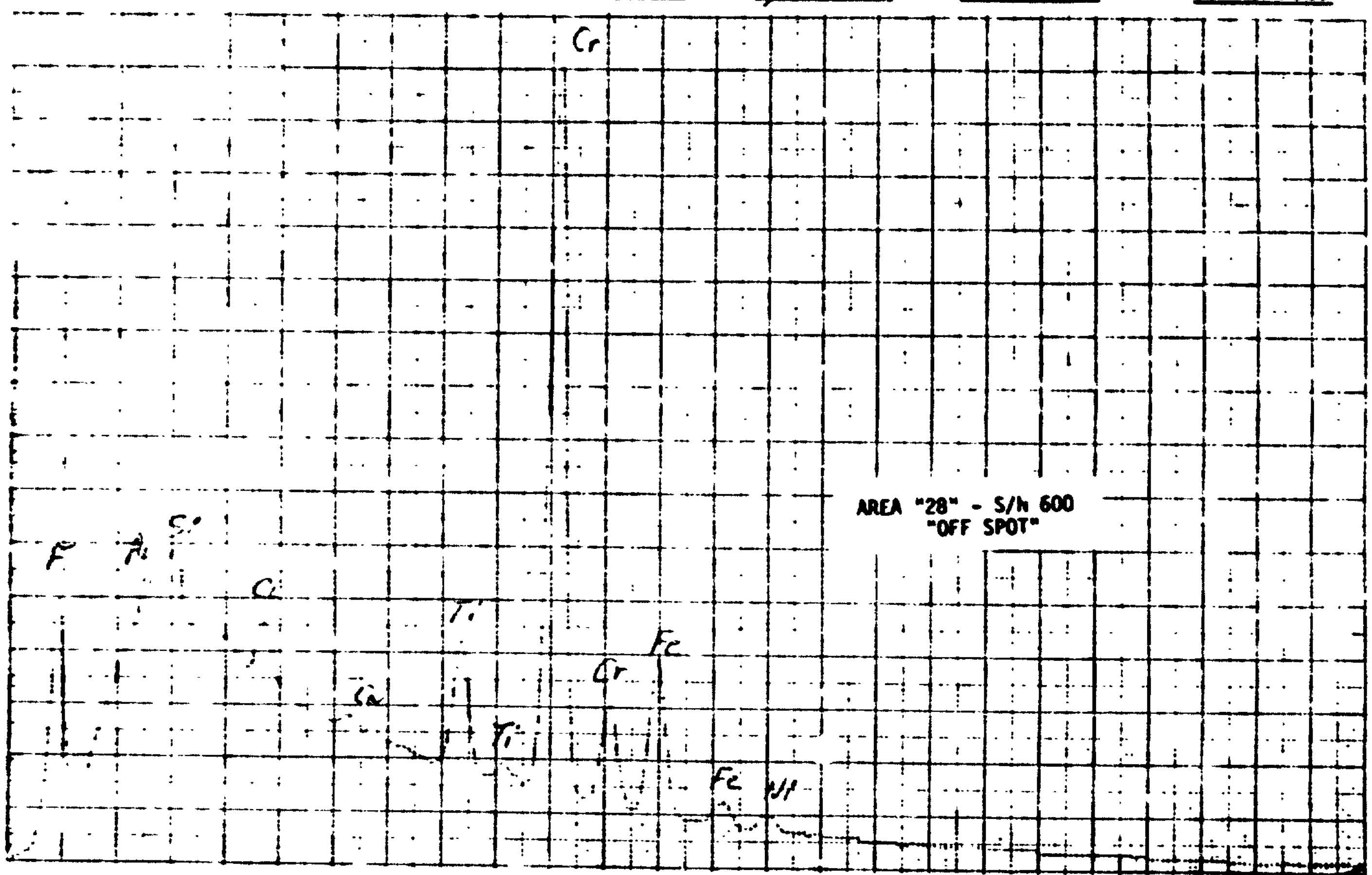
ELECTRON MICROPROBE X-RAY SPECTRUM | AIRESEARCH MFG. CO., PHOENIX, ARIZONA

Job I.D. No.______ Spec. No.______ Photo No. 15,429 Kv. 20 Mag. 1600 X

Scan Mode: Spot ☐ Red Area ☒ STD ☐ Cond. Lens 2.1 Angle 45° Work Dist. 24 mm

Ev Per Ch 25 Acquisition Mode LTM ____ sec. FCT 10,000 cts. RTM ____ sec. CRate 1800 c/sec.

TOTAL X-RAY COUNTS, MAX. PEAK: 10,000 COUNTS



X-RAY ENERGY, ev BEGIN 235 END 13,260 OFF SPOT

Figure 13. - Electron Microprobe X-Ray Spectrum.

(2) Observed complete loss of continuity at 52,000 rpm, fully loaded - CRES-32/Teflon-S; flashed w/gold

(3) Observed nearly complete loss of continuity -many times

(4) Stability and continuity - both sensitive to application of field current

(5) Rotor/bearing interface capacitance - typically 2000 picofarads

(6) Observed charge build on rotor (300 volts), discharge to zero, 1-1/2 - 6 min. cycle in air

(7) Accelerated induced charge/discharge test resulted in damage; similar damage, however, has not been found in WHL bearing failures

(8) Balance can be improved by trim balancing in assembled STR at operating speed

(9) A balanced rotating group improves stability, and improves ability to show loss of continuity

(10) Open and short circuits of one alternator output phase had minimal effect on stability

(11) MoS_2 coating on "1010" mild steel increases lubricity and discourages generation of black debris

(12) Some Teflon coated foils exhibit tendency towards increased starting torque after minimal starts

(13) Static tests have shown rotor/journal bearing continuity even with Teflon coated foils

(14) Static tests have shown no thrust runner/thrust bearing continuity.

Test summary. - A summary of all tests completed during the period January - June 1978 is contained in Tables II through VII which follow. Referenced photos appear in Figures 14, 15, and 16.

Spring Rate Testing

An extensive program of spring rate testing was initiated in early April 1978. The program had the following primary objectives:

TABLE II. - JANUARY 1978 STR TESTS/EXPERIMENTS BIPS - MINI-BRU FOIL JOURNAL BEARINGS

Date	Configuration	Objective	Observations/Results
5-10 Jan 78	CRES-302/Teflon-S (coated by Thermac) R_c = 0.61" Surface finish - >20 rms Cure temperature 650°F Magnetic bars Thickness - 0.0061 in. to 0.0062 in. (Bearings had previously been run for 120 hours at 52,000 rpm with no detectable damage.)	To determine the effects of repeated motorings and running at design speed on bearings installed in the STR. To repeat the time-speed history of the bearings in the Workhorse Loop that experienced the automatic shutdown on December 22, 1977. (number of motoring starts and the running time at each speed were doubled)	Following is a summary of starts and operations at speeds for periods greater than 1 min*: Time, hr:min — Speed, rpm 8:20 — 21,720 to 22,400 (maximum in argon at 12 psig) 1:00 — 55,000, in air 0:10 — 62,000, in air 8:10 — 52,000, in air 2:02 — 22,000 to 51,000 continuous motoring, in air Total starts = 214
16-19 Jan 78	CRES-302/Teflon-S (coated by Thermec) R_c = 0.61" Surface finish - >20 rms Cure temperature 650°F Magnetic bars Thickness - 0.0058 in Length - 0.775 in Spring rate - 1220 lb/in.	To repeat the previous test using a Mini-BRU Test Rig (MBTR) in lieu of the STR. (The MBTR utilized the #2 Mini-BRU Alternator Assembly and Housing. The MBTR provides a better simulation of the actual Mini-BRU because, unlike the STR, the region surrounding the compressor journal bearing is not served by flowing gas but is dependent upon conduction for cooling.)	Following is a summary of starts and operation at speeds for periods greater than 1 min.*: Time, hr:min — Speed, rpm 8:00 — 23,500 to 24,100 (maximum in argon at approx 12 psig) 1:00 — 55,000, in air 0:20 — 60,500 to 62,000, in air 8:00 — 52,000, in air 2:02 — 22,000 to 51,000 continuous motoring, in air Total starts = 195

*Over 180 starts consisted of reaching predesignated speeds and then coasting to stop. Total time for each was < 1 min.

TABLE II. - Continued.

<table>
<tr><th>Date</th><th>Configuration</th><th>Objective</th><th>Observations/Results</th></tr>
<tr><td>16-19 Jan 78
(Contd)</td><td></td><td></td><td>Following is a summary of breakaway torque measurements and results of SEM examination of the foil journal bearings:
<table>
<tr><th>Test Interval</th><th>Breakaway
Torque, in.-lb</th><th>SEM
Foil Examination</th></tr>
<tr><td>Prior to first test</td><td>1.1</td><td>Fairly uniform surfaces; light scratches.</td></tr>
<tr><td>Completion of motorings in argon</td><td>1.1</td><td>(Visual exam)
Somewhat more than normal wear.</td></tr>
<tr><td>Completion of test</td><td>1.1</td><td>Somewhat more than normal wear; some debris observed. However, nothing observed similar to WHL experience.</td></tr>
</table>
The build and/or the environment of the MBTR failed to simulate that which was responsible for the unsatisfactory WHL experience of 12-22-77. See photo of sample foil in Figure 14 and SEM/microprobe analysis in Figures 12 and 13.</td></tr>
<tr><td>23 Jan 78</td><td>CRES-302/Teflon-S
(coated by Thermec)</td><td>To determine the effect of open and short circuits in the output phases of the Mini-BRU alternator</td><td>Unable to introduce more than a very mild instability in the STR by open circuiting a single phase of the alternator output.</td></tr>
<tr><td>27-28 Jan 78</td><td>CRES-302/Teflon-S
(coated by Thermec)
"old" foils, used in many earlier STR tests.</td><td>To determine if an electrical potential exists between the alternator rotor and stator.</td><td>Electrical brush applied to Turbine Dummy Mass. Voltage buildup measured with Electrostatic Voltmeter with 10^{15} ohms internal impedance. Operated at 52,000 rpm and 1340 watts output in air at ambient conditions. After few minutes, voltage slowly rose to 200 volts, then discharged to 0. Cycle repeated a number of times with voltage generally reaching 300 volts before discharging. Time required to build a charge and then discharge varied from 1-1/2 to 6-1/2 minutes.</td></tr>
</table>

TABLE II. - Concluded.

Date	Configuration	Objective	Observations/Results
27-28 Jan 78 (Contd)			An accelerated charge/discharge test followed. An oscillating circuit was used which charged the rotor to 450 volts and then discharged (foils to rotor) to 200 volt level. This cycle was repeated at 8000 Hz while STR was air driven at 52,000 rpm, 1330 watts, for one hour. Accelerated test resulted in damage to several foils in both journal carriers. Areas of wear and distress to the Teflon matched darkened rings on the rotor.
30 Jan 78	"1010" Mild Steel, uncoated. Lot #8561 R_C = 0.61 in. Length - 0.770 in. Thickness- 0.0052 in. Sway space - Compr. - 0.0082 in. Turb. - 0.0078 in.	To determine if electrical charge builds on rotor as it did in previous test.	Two starts made - one to 15,000 rpm, the second to 52,000 rpm, 1434 watts. No appreciable charge noted. Breakaway torque increased from 1.8 to 3.5 in.-lb. Inspection disclosed much wear on compressor foils, somewhat less on turbine foils. Build-ups of very fine black powder on all foils, determined to be iron from foils themselves.
30 Jan 78	CRES-302/Teflon-S (coated by Thermec) Lot #7308 Thickness-0.0048 in. (base metal) R_C = 0.59 in. Surface finish - >20 rms	To determine if electrical charge builds on rotor.	Breakaway torque was a very low 1.1 in.-lbs. Test terminated when gross instabilities were observed at speeds as low as 45,000 rpm. (Bearings were similar to "thin foils" which were removed from WHL in September 77 when it was found that foils from same lot exhibited unstable tendencies in the STR. However, bearings of the same lot successfully operated in the Mini-BRU during conformance testing in March 77 and in successful WHL operation on 9-24-77.)

TABLE III. - FEBRUARY 1978 STR TESTS/EXPERIMENTS BIPS - MINI-BRU FOIL JOURNAL BEARINGS

Date	Configuration		Observations/Results
1 Feb 78	INCO-750/Teflon-S (coated by Crest) R_c = 0.61 in. Spring rate - 3700 lb/in Magnetic bars	To determine if electrical charge builds on rotor.	In attempts to run the STR on 31 Jan 78, high breakaway torque was experienced. Initial torque of 1.5 in.-lb. increased to 3.0 in.-lb. after four starts. After two disassemblies and reassemblies of the STR, torque was 2.1 in.-lb. Five successful starts were made. No charge build was noted during 15 minutes operating at 52,000 rpm, 1491 watts. Test setup was then altered to permit monitoring on oscilloscope for electrical "continuity" between rotor and bearing with 5 vdc applied to rotor. "Continuity" appeared to exist over 10% (~36°) of each revolution of the rotor at all speeds up to 60,000 rpm. Post test inspection disclosed that one foil in each carrier was skewed to the extent that one corner was lifted. Rub rings used in test were Mini-BRU components having a smaller i.d. than the STR rub rings usually installed. The test was rerun with large i.d. rub rings. Results were the same. It was therefore assumed that "continuity" was resulting from the foil bearings being in close proximity to the rotor rather than intermittent contact of rotor with rub rings. Foils were then re-radiused to 0.55 in. in an attempt to reduce the preload. However, preload increased to the point that bearings were very tight on rotor. Investigation disclosed that foils were no longer circular but had flat spots.
2 Feb 78	CRES-302/Teflon-S (coated by Thermec) R_c = 0.61 in. (These bearings were used in STR test of 1-23-78.) Foils were cleaned with detergent rather than Freon, rinsed in deionized H_2O and blown dry with argon.	To check for rotor/foil "continuity" and presence of charge/discharge phenomenon.	At rest, resistance, rotor to stator, was 100 KΩ. Capacitance, rotor to stator, was 1400 pf. At 52,000 rpm, no load, instrumentation showed no "continuity" (infinite resistance), capacitance 2250 pf. No "continuity" was indicated initially at 52,000 rpm with 2.5 amperes field current applied. However, mild instability later developed with some indication of periodic (once per revolution) "continuity".

TABLE III. - Continued.

Date	Configuration	Objective	Observations/Results
2 Feb 78	CRES-302/Teflon-S Magnetic Bar (Static test in STR)	To determine the effect on foils of energizing the alternator field windings.	STR was built with a single foil in the carrier. (Foil was preformed to a radius equal to the carrier i.d. Remainder of the space made vacant by the 7 missing foils was filled with a piece of non-magnetic shim stock.) When field current was applied to the alternator field windings, the magnetic bar of the foil was lifted from the carrier slot until the bar contacted the rotor. There was no attraction of the foil itself.
2 Feb 78	CRES-302-Teflon-S CRES-347 Bar (Non-magnetic)	To determine the effect on foils of energizing the alternator field windings.	Previous test was repeated with a non-magnetic bar. There was no attraction - foil on bar.
10 Feb 78	"1010" Mild Steel Non-magnetic bar Lot #8568 Foil surfaces coated with Dicronite (WS_2) Thickness - 0.0053 in. R_c = 0.57 in. Spring Rate - 1220 lb/in. Length - 0.765 in. Sway Space - C - 0.0078 in. T - 0.0074 in.	To check for rotor/foil "continuity" and charge/discharge phenomenon.	First test of Tungsten disulfide coated foils. (Rotor was also coated with WS_2.) Roll-down time from 52,000 rpm was 37 seconds, attesting to excellent lubricity of coatings. Intermittent to continuous " ontinuity" noted -- increased with load. Breakaway torque increased from 0.8 to 1.5 in.-lb. during 75 minutes running. Post-test inspection disclosed considerable wear on compressor end journal foils. Portions of foil surfaces were covered with extremely fine black powder. Wear patterns were non-uniform. Turbine end journal foils were similar but less wear. SEM examination showed black powder to be iron with small amounts of tungsten and sulfur (from the thin dicronite coating). See photo of Compressor end journal bearings in Figure 15.
13 Feb 78	CRES-302/Teflon-S (coated by Thermec) Lot #8590 Non-magnetic Bars R_c = 0.59 Thickness- 0.0059 in. Spring Rate - 710 lb/in. Length- 0.770 in. Sway Space - Compr - 0.0084 in.	To test for rotor/foil "continuity".	"Continuity" indicated at rest, lost completely at 30,000 rpm, no field excitation. Very stable until field current was introduced. Sub-synchronous wheel was encountered and continuous "continuity" indicated at 51,680 rpm and 920 watts output. Test terminated. An experiment was then conducted to determine the effect of field current on breakaway torque. Torque was 1.5 in.-lb. with zero excitation and increased to 3.2 in.-lb. with 2.5 amperes field current applied.

TABLE III. - Continued.

Date	Configuration	Objective	Observations/Results
14 Feb 78	"1010" Mild Steel Lot #8569 WS_2 coated (Same as STR test of 2-10-78)	To test for rotor/foil "continuity".	Test of 2-10-78 was rerun to determine if the fine powder debris would continue to regenerate after an initial "break-in" period. Partial "continuity" was indicated throughout each revolution at 52,000 rpm, no field excitation. Test terminated. Post test inspection disclosed more fine black powder debris on foils.
15 Feb 78	Same as previous test. Foils cleaned and re-installed in STR.	To test for rotor/foil "continuity".	Third running of this set of foils. At 52,000 rpm, no field excitation, only intermittent "continuity" was noted between rotor and foils. However, "continuity" increased after 6 minutes operation to show continuous during 240° of each revolution. Continuous contact through entire revolution with 0.8 amperes field current. Post-test inspection disclosed fine black debris, but in lesser amount than in two previous runs.
15 Feb 78	INCO-750/Teflon-S (coated by Crest) Lot #8571 Non-magnetic Bars R_c = 0.57" Thickness- 0.0060 in. Spring Rate - 1280 lb/in. Sway Space - C - 0.0080 in.	To test for rotor/foil "continuity" and charge/discharge phenomenon.	At rest, rotor/bearing "continuity" was zero, except for two points as rotor was rotated. No continuity noted at operating speeds. Subsynchronous whirl when field excitation reached 1.5 amperes. No charge build-up noted. Post test showed considerable wear. Some foils showed more wear than others. Wear irregular--some foils showed wear close to trailing edge, others showed wear areas removed from trailing edge.
17 Feb 78	Same as previous test except that foils were flashed with gold (0.000030 in. thickness).	To repeat previous test to determine if the foils actually touch the rotor.	Instrumentation indicated "continuity" between rotor and gold-flashed foils throughout entire test. Lissojous, denoting displacement of the shaft, was very stable until field current reached 0.8 amperes. Lissojous then became fuzzy but did not increase in size. Post-test inspection disclosed considerable wear on foils. Wear area was narrow and non-symmetrical.
18 Feb 78	"1010" Mild Steel Lot #8568 (Same as tests of 2-10-78, 2-14-78, and 2-15-78). Newly chromed rotor used in lieu of dicronited rotor.	To test for rotor/foil "continuity" and charge/discharge phenomenon. To continue burn-in by running 2 hours.	Fourth running of this set of foils. Many points of "continuity" noted initially. Improved after 23 minutes running but continued throughout 2 hours run. Considerable wear -- irregular pattern. More black debris was generated but less than previous runs.

TABLE III. - Concluded.

Date	Configuration	Objective	Observations/Results
22 Feb 78	"1010" Mild Steel Lot #8568 (Same as test of 2-18-78)	To check stability.	Tests with other foils on 2-20-78 were terminated when instabilities were encountered. Since the "1010" foils were very stable in 2-18-78 test, these were again run to check stability of the rotating group. At 52,000 rpm, the Lissojous pattern was large (0.8 mil dia.) It was concluded that some part of the rotating group had been damaged. Later inspection disclosed damage to rotor curvic coupling, accounting for marginal stability.
25 Feb 78	"1010" Mild Steele, Lot #8568 (Same as previous test except that previously-Dicronited rotor was used.)	To test for rotor/foil "continuity".	Sixth running of these foils. Eleven starts made during several hours of testing. Torque increased from 0.9 to 2.4 in.-lb. Instrumentation showed "continuity" ranging from continuous to intermittent throughout the test. Continuity is throught to result from black iron powder generated by start-stops. Post-test inspection disclosed the typical black debris but not in excessive amounts. Roll-down time after first start was 47 seconds. Roll-down after 10 starts was 34 seconds.
27 Feb 78	INCO-750/Teflon-S Lot #8571 (Same as used in tests of 2-15-78 and 2-17-78 except that foils were shortened by 0.040 in. and reradiused to R_C = 0.60 in.) Some gold remained on surfaces.	To test for rotor/foil "continuity" with shortene shortened foils.	At 52,000 rpm, without field excitation, once per revolution continuity through high resistance was indicated. After second start, unit was loaded to 1250 watts; little or no contact was indicated (possibly due to loss of conducting gold plating). No charge on rotor was detected. With rotor at rest, breakaway torque was measured as field current was applied. Torque increased from 1.9 in.-lb., with zero excitation, to 2.5 in.-lb. with 2.5 amperes applied to the field. An air start was then attempted. High torque was indicated. Torque had risen to 3.0 in.-lb. Post-test inspection disclosed that bearing surfaces were well burnished over a larger area than usual, indicating that shortening the foil length had apparently spread load over larger area. (An attempt was made on 2-28-78 to duplicate the sudden increase in torque. However, torque incre increased from 1.9 to only 2.0 in.-lb. in going from 0 to 2.5 amperes of field current. This suggests that the phenomenon was thermally induced since the STR was warm when the increase in torque occurred.)

TABLE IV. - MARCH STR TESTS/EXPERIMENTS WITH VARIOUS FOIL BEARING MATERIALS

Date	Configuration	Objective	Observations/Results
3 Mar 78	Inco 750/Teflon-S Lot No. 8571 R_c = 0.60 in. Foil length shortened by 0.030 in. (flashed with gold)	Check for rotor/foil continuity; check performance	First time continuity checked with small resistor (1000 Ω - 100K Ω). Intermittent contact over one-third each revolution at 52,000 rpm, full load. Solid contact at 55,000 rpm. Lissajous - 0.25 mil dia., very stable at all speeds.
6 Mar 78	"1010" mild steel; Lot No. 8568, R_c = 0.60 in. Foil length shortened by 0.030 in. (some dicronite may remain on foils)	Check for rotor/foil continuity; check performance	Seventh running of these foils in one configuration or another. Continuous contact (continuity) indicated. Lissajous - 0.4 mil dia., nervous and whirling, w/o field excitation at 52,000 rpm; stabilized when field current was added - 0.3 mil dia. but displaced - 0.5 mil. Relatively low spring rate.
7 Mar 78	"1010" mild steel; Lot No. 8588, MoS_2 coated. R_c = 0.57 Sway space - 0.0078 -C in. - 0.0074 -T	Check for rotor/foil continuity; check performance	At 52,000 rpm, w/o field excitation, nearly continuous contact initially, became nearly open. With 1 amp field current, contact nearly continuous. Roll down from 52,000 rpm - 50 seconds.
10 Mar 78	"1010" mild steel; Lot No. 8588, MoS_2 coated, R_c = 0.57 Sway space - C - 0.0078 in. T - 0.0074 in.	Check to determine effect of reducing voltage from 5 volts to 0.25 volt for continuity check.	Continuous contact at 52,000 rpm using 5 volts. (No contact at 50,000 rpm.) No contact indicated at 52,000 rpm, fully loaded, when 0.25 volt used.
13 Mar 78	--	--	Two different sets of foil were run but subsequent checks showed rotating group to be out of balance. Rebalanced on 14 March 78.
15 Mar 78	CRES-302/Teflon-S Lot No. 8591, R = 0.59 Spring rate = 694 lb/in. Sway Space - C - 0.0095 in. T - 0.0088 in. Surface Finish - 8 rms	Check stability	At 52,000 rpm, no excitation, Lissajous was 0.5 mil, whirling to 0.8 mil. With 1 ampere field current, whirling increased. Lissajous pulsed between 0.5 mil and 1 mil in dia. Rolldown was 60 seconds.

TABLE IV. - (Continued)

Date	Configuration	Objective	Observations/Results
15 Mar 78	"1010" mild steel; Lot No. 8588, MoS_2 coated. R_c = 0.57 in. Sway Space - C - 0.0078 in. T - 0.0074 in. Spring Rate - 877 lb/in.	Check for rotor/foil continuity; check performance.	Lissajous - 0.25 mil dia.; stable throughout test. At 52,000 rpm, no excitation, no contact was indicated. Contact became intermittent at 0.5 amp field current and continuous solid contact at 1.0 ampere field current. When load bank was connected, no contact indicated until 0.8 ampere field current was applied. Rolldown - 46 seconds.
18 Mar 78	CRES-302/Teflon-S, Lot No. 8592, R_c = 0.57 in. Surface Finish - 8 rms Sway Space - C - 0.0089 in. T - 0.0081 in. (Foils taken from mini-BRU build of 3-17-78)	Check stability at full load; check for rotor/foil continuity and charge/discharge.	No continuity indicated above 40,000 rpm with full load. (Continuity observed at various positions, rotor at rest.) Lissajous remained 0.4 x 0.5 mil with load. No charge build observed.
21 Mar 78	CRES-302/Teflon-S, Lot No. 8596, R_c = 0.57 in. Spring Rate = 833 lb/in. Sway Space - C - 0.0094 in. T - 0.0089 in. Surface Finish - 8 rms	Precondition bearings; check for continuity (at rest and at speed); check for stability.	Continuous continuity indicated with rotor at rest. Continuity was lost between 20,000 rpm and 47,000 rpm in 8 of 10 starts, w/o field current. Rolldown times increased with each start - from 44 to 50 sec. With 235 watts load, Lissajous increased to 1.0 mil dia. (from 0.6 mil). Results similar to first test of 15 Mar 78, when foils with similar sway space and spring rate were tested.

TABLE IV. - (Continued)

Date	Configuration	Objective	Observations/Results
22 Mar 78	CRES-302/Teflon-S, Lot No. 8598, R_c = 0.57 in. Surface Finish - 8 rms Sway Space - C - 0.0086 in. T - 0.0081 in. Spring Rate - 1063 lb/in.	Check stability; check for continuity (at rest and at speed). Sway space is close to that predicted to exist in hot WHL operation.	Continuity indicated (rotor/housing) for most positions of shaft (at rest). Continuity improved from "continuous" to "once per rev." during 15 start/stops, w/o field excitation. Rolldown increased from 33 to 44 seconds during this break-in period. With 790 watts load, Lissajous increased from 0.45 mil to 2.0 mils dia., large whirl. STR disassembled; minimal black debris. Foils cleaned and STR reassembled. Attempt to check balance and balance rotating group in STR was successful in reducing Lissajous from 0.5 mil dia. to 0.1 mil dia. After flashing field with 2.5 amperes, STR was loaded to 1376 watts. Lissajous remained very stable, very small - 0.1 mil dia. This was first attempt to balance while assembled in STR.
23 Mar 78	CRES-302/Teflon-S, Lot No. 8598, R_c = 0.57 in. Surface Finish - 8 rms Sway Space - C - 0.0086 in. T - 0.0081 in. Spring Rate - 1063 lb/in.	Check stability; check for continuity (at rest and at speed). Sway space is close to that predicted to exist in hot WHL operation. Test continued with balanced rotating group.	STR loaded to 1388 watts. Lissajous very stable, small (0.1 mil dia.). Continuity was not lost but was "trying to lift." Balance check was made and improved balance resulted. STR was started; continuity lost at 45,000 rpm. Very little continuity at 52,000 rpm, 1350 watts load. Weight added for balancing was removed to recheck imbalance. STR was started. Lissajous was 0.6 mil; at 525 watts output, whirl exceeded 1.0 mil. This was similar to instability displayed prior to trim balancing. STR was disassembled. After removing small amount of black debris (Teflon), journal foils appeared to be "brand new" except for very smooth burnish near trailing edges.
24 Mar 78	CRES-302/Teflon-S, Lot No. 8598, R_c = 0.57 in. Surface Finish - 8 rms Sway Space - C - 0.0086 in. T - 0.0081 in. Spring Rate - 1063 lb/in. (with thin flash of gold added to Teflon surface)	Check for loss of continuity.	Balance check was made; rotating group was trim balanced, Lissajous reduced from 0.5 mil dia. to 0.1 mil dia. with load. Completely stable throughout test. With no field current, continuity was nearly lost at 45,000 rpm; completely lost at 50,000 rpm. At 52,000 rpm, 1330 watts load, continuity was lost with exception of one point. (On 27 Mar 78, during controls testing with same build, continuity was completely lost with full load.)

TABLE IV. - (Continued)

Date	Configuration	Objective	Observations/Results
27 Mar 78	CRES-302/Teflon-S Lot No. 8598 (w/thin flash of gold added to Teflon surface) Same build as 24 Mar 78	Controls testing	Seven starts were made. Continuity was completely lost while running at 52,000 rpm, full load. Disassembly of STR disclosed that gold was removed from burnished area of foils just forward of trailing edge. Green Teflon was exposed. No evidence of black debris. Total starts on foils - 55. Fourteen starts since gold was applied.
28 Mar 78	CRES-302/Teflon-S Lot No. 8596 R_C = 0.57 in. Surface Finish - 8 rms Sway Space - C - 0.0094 in. T - 0.0089 in. Spring rate - 833 lb/in. Thickness - 0.0060 in.	Determine if good balance can improve stability of weak foils. (Foils had shown instability when loaded to 235 watts on 21 Mar 78.)	Build apparently retained good balance of previous build. Lissajous, very small (0.1 mil dia.) and stable at 52,000 rpm, no field excitation. However, it "pulsed" larger and larger as load was applied--0.3 mil at 475 watts, and 0.7 mil dia at 1200 watts. Throughout test, continuity was nearly lost but not entirely. Total of six starts. Torque was 1.5 in. lb at beginning of test; increased to 2.0 in. lb at end. Rolldown - 56 sec.
29 Mar 78	CRES-302/Teflon-S Lot No. 8592 R_C = 0.57 in. Surface Finish - 8 rms Sway Space - C - 0.0086 in. T - 0.0081 in. Spring rate - 1000 lb/in. Thickness - 0.0062 in.	Repeat the history of Mini-BRU test of 27 Mar 78 to determine if torque increases as it did in Mini-BRU test. (Bearings are those seen in Mini-BRU on 17 Mar 78 and 27 Mar 78; carriers and rotor are STR hardware.)	Two starts were made, one to 50,240 rpm, 100 watts load, the second to 52,000 rpm, 2.4 amperes field current, no load. Attempts to motor start were unsuccessful, just as they had been in Mini-BRU test. Torque was found to have increased from 1.5 to 3.0 in. lb. Disassembly disclosed extremely little black residue. Good balance of previous build was not evident. Lissajous was 0.4 mil dia.
30 Mar 78	CRES-302/Teflon-S Lot No. 8592 R_C = 0.57 in. Surface Finish - 8 rms Sway Space - C - 0.0086 in. T - 0.0081 in. Spring rate - 1000 lb/in. Thickness - 0.0062 in.	Repeat previous test, attempting to regain good balance. Determine if good balance will eliminate increase of torque previously experienced.	Four starts were required to decrease Lissajous from 0.3 to 0.15 mil dia. Fifth air driven start attempt was unsuccessful. Breakaway torque had increased from 1.7 to 4.0 in. lb. Disassembly disclosed small amount of black debris forward of trailing edge, other foils appeared to be in excellent shape. Foils were cleaned and cured at 630°F for 20 min. Previous cure of 570°F for 30 min may be insufficient. Foils will be rerun at later date.

TABLE IV. - (Concluded)

Date	Configuration	Objective	Observations/Results
31 Mar 78	"1010" mild steel (with some MoS_2 coating remaining) Lot No. 8588 R_c = 0.57 in. Sway Space - C - 0.0087 in. T - 0.0084 in. Spring rate - 714 lb/in. Thickness - 0.0053 in. Shortened by 0.030 in. Magnetic Pins	Check stability (foils were previously tested on 15 Mar 78, now shortened by 0.030 in.).	At 30,000 rpm, Lissajous was 0.5 mil dia. At 50,000 rpm, whirling increased it to 0.8 mil dia. At 52,000 rpm, whirl exceeded 0.8 mil dia, and test was terminated. Foils will be re-radiused to 0.61 in. to increase preload and tested at later date.
31 Mar 78	"1010" mild steel, no coating. Lot No. 8561 R_c = 0.61 in. Sway Space - C - 0.0091 in. T - 0.0088 in. Spring rate - 735 lb/in. Thickness - 0.0052 in. Magnetic Pins	Check performance with increased sway space. (These foils were previously run on 30 Jan 78 with sway space of 0.0085 in., both ends. After 2 starts, torque increased to 3.5 in. lb. Disassembly showed much fine black powder had been generated.)	At 52,000 rpm, Lissajous was 0.4 mil dia. Continuous continuity indicated through 250 ohms. At 52,000 rpm, 1353 watts load, Lissajous decreased to 0.3 mil dia, but was filled with whirls. Continuous continuity indicated through 100 ohms. Breakaway torque increased from 1.5 to 3.7 in. lb. Inspection disclosed much fine black powder, similar to test of 30 Jan 78. A coating of MoS_2 seems to prevent the generation of the powder debris.

TABLE V. - APRIL STR TESTS/EXPERIMENTS WITH VARIOUS FOIL BEARING MATERIALS

Date	Configuration	Objective	Observations/Results
6 Apr 78	CRES-302/Teflon-S (coated by Crest) Lot No. 8594 R_c = 0.59 in. Surface Finish - 8 rms Cure Temp. - 630°F Sway Space - C - 0.0094 in. T - 0.0089 in. Spring Rate - 1400 lb/in. Thickness - 0.0060 in.	Test journal foil bearings similar to those currently running in the WHL	Initial Lissajous of 0.4 mil dia. was reduced to less than 0.2 mils by trim balancing in STR. Bearings performed reasonably well. Some whirling evident, with application of field current and load. Torque increased modestly from 1.7 to 2.2 in.lb., after 8 starts. No continuity between rotor and carriers was detected - at rest or in motion. No charge buildup on rotor was detected. Roll down was 39 seconds. Post-test inspection disclosed only small amounts of black debris on foils.
7 Apr 78	CRES-302/Teflon-S (Build same as test configuration of 6 Apr 78)	Controls tests - motoring starts.	Twelve motoring starts were made to low speeds (8-9,000 rpm) for controls testing. Initial breakaway torque increased from 1.9 to 3.1 in.lb.
13-14 Apr 78	"1010" Mild Steel uncoated. Lot No. 8561. R_c = 0.61 in. Sway Space - C - 0.0091 in. T - 0.0088 in. Spring Rate - 735 lb/in. Thickness - 0.0052 in. 0.0052 in. Magnetic pins (Previously tested on 31 Mar 78)	Controls tests - motoring starts and operating with load.	Stability was sufficient to complete controls tests; however, Lissajous pattern was much larger than in last test of these bearings and considerably more whirl was encountered. (Desire to expedite controls test precluded trim balancing of rotating group. Poor performance suggests, once again, that repeatability of balance - build to build - is not usu y achieved.

TABLE V. - (Concluded)

Date	Configuration	Objective	Observations/Results
23-21 Apr 78	CRES-302/Teflon-S (coated by Thermec) "Box 133" Non-pedigreed P = 1.61" Surface finish - 20 to 40 rms Cure Temp - 650°F C - 0.0059 in. T - 0.0093 in. Spring Rate - 960 lb/in. Thickness - 0.0059 - 0.0060 in.	Attempt to duplicate WHL bearing damage by reducing sway space in one of the two bearing carriers. (While awaiting delivery of required hardware, experiment was conducted using available hardware)	Nine starts were made; 5 hours, 30 minutes running logged at 52,000 rpm, 1300 watts. Lissajous - 0.5 x 0.7 mils, completely stable with and without load. Imbalance introduced for final hour of run - Lissajous, originally 0.9 x 1.2 mils, increased to 1.1 x 1.3 mils late in run due to slight whirl. Imbalance intentionally introduced to simulate 1.4 mil dia. (0.8 mil static shaft runout) of 12-08-77 WHL.) Inspection showed some wearing of Teflon on compressor journal foils near trailing edge but not excessive. Relatively little wear on turbine foils.
24-27 Apr 78	CRES-302/Teflon-S (Same as previous build except compressor and turbine foils were reversed and "tight" sway space was at turbine end.) Sway Space - C - 0.0082 in. T - 0.0056 in. Spring Rate - not re-tested	Same as previous test, with one modification. (In previous test, reduced sway space was at compressor end where STR temperatures are lowest due to proximity of cooling effect of air turbine drive. Reduced sway space placed at warmer turbine end.)	Initial build had 0.0098 in. sway space at compressor end; unstable when load was applied. Sway space reduced to 0.0082 in. by substituting thicker foils. Initial Lissajous - 0.5 mil dia. operated for 4 hours. During last 1:42 period, heat was applied to turbine end of STR with heat gun. Lissajous gradually degraded, reaching point where its 0.7 mil dia. was completely filled with whirling. Total time accumulated on foils at turbine end - 9 hours, 34 minutes; 16 starts. Foils showed surprisingly little wear. Heat may have only heated housing, resulting in increased sway space, negating objective of accelerating test and, instead, adding to instability of rotating group. No continuity noted, even with rotor at rest.

TABLE VI. MAY 1978 STR TESTS/EXPERIMENTS - BIPS - MINI-BRU FOIL JOURNAL BEARINGS

Date	Configuration	Objective	Observation/Results
2-3 May 78	CRES-302/Teflon-S Lot No. 8622 (New bearings made of "old" thermal material) Cure Temp. - 650°F R_c = 0.61 in., reradiused from 0.57 in. Surface finish - >20 rms Sway space - C - 0.0058 in. T - 0.0086 in. Spring rate - 1220 lb/in. Thickness - 0.0051, 0.0052/ 0.0061 in. Built as Mini-BRU Test Rig (MBTR)	Attempt to duplicate damage to foil journal bearings by simulating conditions present in WHL builds which resulted in shutdowns in Nov. and Dec. 1977. (Sway space in compressor journal carrier reduced even more than that in WHLs).	MBTR built with compressor backface shroud and solid (not serrated) rub ring in compressor carrier to restrict flow in compressor journal region. Histogram of 12-22-77 WHL followed where possible. Total of 182 starts were made - 80 to speeds not exceeding 15,000 rpm. Operated at 28,000 rpm for 10 hours. Eight hours running at 52,000 rpm, 1300 watts load. Total time - 20 hours, 34 minutes Lissajous - 0.4 mil dia; shaky when loaded but no growth. Max. compressor carrier temp - 149°F while operating at 52,000 rpm, 1300 watts.
5-9 May 78	Same as previous test except for: Sway space - C - 0.0060 in. T - 0.0085 in. Spring rate - 1280 lb/in. Built as STR	Same as in previous test. In addition to reduced sway space, mild imbalance (1.7 mil. dia. Lissajous) was intentionally introduced to simulate the 1.4 mil dia. Lissajous (0.8 mil static runout) of the 12-22-77 WHL build.	Run initially for 9 hours at 52,000 rpm, 1284 watts. Some whirl evident with load but 1.8 mil Lissajous remained well controlled. Teardown inspection disclosed wear on trailing edge outboard corners of compressor foils. STR was rebuilt and run 27 additional hours at 52,000 rpm, 1300 watts. Max. compressor carrier temp - 145°F. Lissajous steadily degraded from a beginning pattern of 1.7 x 1.8 mils (stable), it ended as a pulsing pattern continuously cycling from 1.1 x 1.3 mils to 2.2 x 2.4 mils. Surprisingly, disassembly disclosed little additional wear on foils.

TABLE VI. (Concluded)

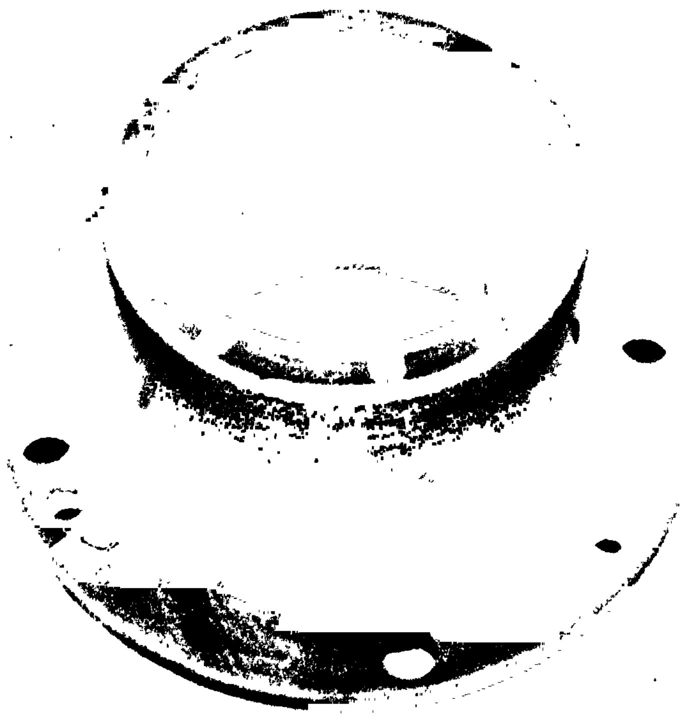
Date	Configuration	Objective	Observation/Results
10-11 May 78	CRES-302/Teflon-S Lot No. 8624 (New bearings made of "new" Crest material) Cure temp - 630°F R_C = 0.61 in. re-radiused from 0.57 in. Surface finish - 15 rms Sway space - C - 0.0056 in. T - 0.0081 in. Spring rate - 2380 lb/in. Thickness - 0.0052/0.0062 in. Bars modified to reduce bar/slot clearance	Same as in two previous tests, i.e., to produce damage or abnormal wear. In addition to reduced sway space, reduced bar/slot clearance was introduced in an attempt to simulate the narrow carrier slots which existed in the November and December 1977 WHL shutdowns.	In lieu of narrow-slotted carriers, bars on foil bearings were made thicker by tack welding 0.003 in. shim stock to bars. (This resulted in bars which readily slipped into carrier slots but fit was not "sloppy" as with current wide slots.) The reduced bar/slot clearance was apparently responsible for increasing spring rate to 2380 lb/in, same as in 12-22-77 WHL. STR was run for 8 hrs., 50 min - 8 hrs at 52,000 rpm/1300 watts; 10 minutes at 52,000 rpm/2100 watts; 30 minutes at 55,000 rpm/2026 watts; 10 minutes at 62,000 rpm/1400 watts. (Speeds and loads simulated WHL experience in December build.) Max. compressor carrier temp - 150°F at 55,000 rpm/2026 watts. Lissajous - 0.3 mil. diameter, stable throughout except for very slight instability at 62,000 rpm. Post test inspection - abnormal wear on compressor end journal foils; turbine end foils showed relatively little wear.
11-12 May 78	Same as previous test	Same as previous test. In addition, a mild imbalance was introduced which resulted in a Lissajous pattern of 1.7 mil. dia.	STR was run for 13 hours at speeds ranging from 28,000 to 55,000 rpm. Max. compressor carrier temp - 171°F at 52,000 rpm/1990 watts. Lissajous pattern increased slightly in size and became slightly unstable as test progressed (but much more stable than that of the 5-9-78 test). Post test inspection - Compressor journal foils sustained excessive and abnormal wear over most surface area exposed to shaft. Wear worse in region adjacent to outboard edge of foils. Some wear and loss of Teflon at leading edges over the bars. Most turbine journal foil wear was confined to band just forward of trailing edge. This is closest simulation to date of WHL experience. Results suggest that the reduced bar/slot clearance was at least partially responsible for the increased spring rate and the increased wear of the foils.

TABLE II. - JUNE STR TESTS/EXPERIMENTS WITH VARIOUS BEARING MATERIALS

Date	Configuration	Objective	Observation/Result
13 June 78	CRES 302/Thermec Teflon Lot No. 8622 R_C = 0.61 in. Tight slots Sway space - C - 0.0064 T - 0.0083 Spring rate = 6000 lb/in.	Simulate WHL failure by use of tight pins.	Highest spring rate ever tested. Breakaway torque up to 4.1 in.-lb. After testing moderate burnishing was evident; two fret lines very distinct; but no serious bearing wear or distress.
16 June 78	CRES 302/8 rms Crest Teflon Lot No. 8623 R_C = 0.57 in. Normal slots Sway space - C - 0.0121 in. T - 0.0118 in. K_L = 450 lb/in.; K_H = 1600 lb/in.	Determine sway space at which system becomes unstable.	Unit began to show unstable Lissajous at 30K rpm; increased in size until audible metallic contact heard at 45K; no magnetic excitation; good balance.
20 June 78	Inco X-750/MOS_2 Lot No. 8652 R_C = 0.57 in. Normal slots Sway space - C - 0.0094 T - 0.0086 K_L = 465 lb/in.; K_H = 2500 lb/in.	One shot test to verify MOS_2 as a prime candidate for "uncoated" bearing.	Bearings tested in STR. Initial BAT = 26 in.-oz. Final BAT = 45 in.-oz. Considerable removal of coating in loaded area and transfer of residue to other areas. This particular configuration became unstable under magnetic loads above 0.5 amp field current.

CRES 302/TEFLON-S
FOIL S/N 610

Figure 14. - Foil Removed From STR After Completion of 19 January 1978 WHL Histogram Test.

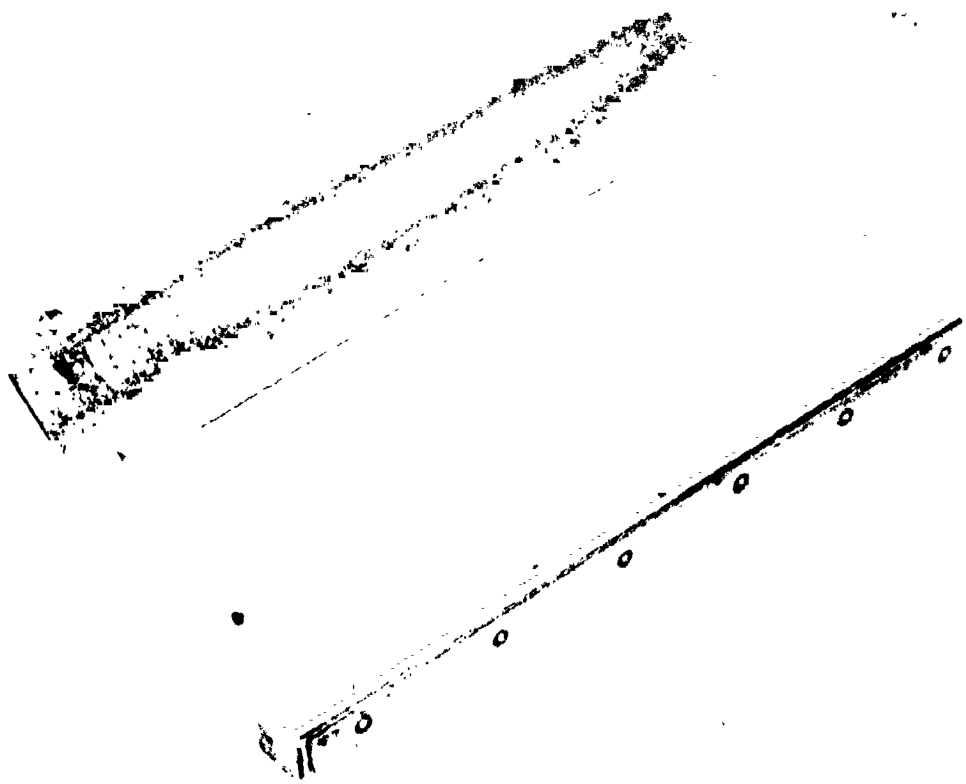


LOT NO. 8568
1010 MILD STEEL FOILS
WITH DICRONITE (WS_2) COATING
AFTER STR TEST OF 10 FEB 1978

NOTE IRREGULAR WEAR AND GENERATION OF
FINE BLACK POWDER

Figure 15. - Compressor End Journal Bearing.

MP-63981



LOT NO. 8624
CRES 302/TEFLON-S
WITH THICK BARS

NOTE EXCESSIVE, ABNORMAL
WEAR TOWARDS LEFT EDGE

Figure 16. - Compressor End Foil Removed From STR Test of 12 May 1978.

MP-63982

(1) To measure the effect on spring rate when sway space, foil length, and foil radius of curvature are varied.

(2) To improve the method of testing spring rate by developing and testing a new spring rate test rig.

Six sets of foil journal bearings were fabricated specifically for use in testing spring rates. All bearings were fabricated from CRES-302 sheet stock (nominally 0.005 in. thickness) which had been coated (by CREST) with Teflon-S (nominally 0.001 in. thickness). All bars a.e non-magnetic. The radius of curvature of the foils was accurately measured using a 10 to 1 contour reader.

Specific parameters of these foils appear in Table VIII.

In addition to the six sets of CREST coated foils, one set was fabricated from THERMEC coated stock received during 1977. These were Lot No. 8622, originally radiused to 0.61 inches. Length was 0.771 inch, thickness 0.0061 inch, cure temperature 650°F, and surface finish 22 to 40 rms.

The initial tests used foils from Lot Numbers 8609A and 8610. These tests were run using what will be referred to as the "Old Rig" or "former method." This is shown schematically in Figure 17(a). A standard Mini-BRU alternator rotor is supported by the foil bearings installed in standard Mini-BRU journal bearing carriers. The dial indicator, used to measure vertical displacements of the rotor, is then zeroed. Weights are then added (one pound at a time) until six pounds have been applied to the rotor. The displacement is recorded for each one pound increment. The six displacements measured are then plotted as in Figure 17(b). Since the interest is in the spring rate for one bearing, the pounds are halved.) It has been customary to calculate the spring rate, K_L, over the initial displacement. Hence, K_L = 0.5/displacement, "A". Similarly, K_H = 3.0/displacement, "b". (Throughout the Mini-BRU program and BIPS testing, the spring rate, K_L, has been used as calculated above. While it is evident that the weight of the rotor causes an initial offset in the zero point, this method of calculating spring rate has been retained. Thus one spring rate may be compared with another.)

Results of tests conducted on two sets of foils using this method ("Old Rig") appear in Figure 18. Sway space was varied by using carriers with different inner diameters.

TABLE VIII. - CRES 302/TEFLON-S FOIL JOURNAL BEARINGS

[Fabricated from Crest coated sheet stock specifically for spring rate tests. All bars are nonmagnetic.]

Lot No.	Radius of curvature, in.	Length, in.	Thickness, in.	Cure temp., °F	Surface finish, rms
8623	0.57	0.773	0.0061	630	8
8624	0.57	0.773	0.0062	630	15
8610	0.59	0.771	0.0061	570	15
8609A	0.59	0.735	0.0062	570	15
8616	0.62	0.766	0.0061	630	15
8616A	0.62	0.744	0.0061	630	15

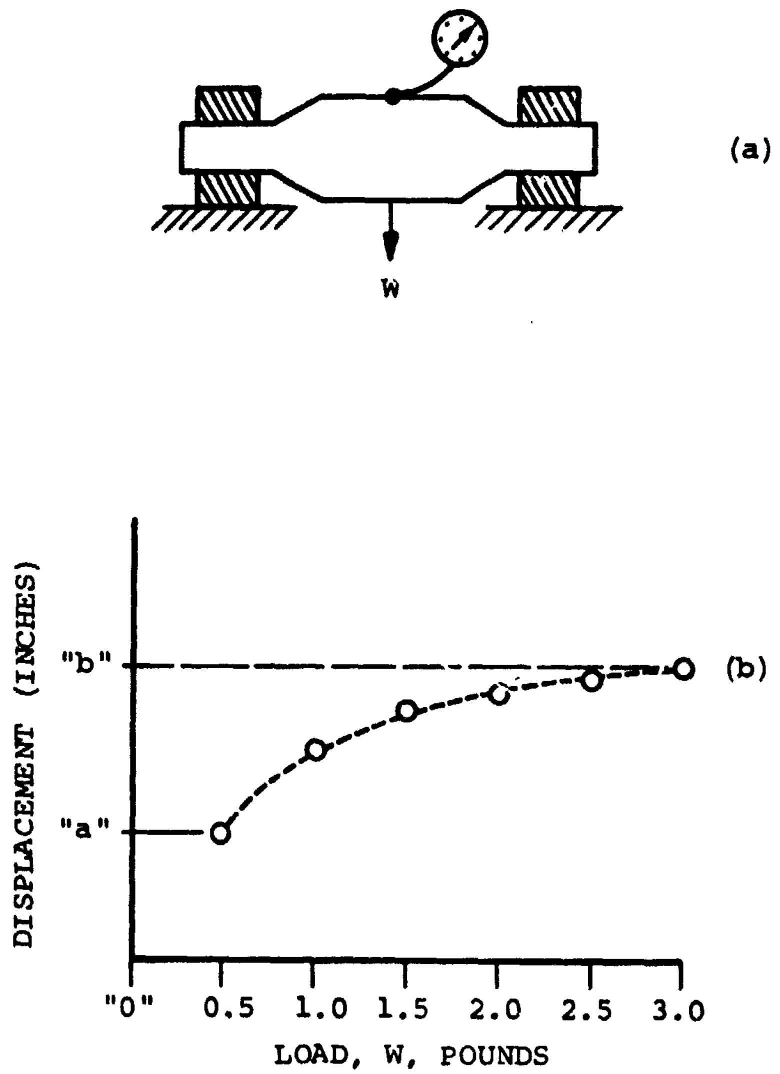
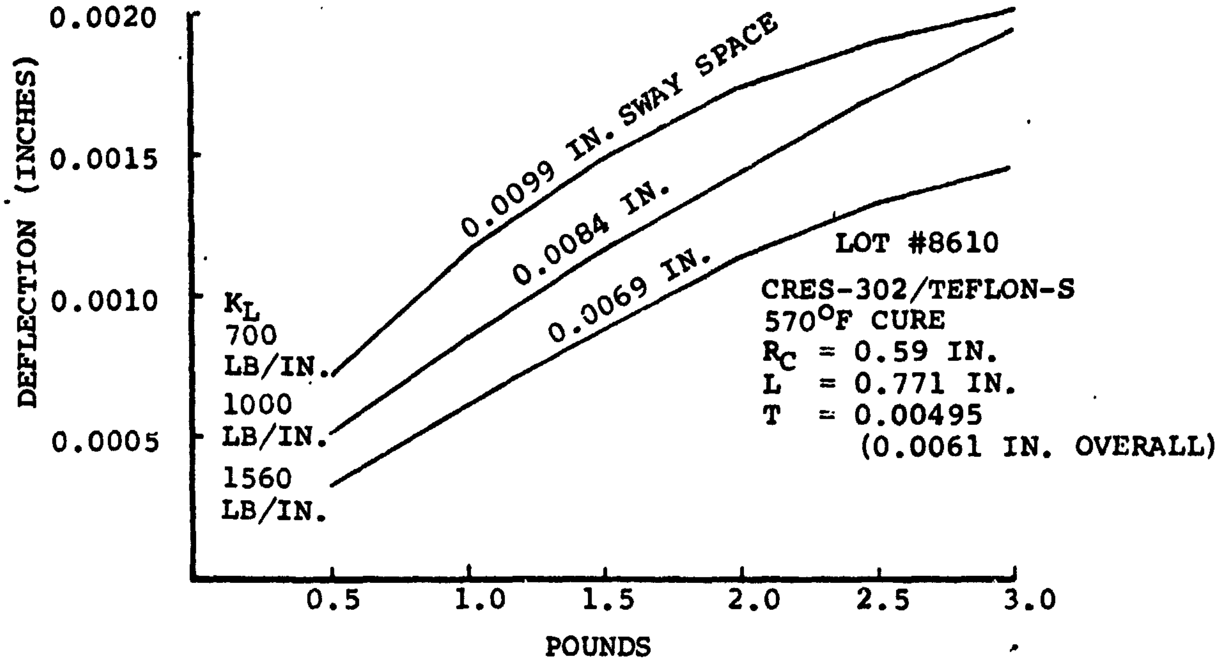


Figure 17. - Spring Rate - "Old Rig," Schematic and Method of Plotting.



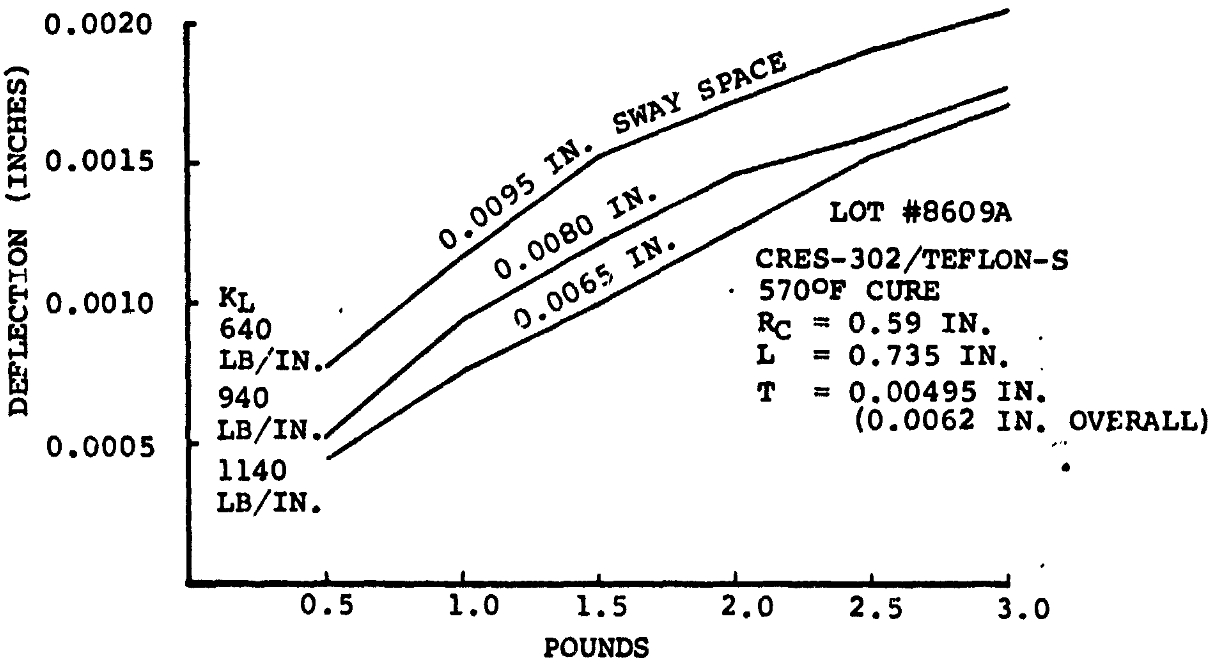


Figure 18. - Spring Rate, K_1, Versus Sway Space (two sets of foil bearings).

Two sets of foils were repeatedly tested, the measurements averaged, and the resulting data plotted. The two sets of foils were similar except for length. Lot No. 8610 was "standard" length; Lot No. 8609A was approximately 0.035 in. shorter in length. As anticipated, stiffness (spring rate) for each set of foils increased as the sway space was decreased. These results, however, did not fully support the contention that reducing the foil length would in all cases reduce the spring rate for a given sway space. For the smallest sway spaces (0.0065 in. and 0.0069 in.), the shorter foils did, indeed, exhibit a lower spring rate for all loads from 0.5 through 3.0 pounds. However, the plots for the other larger sway spaces are inconclusive.

The major shortcoming of this method of determining spring rate is that it allows the bearing to be loaded in only one direction. It was recognized that an improved test rig was needed which would overcome this deficiency and permit the zero load point to be located. As a result, a "New Rig" was designed and fabricated. It is shown schematically in Figure 19 and appears in the photograph, Figure 20.

When using the "New Rig," the sway space of the foils undergoing test is changed by changing the rotor diameter while the inner diameter of the bearing carrier is held constant. (Five rotors are available. These permit sway space to be varied over a range of 0.005 in. in increments of 0.001 in.)

The test rig permits the bearing to be loaded and unloaded by the addition and removal of weights from the upper tray. In Figure 20, a weight of five pounds has initially been placed on the lower tray. The system is then stabilized, and the dial indicator set to zero. Deflection readings are then taken as weights are added and removed from the upper tray. Seven different sets of foils were tested in this manner prior to May 19, 1978 by this method. A plot of a typical set of data is shown in Figure 21. The spring rate is non-linear. For purpose of making comparison, the two pound increment from a load of +1.3 pounds to -0.7 pounds has been used in all tests. (These points correspond to weights applied during the test, thus making it simple to calculate the spring rate before the data are plotted.) It has been found that use of these points results in a spring rate closely approximating that obtained by using the increment from +1 to -1 pounds applied force.

Table XIX summarizes spring rates determined by this method and compares the results with those obtained using

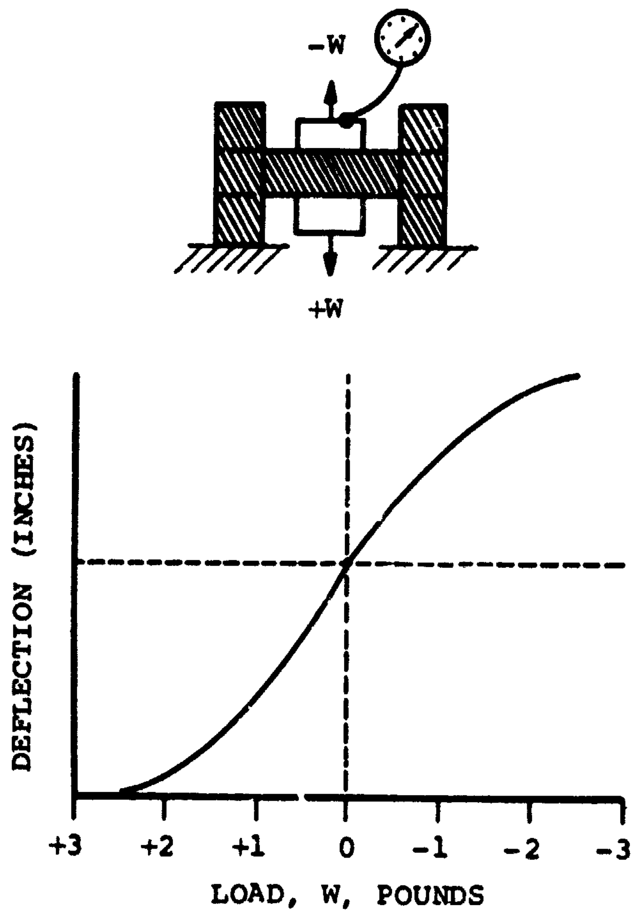


Figure 19. - Spring Rate - "New Rig," Schematic and Example of Plot.

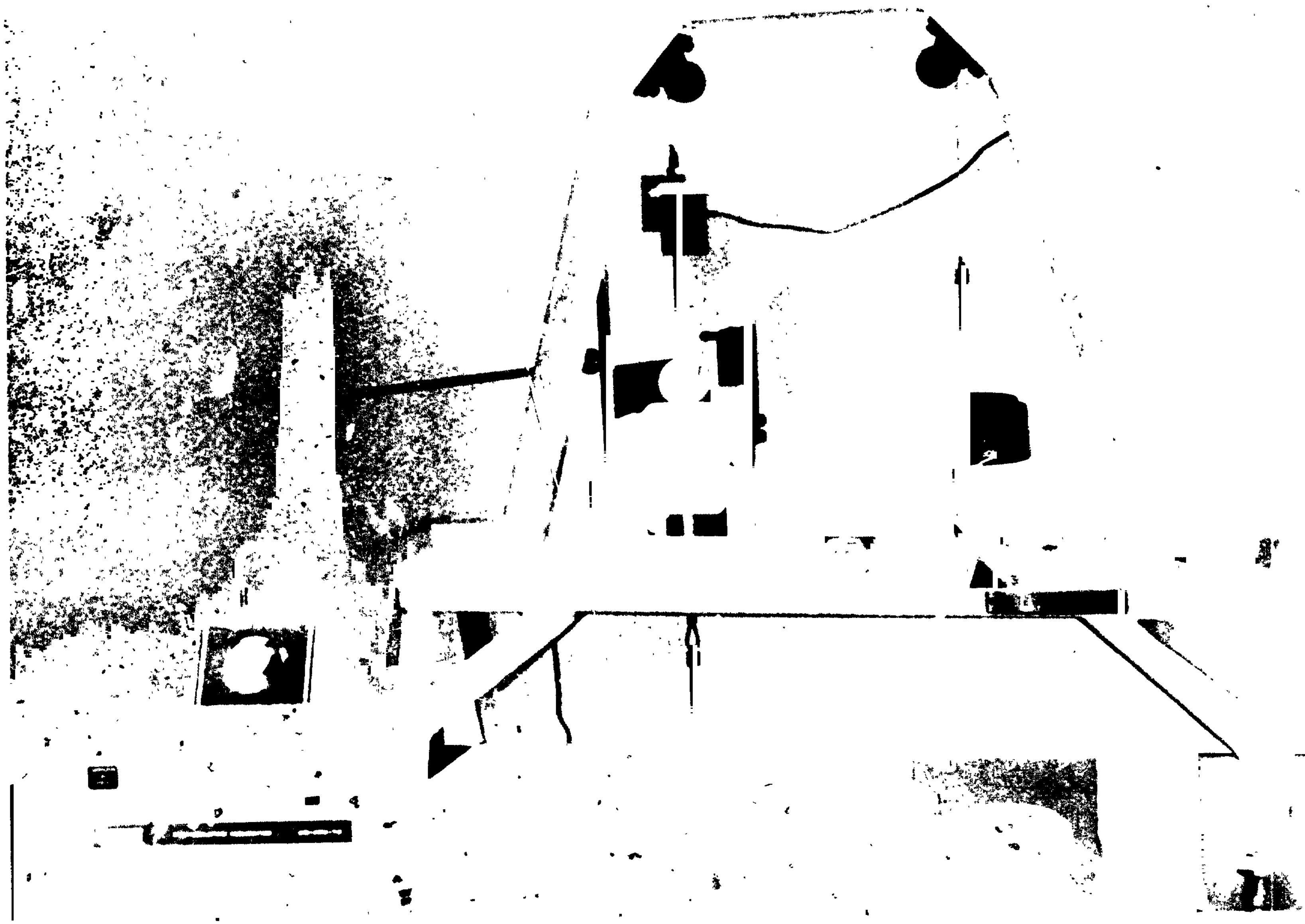


Figure 20. - "New" Spring Rate Test Rig.

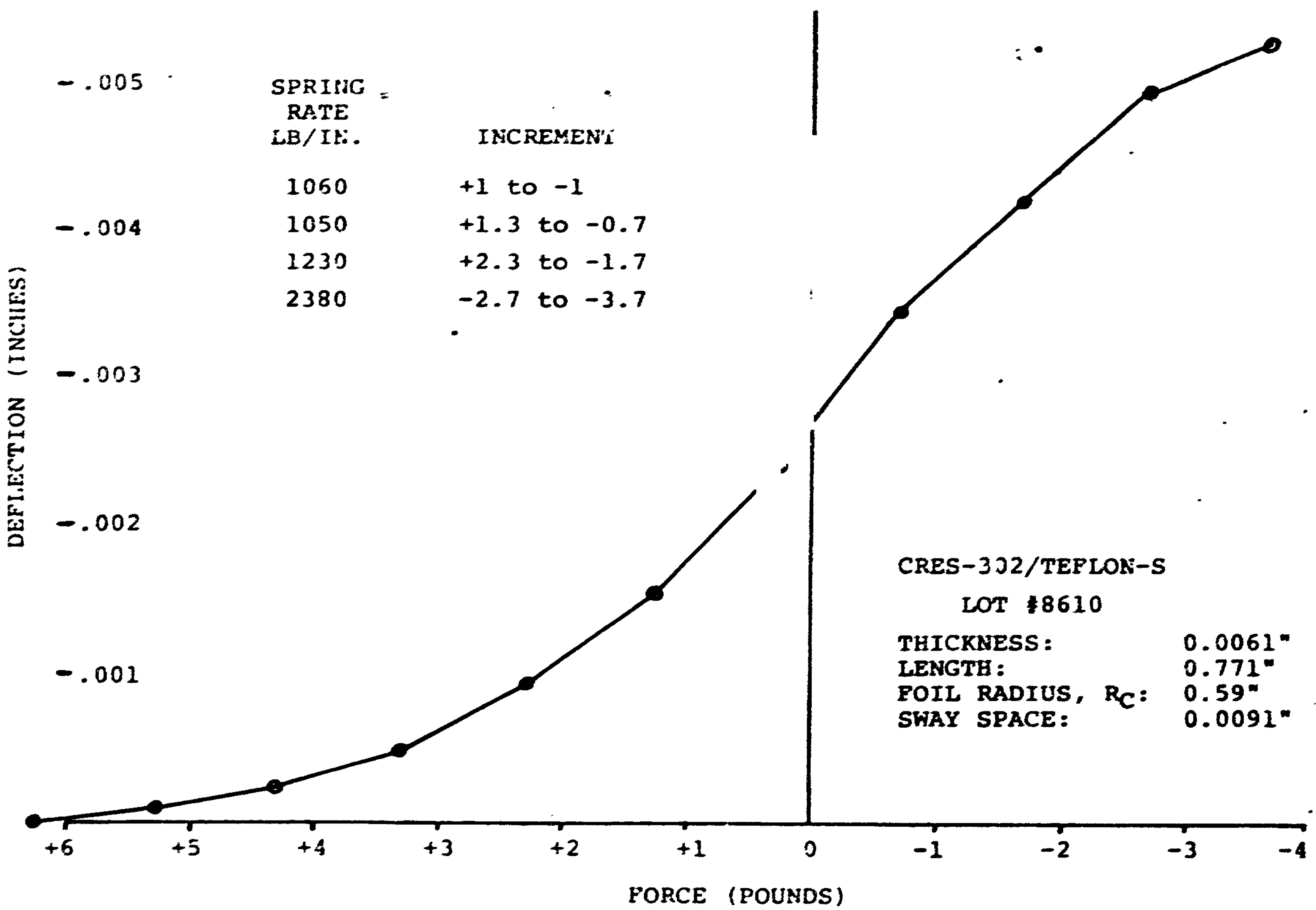


Figure 21. - Foil Bearing Spring Rate Plot.

TABLE IX. - SUMMARY OF SPRING RATE MEASUREMENTS

[Through May 18, 1978]

(Electrical vibe) "new rig" full range					"Old rig" 1/2 full range (hand vibe)		
Lot no.	R_C, in.	L, in.	Sway space, in.	K_L, lb/in.	K_L, lb/in.	Sway space, in. Compressor	Sway space, in. Turbine
8623	0.57	0.773	0.0091	930			
8624	0.57	0.773	0.0087	1300			
	0.61 w/ thick bars	0.773	0.0087	1190(!)	2380	0.0056	0.0081
8610	0.59	0.771	0.0091	1050	700 1000 1560	0.0099 0.0084 0.0069	0.0099 0.0084 0.0069
8609A	0.59	0.735	0.0087	630	640 940 1140	0.0095 0.0080 0.0065	0.0095 0.0080 0.0065
8616	0.62	0.766	0.0091	1490			
8616A	0.62	0.744	0.0091	1290			
8622	0.57	0.771	0.0091	710			
(later)	0.61	0.771	0.0091	740	1220 (Before MBTR) 1320 (After MBTR)	0.0058 0.0058	0.0086 0.0086

TABLE X. - SPRING RATE TESTS - 5-22-78

	("Shortened procedure")				Full range	
	(New rig)		(Hand vibe)		(New rig)	(Elec vibe)
Lot No.	R_C in.	L in.	Way space, in.	K_L lb/in.	K_L lb/in.	(Previously measured)
8623	0.57	0.773	0.0091	860	930	
8624	0.61 w/ thick bars	0.773	0.0087	1160	1190	(2380 lb/in. by "Old Method")
8610	0.59	0.771	0.0091	970	1050	
8609A	0.59	0.735	0.0087	620	630	
8616	0.62	0.766	0.0091	1250	1490	
8616A	0.62	0.744	0.0091	970*	1290	
8622	0.61	0.771	0.0091	720	740	

*Retested 6-1-78.

the "old rig." "Electrical Vibe" and "Hand Vibe" refer to the method used to vibrate the rig to a point of stability after each weight is applied. It was found that tapping the rig produced system equilibrium more rapidly than using the small electric vibrator provided. "Full range" refers to the use of weights from zero to ten pounds and back to zero. The "One-half full range" refers to the zero to six pounds typically used in the old rig. The new rig provides a more accurate measurement of the foil bearing spring rate.

Further experimentation disclosed that an abbreviated procedure could be used with satisfactory results. In this procedure, 1 pound is placed on the lower tray and becomes the zero point. Weights from 1 to 4.5 pounds and back to zero are then added and removed from the upper tray and deflections read from each force. Table X contains results obtained using this procedure and compares these results with those obtained earlier by the longer procedure. As may be seen, with one exception, there is close agreement.

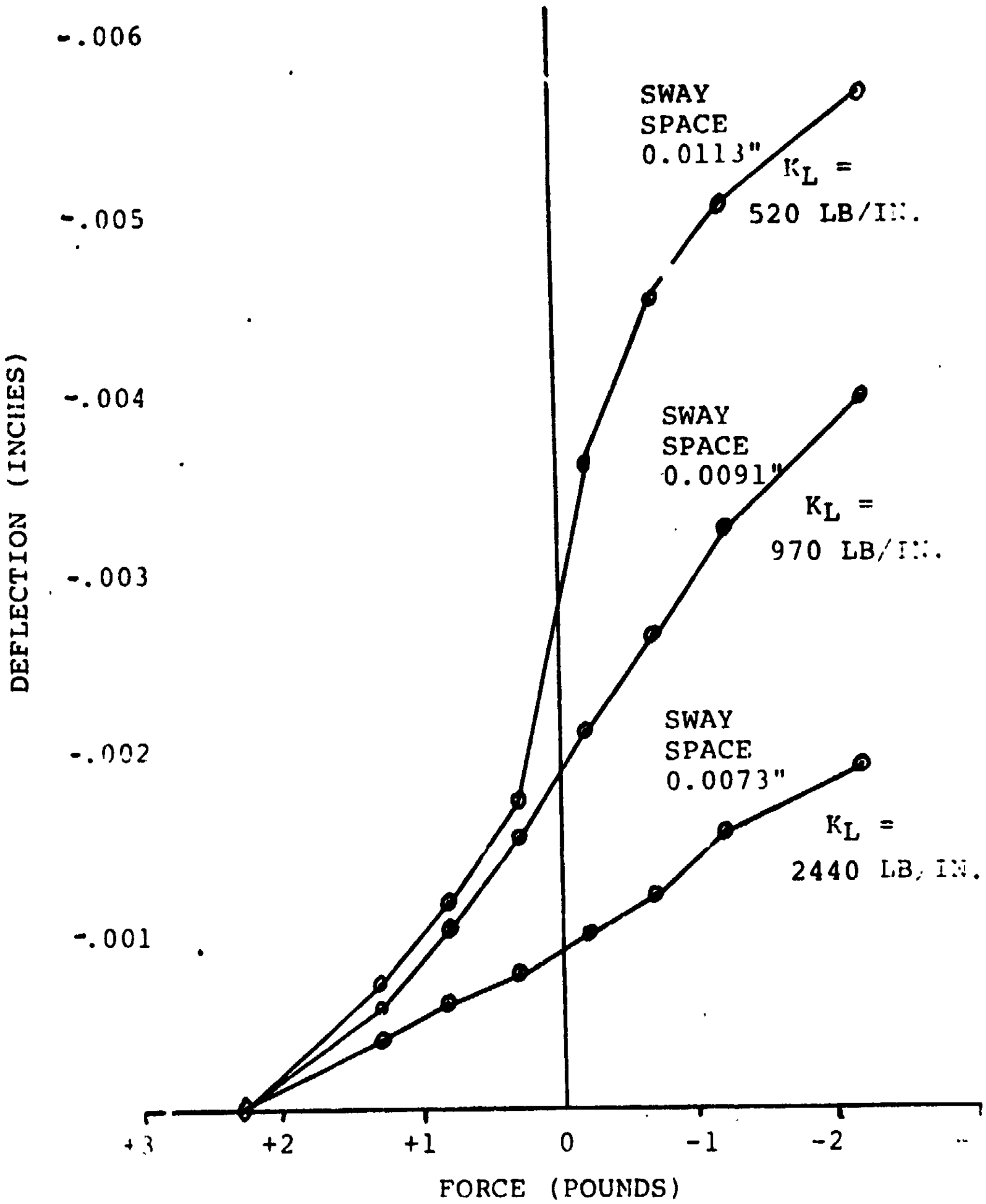
Figure 22 is another example of data obtained. It provides data for three different sway spaces. (Data were obtained through use of the shortened procedure.) As has been observed in earlier tests, spring rate increases as the sway space is decreased.

Figure 23 depicts the effects of varying the radius of curvature, R_c. Figure 24 is a smililar plot for "shortened" foils.

The effect of shortening foil length is shown in Figure 25. This shows that shortening the foil results in a lower spring rate for any given sway space.

Pressurized Bearing Rig Tests

One of the possible causes of Mini-BRU compressor journal bearing failure was identified as high bearing power loss in xenon/helium at pressure. This phenomenon was originally noticed when a bearing rig normally used in air at ambient conditions was placed in a tank and pressurized with argon. Data proved that power losses were significantly higher than predicted by analytical methods. At this time it was deemed necessary to have a bearing rig built specifically for testing in various gas environments at elevated pressures. Subsequently, the pressurized bearing test rig (PBTR) was designed, fabricated and put into full operation when problems developed with the Mini-BRU compressor journal



CRES-302 TEFLON-S LOT #8610

$T = 0.0061"$ $L = 0.771"$ $R_C = 0.59"$

Figure 22. - Sway Space Versus Spring Rate K_1.

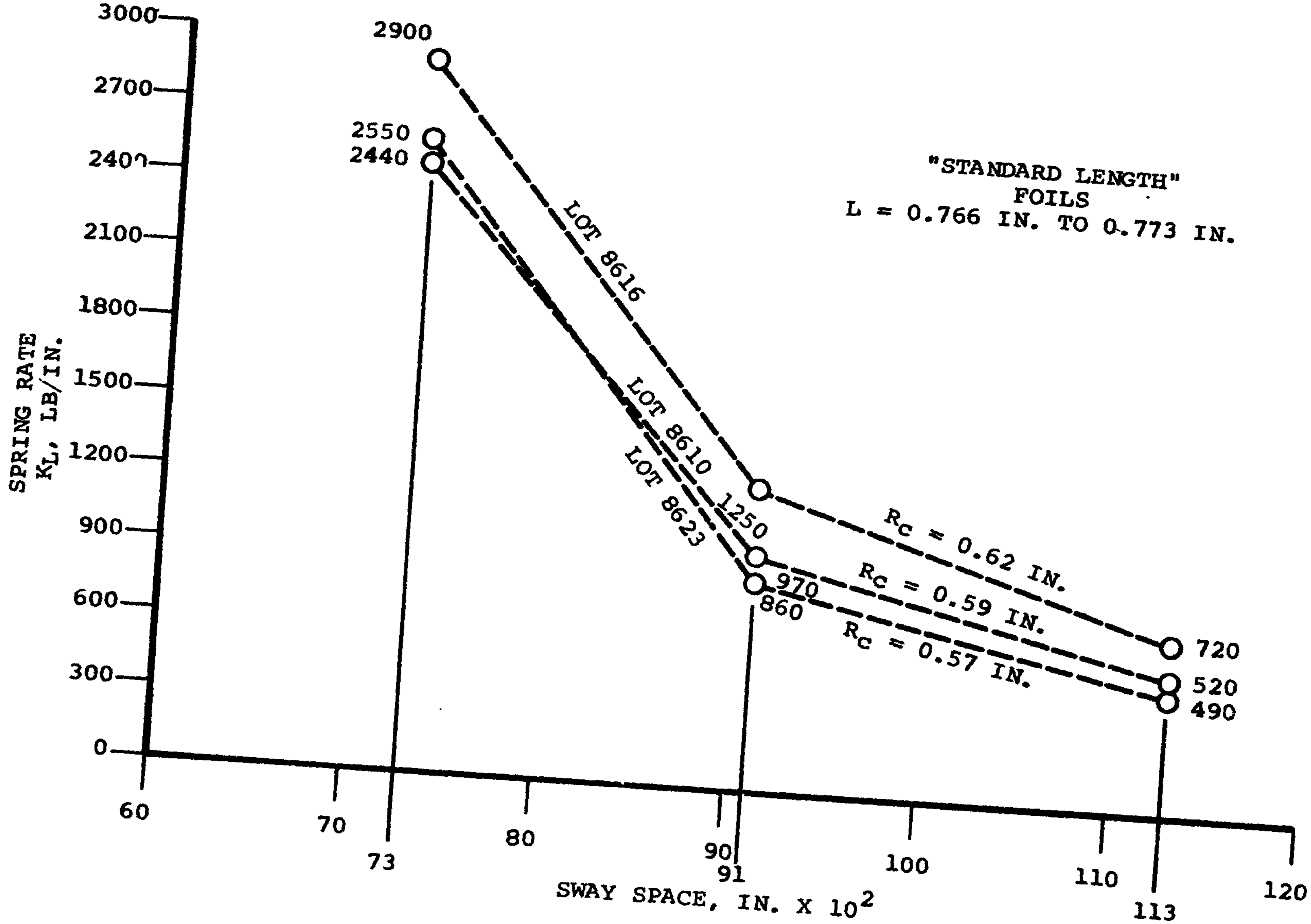


Figure 23. -- Spring Rate Versus Sway Space for Different Radii of Curvature.

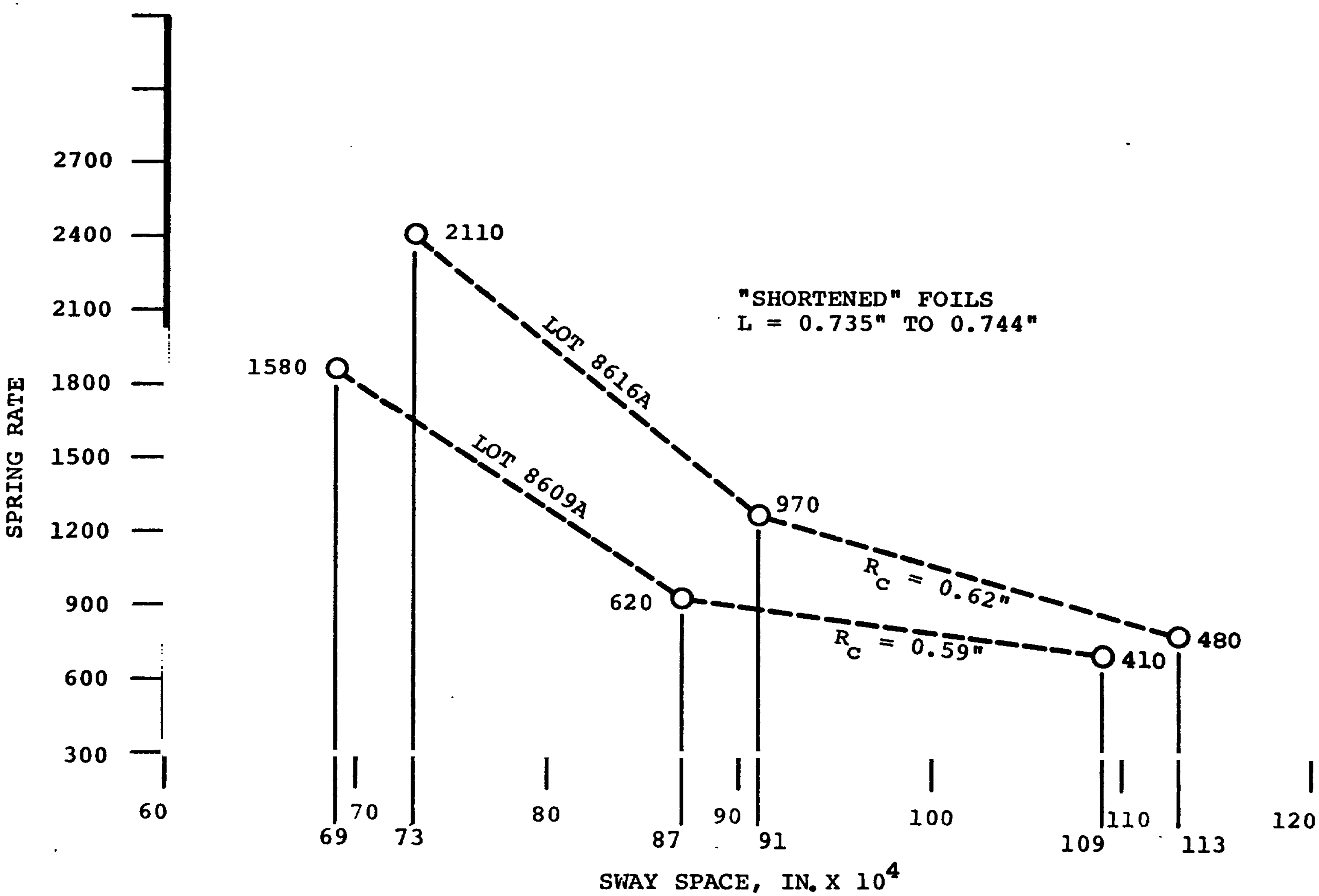


Figure 24. - Spring Rate Versus Sway Space for Different Radii of Curvature.

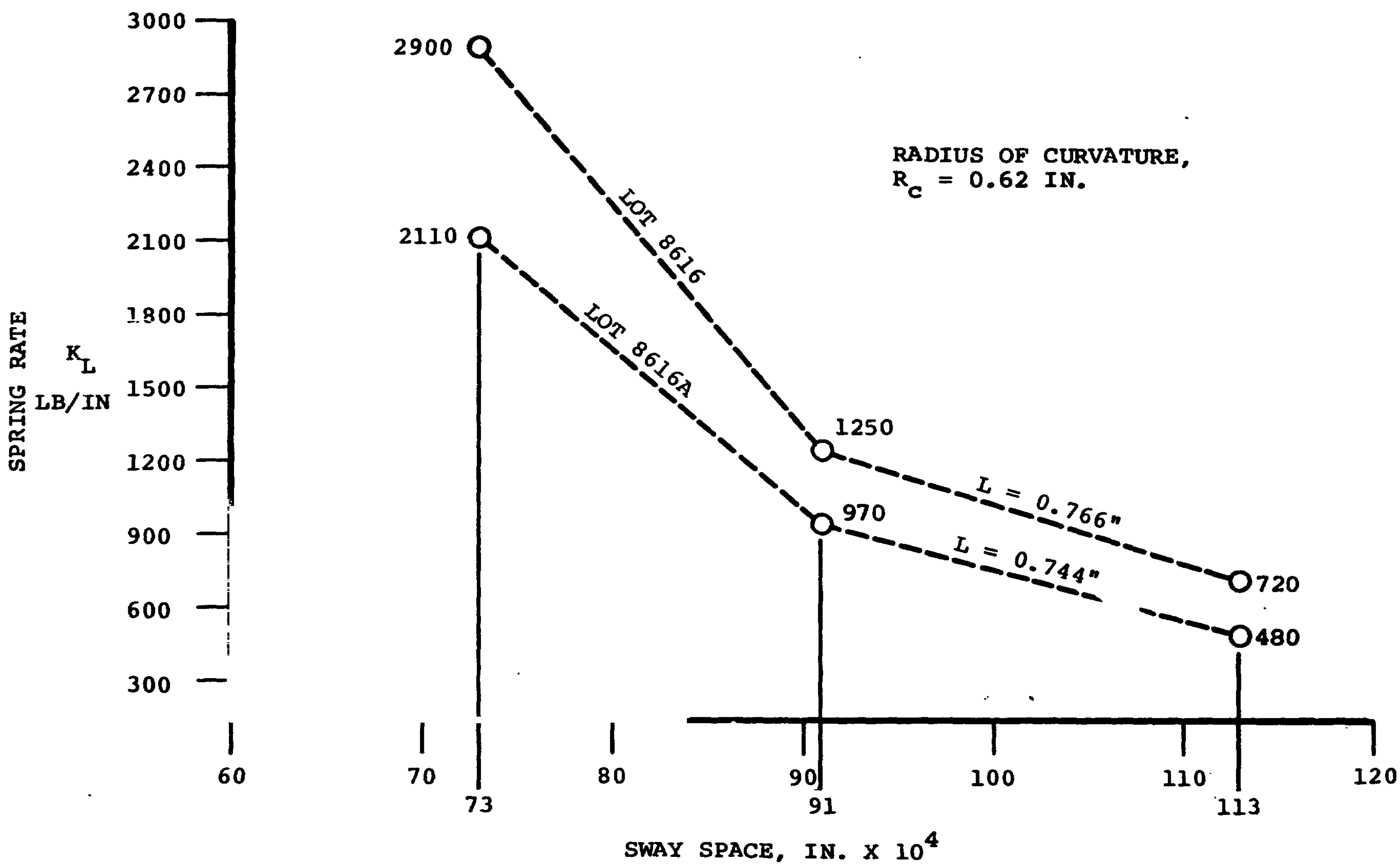


Figure 25. - Spring Rate Versus Sway Space for Different Foil Lengths.

bearing. A cross section of this test rig is shown in Figure 26.

In order to determine how gas type and pressure affect bearing performance, three gases were utilized for testing - air, argon, and krypton. Krypton was especially significant since it is characterized with the same molecular weight and nearly the same viscosity as the xenon/helium mixture used as the BIPS working fluid. An additional benefit of the pressurized bearing test rig was its ability to evaluate alternate bearings as possible candidates for future Mini-BRU engine testing. Various coatings and configurations were tested in order to compare their performance with the "standard" Mini-BRU bearing.

Test discussion. - Operation of the pressurized bearing test rig is shown in Figure 27. While the unit is running a load is applied to the bearing carrier through a hydrostatic pad. A strain gauge measures the carriers tendency to rotate with the shaft. Figure 28 shows the rig rotating group with the test bearing in place. The strain gauge torque measurement is accurate to within 0.001 in.-lbs and overall test rig repeatability has been demonstrated to be within 6 percent.

The bearing chosen for the high pressure tests was expected to closely resemble the bearing then being used in the Mini-BRU engine. Pressurized tests began in January, 1978. The Mini-BRU build of 12-22-77 used foils with a 0.61 in. radius and a sway space of 0.0082 in. The build of 2-24-78 had a 0.59 in. foil radius and 0.0087 in. sway space. The bearing used for pressurized tests had the following characteristics:

Eight (8) Teflon-S Foils

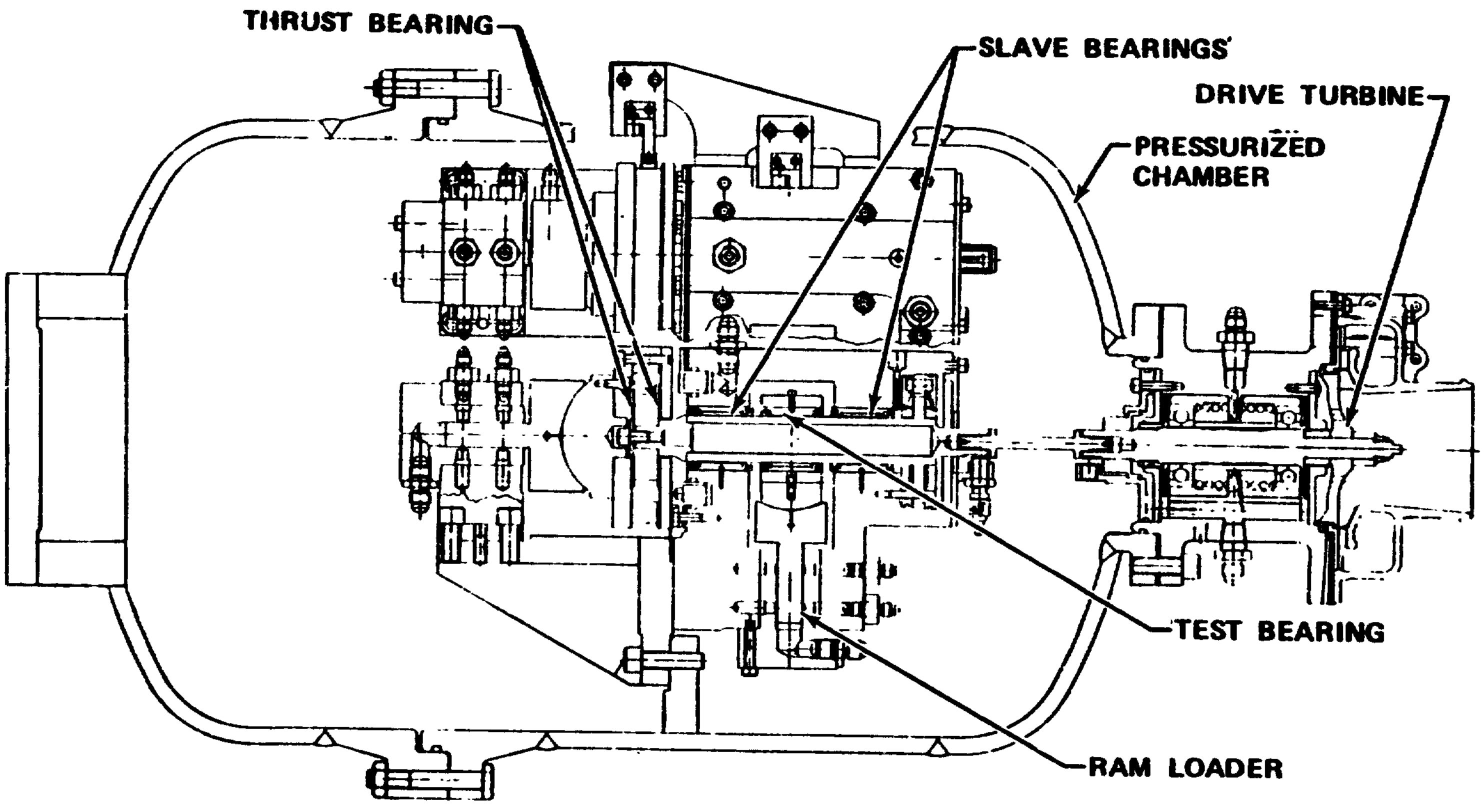
0.0058 in. total thickness

0.770 in. long

0.61 in. radius

0.0084 in. sway space

Tests were conducted in air, argon and krypton from 0 - 100 psi at 10 psi increments. Shaft speed was held at the Mini-BRU design speed of 52,000 rpm and load was varied at each pressure from 0 - 4 lbs. Loads were limited to 4 pounds to minimize test time and because Mini-BRU journal bearing loads are not expected to exceed 3 pounds.



FEATURES

- SIMULATED THERMAL ENVIRONMENT
- 3 BEARING SYSTEM
- HYDROSTATIC RAM LOADER
- SIMULATED PRESSURE ENVIRONMENT

MEASURED BEARING PARAMETERS

- LOAD
- TORQUE
- SPEED
- TEMPERATURE

Figure 26. - Cross Section of the Pressurized Bearing Test Rig (PBTR).

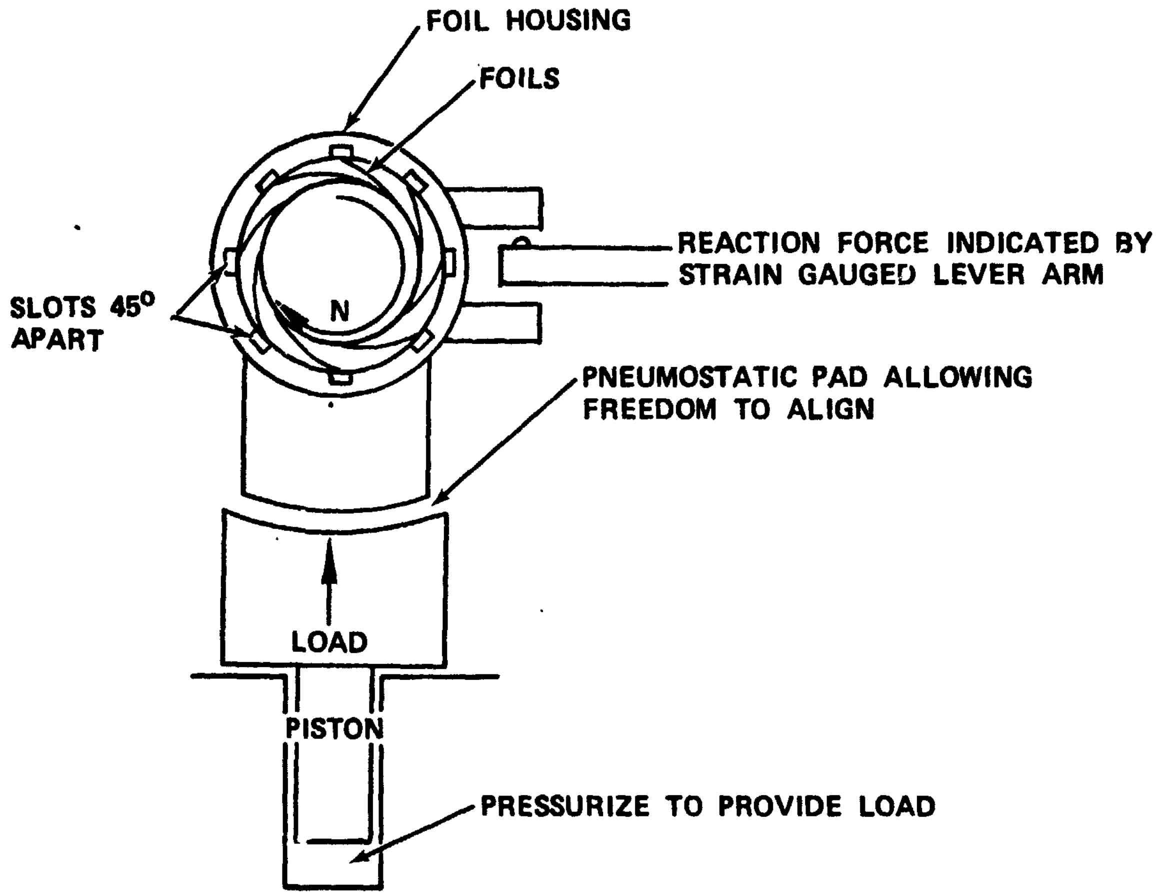


Figure 27. - Pressurized Bearing Test Rig Schematic.

Figure 28. - Pressurized Bearing Test Rig (PBTR).

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Ambient gas temperature within the test chamber was maintained at 100°F for all tests in order to keep conditions as nearly alike as possible. Figure 29 shows a comparison of torque values in the three gases at ambient conditions. Figure 30 through 32 depict how power loss varies with load and pressure in air, argon and krypton.

Tests to determine how different coatings and configurations affect bearing performance were conducted in air at ambient pressure. As in the pressurized tests, bearings were loaded to 4 pounds. A comparison of the performance of these bearings is shown in Figure 33. A complete description of the six candidate bearings is given in Table XI.

Test results. - Bearing power loss in krypton at Mini-BRU compressor journal bearing cavity presure (54 psia) and zero load was found to be 43.6 watts. This is higher than the 35 watts originally predicted. By examining the methods by which the prediction was made, it can be seen that several incorrect assumptions led to the lower power loss value. At the time that the BIPS data reduction computer program was being compiled, only limited data in air and argon was available from a test setup that permitted testing at limited pressures. From this original data, it was assumed that the slopes of power loss versus pressure curves would be linear and that the resultant curves for air, argon and krypton would be parallel. Subsequent testing in the PBTR showed that the slopes of these curves increase with pressure (Figure 34). Also, when testing in krypton was completed, it was found that power loss in high molecular weight gas increased much more rapidly with pressure. The assumption that the various power loss versus pressure curves would be parallel was the largest source of error in the original estimation. The data reduction program included a ratio of gas viscosities in its bearing loss calculation, but a ratio of molecular weights (densities) should have been included.

Effect of coatings. - By referring to Figure 33, several observations can be made from the coating/configuration tests. The quality of the coating appears to play an important part in the performance of the bearing. This can be seen by comparing bearings No. 4 and No. 5. Bearing No. 4 has the original Teflon coating used in the initial builds of the Mini-BRU while No. 5 has the superior Crest Teflon coating. While both bearings display the same torque at zero load, the performance of No. 4 deteriorates much more rapidly. It should be noted that the Crest Teflon bearing had a smaller sway space and higher preload than No. 4.

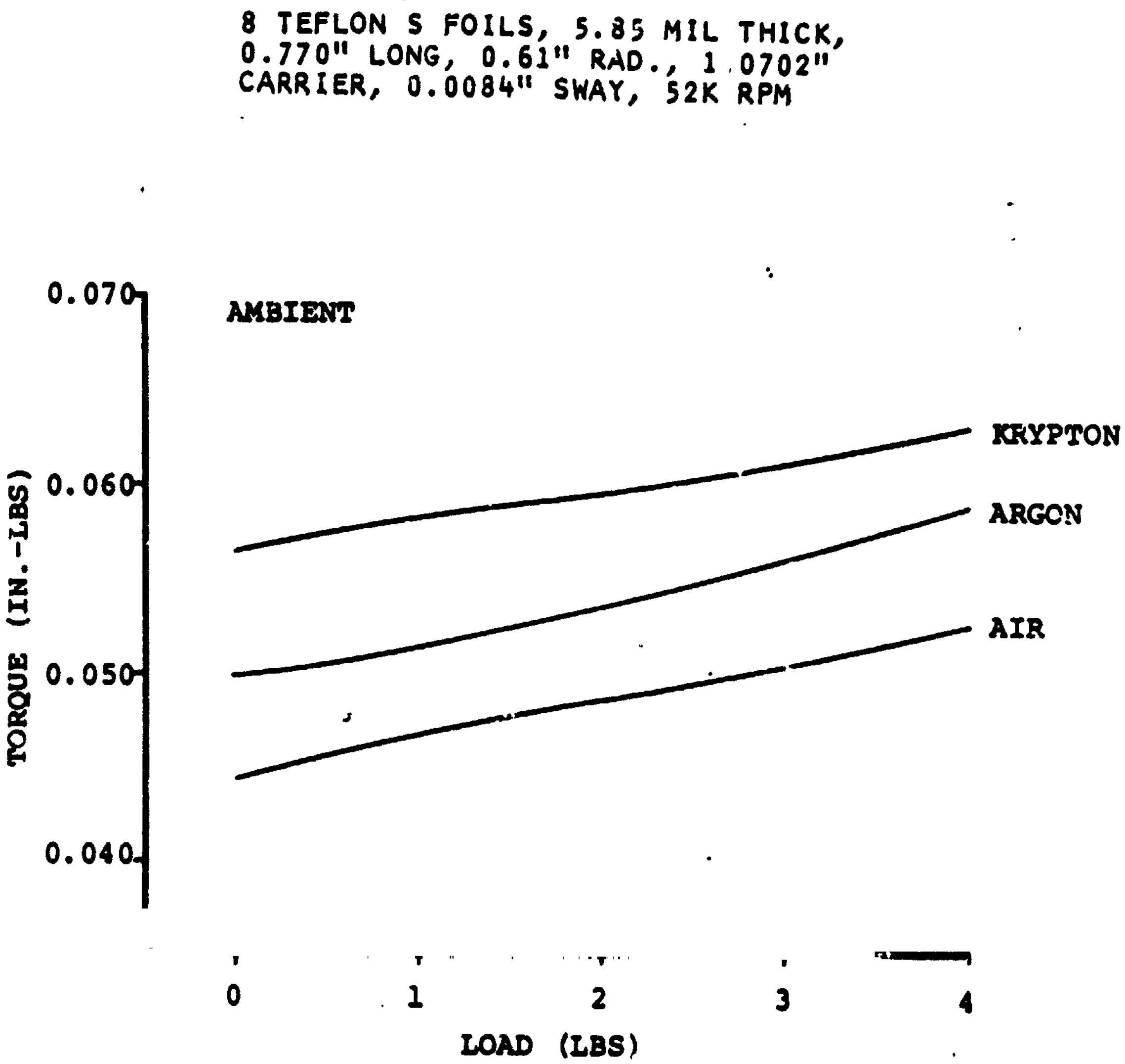


Figure 29. - Torque Versus Load for Three Gasses at Ambient Conditions.

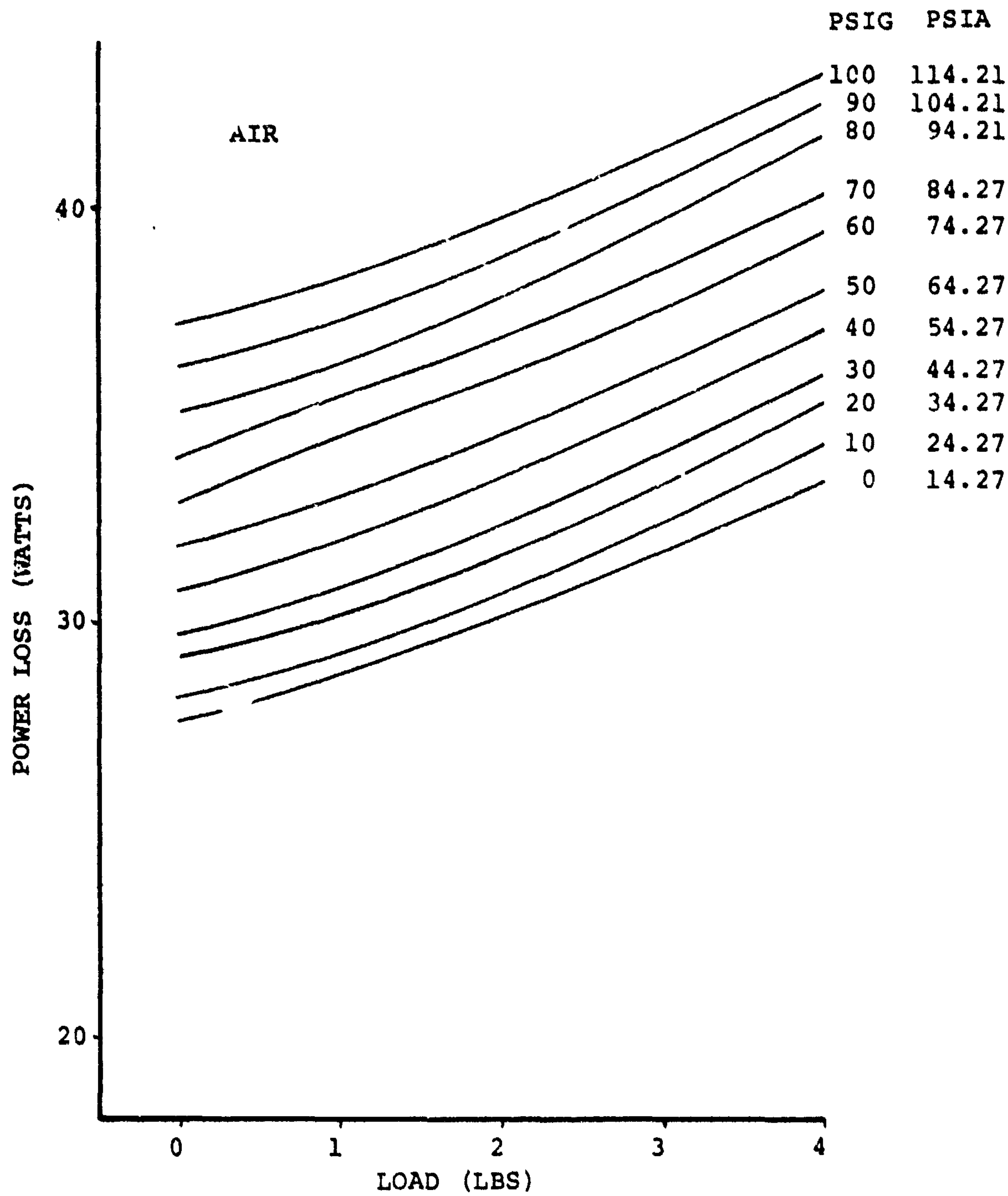


Figure 30. - Power Loss Variation With Load and Pressure.

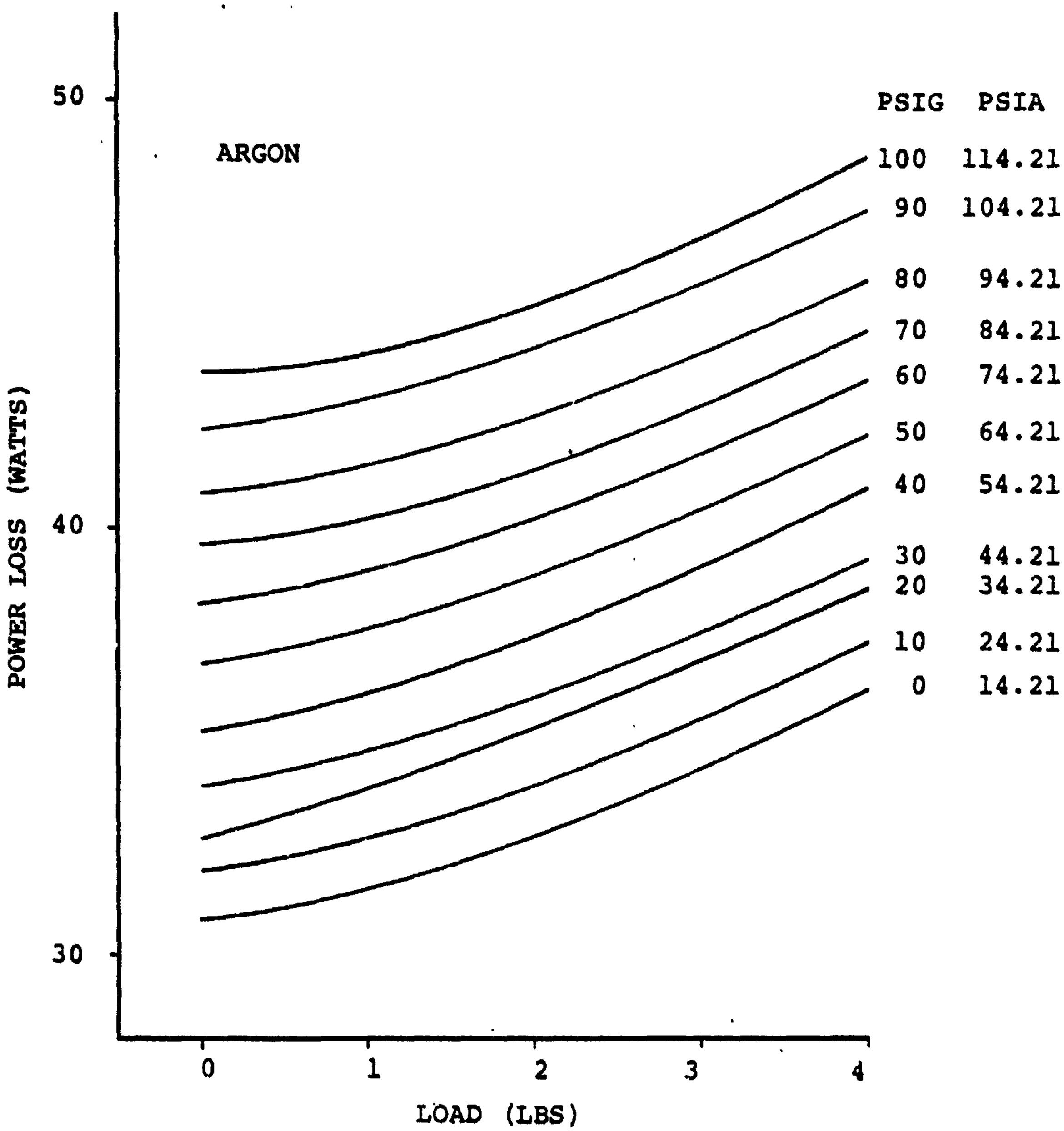


Figure 31. - Power Loss Variation With Load and Pressure.

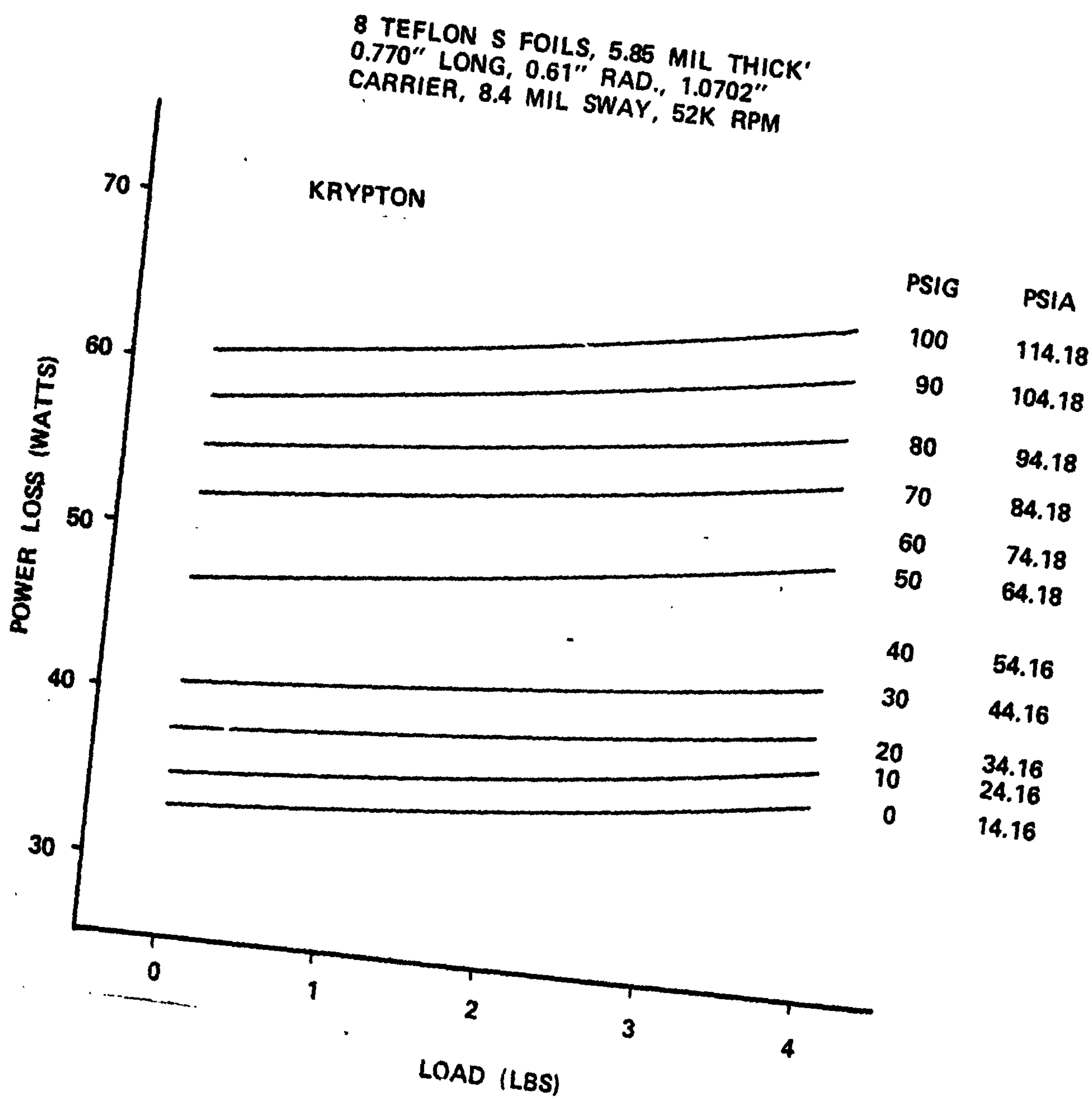


Figure 32. - Power Loss Variation With Load and Pressure.

COATING/CONFIGURATION TESTS

	MATL	COATING	SWAY	FILE NO.
1	1010	DICRO	0.0070	21
2	1010	MOLY-DIS	0.0074	22
3	302	IOSSO	0.0074	110
4	302	TEF S	0.0084	BASELINE
5	302	TEF (CREST)	0.0070	26
6	INCO750	TEF/GOLD	0.0078	15

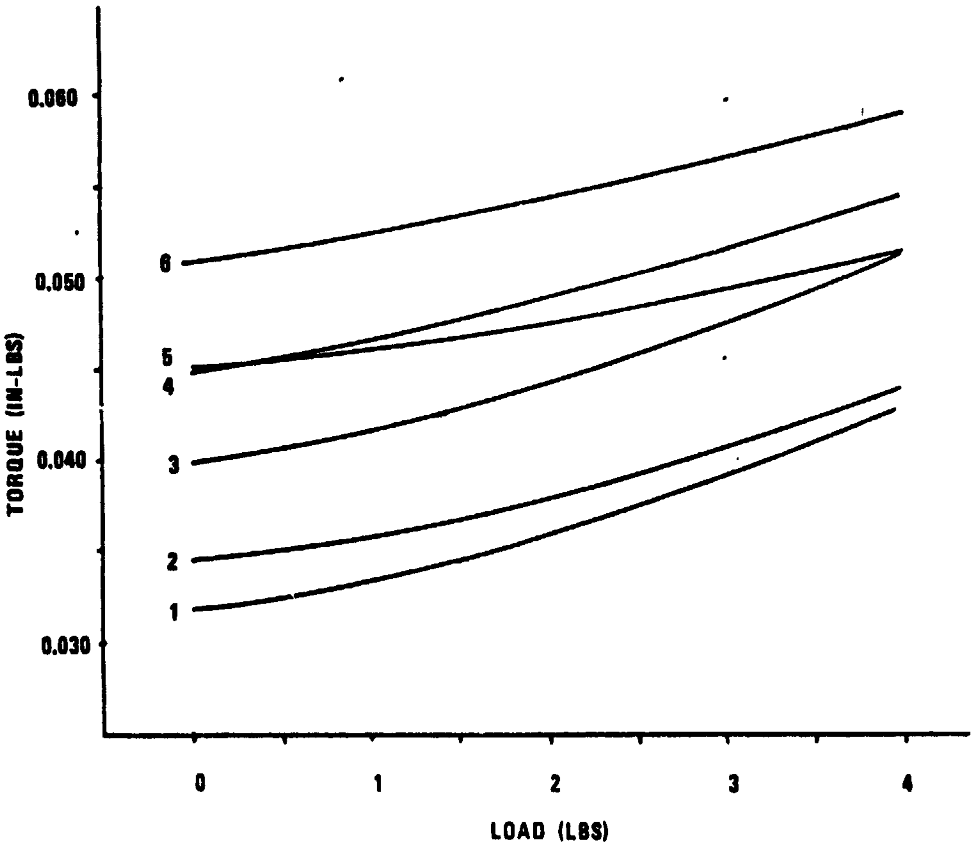


Figure 33. - Torque Versus Load for Air at Ambient Conditions.

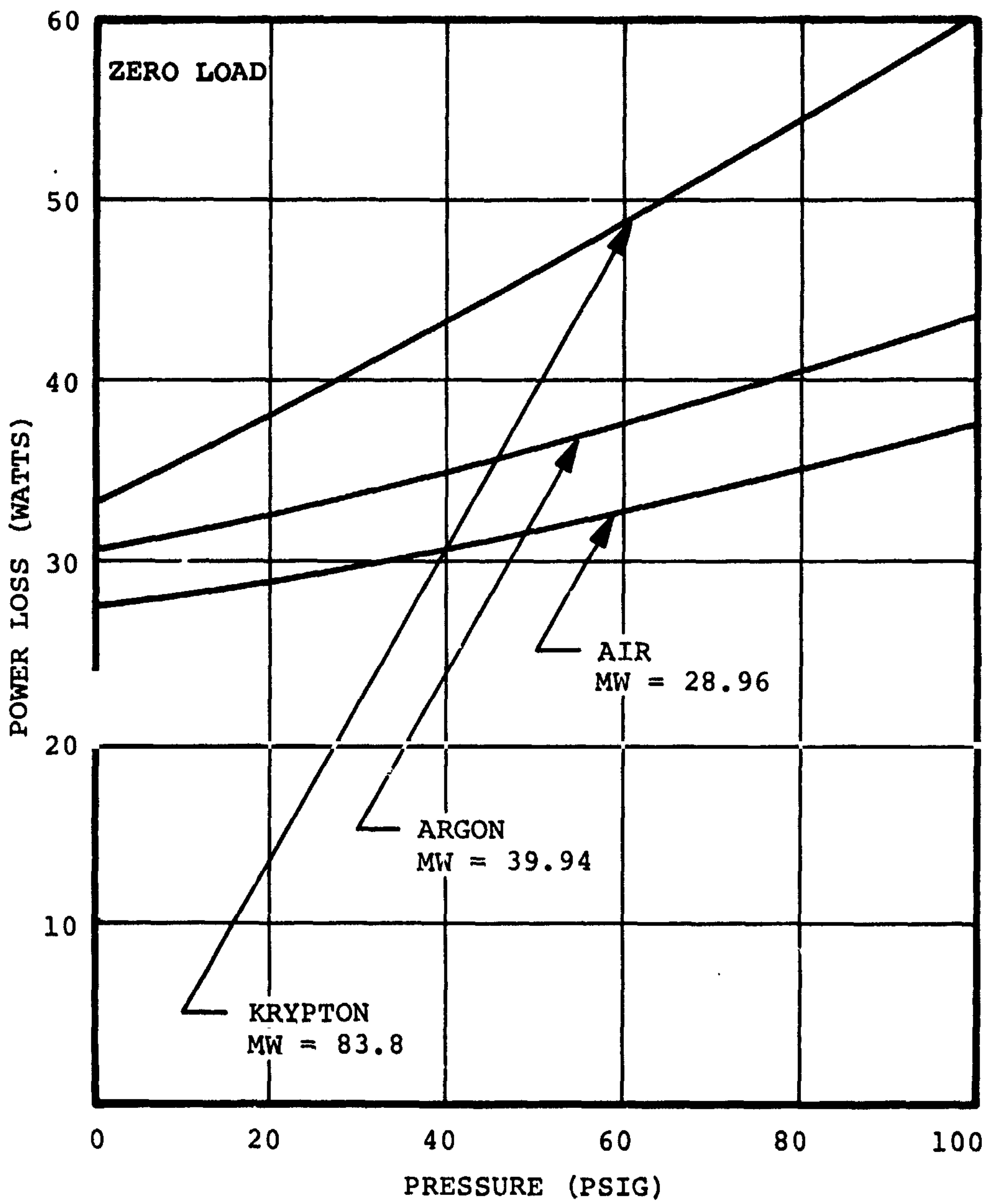


Figure 34. - Power Loss Variation With Pressure.

TABLE XI. - COATING/CONFIGURATION COMPARISON

No.	Material	Coating	Total Thickness	Length	Radius	Sway
1	1010	Dicronite	5.3 mils	0.745 in.	0.59 in.	0.0070 in.
2	1010	MoS_2	5.2	0.770 in.	0.57 in.	0.0074 in.
3	302	IOSSO-FE	5.2	0.770 in.	0.61 in.	0.0084 in.
4	302	Teflon-S (Baseline)	5.85	0.770 in.	0.61 in.	0.0084 in.
5	302	Teflon-S (crest)	6.2	0.770 in.	0.59 in.	0.0070 in.
7	INCO750C	Teflon/Gold	6.0	0.740 in.	0.60 in.	0.0078 in.

While Bearing Nos. 1, 2, and 3 all display lower operating torque than the others, their rapidly increasing torque with load indicates poor load capacity. With the proper combination of stiffness, preload and sway space, however, these bearings could all display better overall performance than Teflon coated foils.

High specific area bearings. - A few tests were conducted with high specific area bearings. High effective area bearings were developed to increase the specific load capacity of the bearings. A photograph of several types is shown in Figure 35.

Several tests were conducted with early versions of the bearing. The load capacities did not meet expectations indicating the need for additional configuration development. Since the conclusion of testing on this program, advanced versions tested under a contractor sponsored program have exhibited load capacities considerably in excess of conventional foil bearings.

Material Analysis

An important contribution to the final solution of the bearing problem was made in the area of materials analysis. Scanning Election Miciosсope (SEM) techniques were used to evaluate the failed WHL bearings and test rig bearings. Data from the rig tests was shown in an earlier section. Data for the November and December WHL tests are included in Appendix I.

A summary of the pertinent materials findings is as follows:

(1) Primary procedure - SEM with EDX analysis

   (a) Allows definition of surface

   (b) Allows chemical analysis of area of interest

(2) Hardware observed

   (a) WHL hardware

   (b) SBTR test samples

   (c) MBTR test runs

(3) Observations

   (a) As coated surface contains ripples, dimples and craters

Figure 35. - High Specific Area Bearings.

MP-63996

(b) Coating burnished by shaft in band near trailing edge

(c) Burnished bearings show fine Teflon debris

(d) Black areas are primarily smeared Teflon particles

(e) Smeared areas and debris show evidence of rotor material with Teflon

(f) Shiny particles not always metallic analysis shows content similar to smeared Teflon in mixture of Teflon and rotor

(g) WHL failure much more advanced than any of the test foils

(h) Particles noted in WHL grooves most probably mixture of Teflon and rotor

(i) No materials foreign to bearing cavity noted

Another important aspect of the materials analysis was in the evaluation of Teflon coating vaporization. It was theorized that at the temperatures predicted for the bearing surface, substantial Teflon vaporization might occur over the mission life which would reduce the foil thickness and change the bearing sway space thereby adversely affecting the stability of the rotor system.

The results of tests conducted at AIRPHX and at Battelle Columbus Laboratories are summarized in Tables XII, XIII, and XIV.

The important result of this work was the finding that the expected vaporization rate was of the order of 10 percent for the proposed 7 year mission duration. This was judged to have an insignificant effect on long term bearing performance.

Fabrication and Inspection Methods

During this period of bearing development the existing methods of foil bearing fabrication and inspection were critically reviewed and improved upon wherever warranted.

TABLE XII. - MATERIALS INVESTIGATION --- COATING

BCL Tests

Microbalance evaporation

hot stage microscopy

Results

Recession of coating primarily sublimation. Some slight balling of material noted during evaporation. Particle size much less than air film thickness.

No bubbling or gross debonding noted. Evaporation of half the Teflon left a smooth surface.

Small amount of very fine particles left behind--may be additions for color.

Coating recession rapid at 500°F, moderate to low at 350°F.

TABLE XIII. - BCL MATERIALS TESTING

Teflon-S

Microbalance testing in Xe/He

Initial vaporization rate at 500°F = 5×10^{-5}		GM/CM^2-HR
Initial vaproization rate at 350°F = 2×10^{-7}		GM/CM^2-HR
Long term vaporization rate at 350°F = 4×10^{-8}		GM/CM^2-HR

Mass specification analysis at temperature

Lower temperature	H_2O, CO, CO_2 CH_4 (residual binder)
Higher temperatures	CF_2, CF_4 (from $NICF_2$)

Hot stage microscope testing

Visual check for surface eruptions - negative

OBD-26

Microbalance testing in Xe/He

Initial vaporization rate at 500°F = 4×10^{-5}		GM/CM^2-HR
Initial vaporization rate at 350°F = 2×10^{-7}		GM/CM^2-HR

Mass specification analysis at temperature

Lower temperature	S, SO, SO_2
Higher Temperature	HCL (intense)

TABLE XIV. - AIRPHX MATERIALS TESTING

Test Document:

1. Determine chromatographic "fingerprint" of dis-dressed Teflon-S in preparation for engine test

2. Determine the temperature limits of operation of Teflon-S

3. Determine the above for OBD-26 coating

Method:

Heated sample foils in helium: effluent directed to gas chromatograph

Findings:

1. Detectable products of degradation are CO_2 and CH_4 - as detected in engine loop November 8, 1977

2. Teflon decomposition rate of 1.8×10^{-5} GM/CM^2-HR at 500°F

3. Sublimation evident in test container - test of empty container yields same products - "finger-print" detection of bearing failure not probable without complete loop teardown and cleaning.

<u>Foil Bearing Fabrication</u>. - Traditionally, foil journal bearings have been fabricated by hand by skilled technicians. The individual pads are sheared or chemically etched from a large sheet of Teflon coated material and rolled to the desired radius of curvature. A 90 degree bend is then turned on one end and a rectangular retainer bar is spot welded on. Finally the pad is hand finished to break edges, remove sharp corners and deburr. The design drawing in its final form for the Mini-BRU journal bearings is shown in Figure 36 (Drawing 3604338).

Forming the radius of curvature is the most critical item in the process; this determines, in addition to the true radius, the edge skew and out of roundness of the surface as shown in Figure 37. Considerable development effort was devoted to assuring that a correct radius was formed.

Originally the radius was formed by careful utilization of a three element roller. An attempt was made to develop a forming die which would use fixed geometry dies to make the process absolutely uniform. This die is shown in Figure 38. The foils formed were found to be very uniform but slight variations in material thickness or rate of forming would cause variations in the true radius. A comparison of "rolled" and "formed" foils is shown in Figures 39 and 40. Table XV gives a numerical comparison of key parameters for rolled and formed foils.

A disadvantage of the forming die was the large quantity of dies required to accommodate variations in foil radius, foil length, foil thickness and foil coating. It was concluded that the roll form, carefully used, was adequate for development use whereas the forming die would be very suitable for production quantities.

Another fabrication problem was reradius of foils. In the earlier development phases, test foils had been reradiused, sometimes more than once, to vary the radius of curvature. As better inspection techniques were implemented, it became apparent that this procedure almost always caused a double radius with a strong effect on spring rate. This practice was discontinued and changes in radius of curvature necessitated fabrication of new foils.

Another facet of the improvement in bearing fabrication methods was the implementation of a detailed cataloging system for tracking the bearing through the fabrication process. During the course of the program a wide variety of bearings, many very similar in configuration, were made and tested. The cataloging and file system was utilized to keep track of the following parameters:

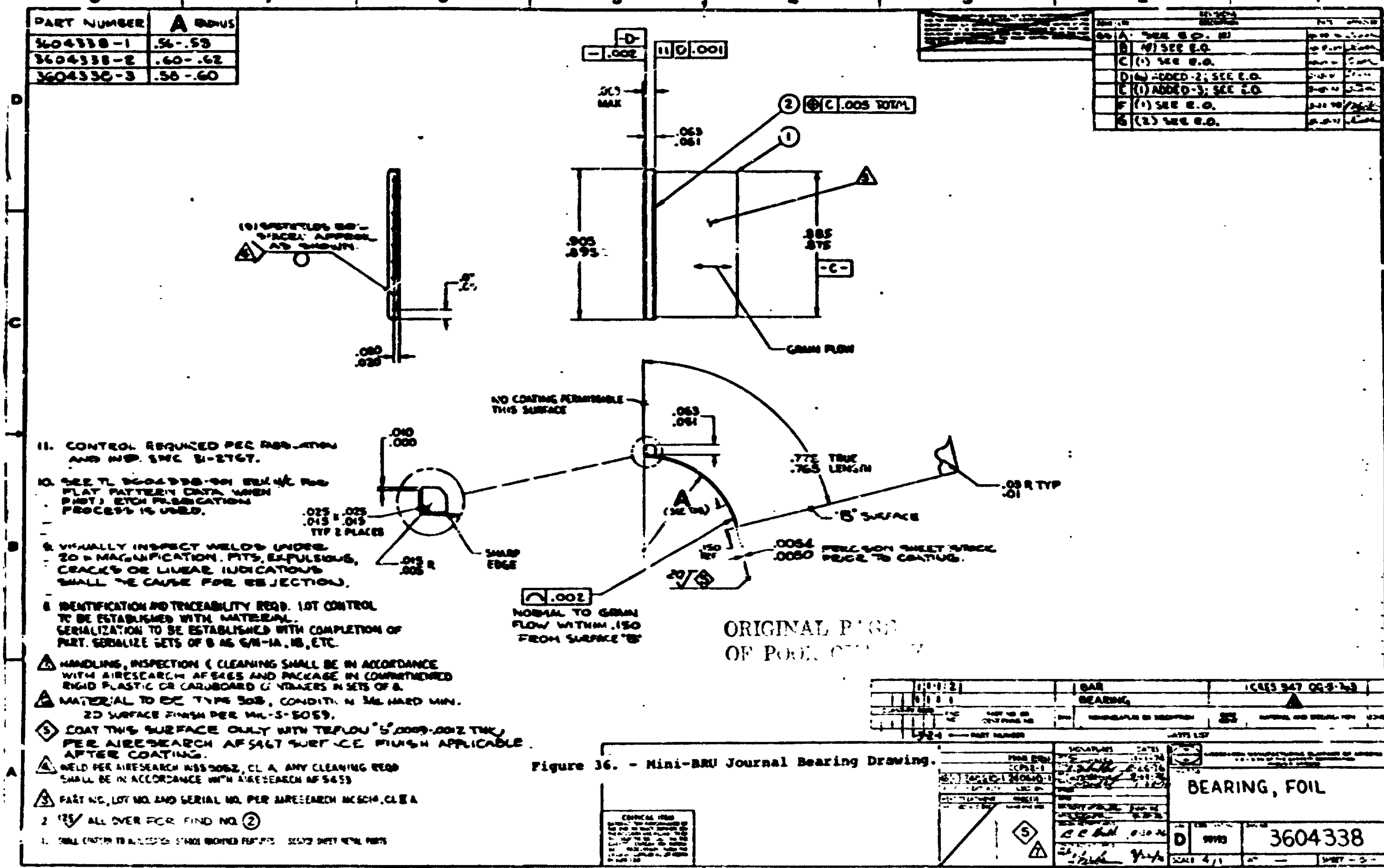


Figure 36. - Mini-BRU Journal Bearing Drawing.

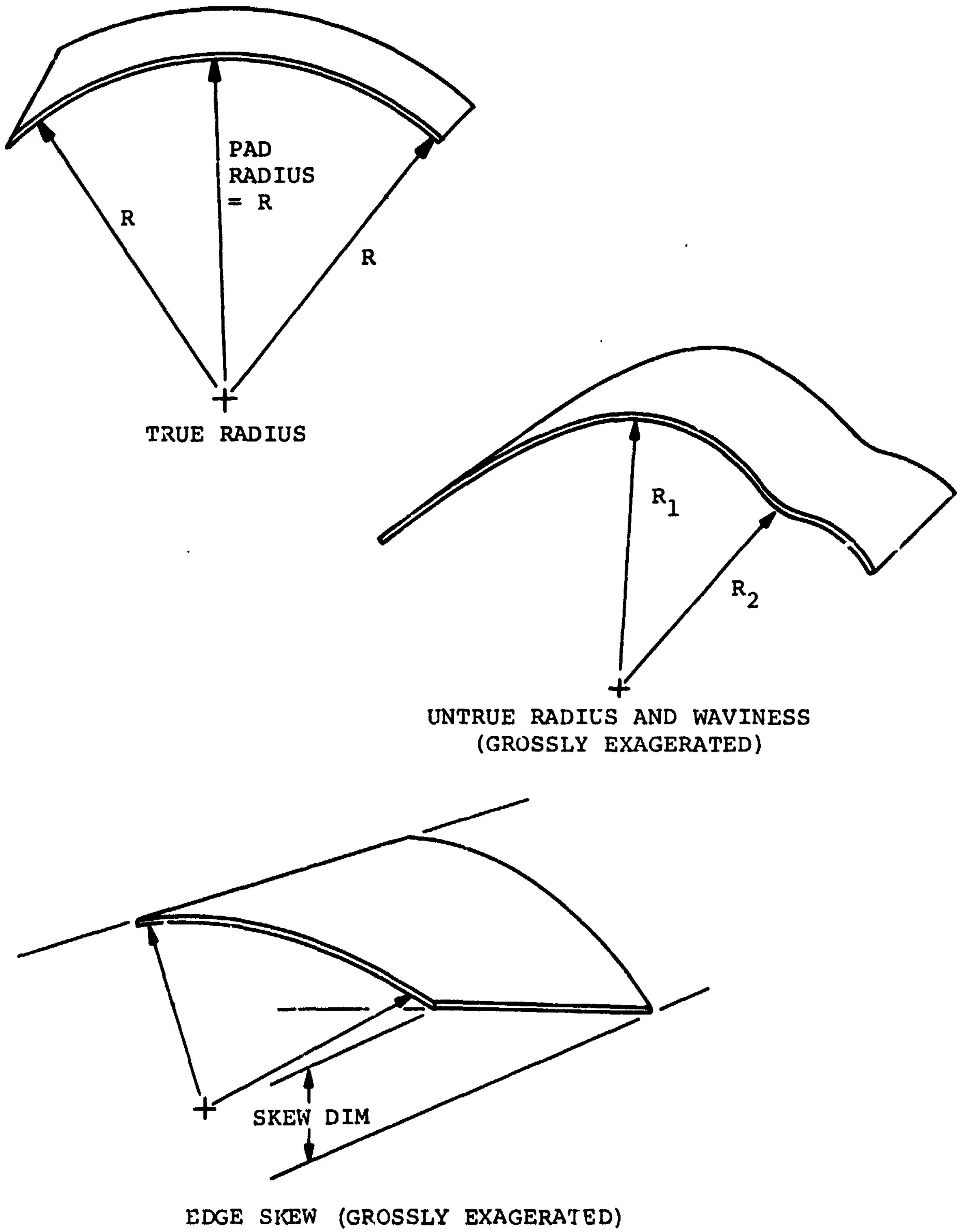


Figure 37. - Foil Forming Parameters.

Figure 38. - Foil Bearing Forming Die.

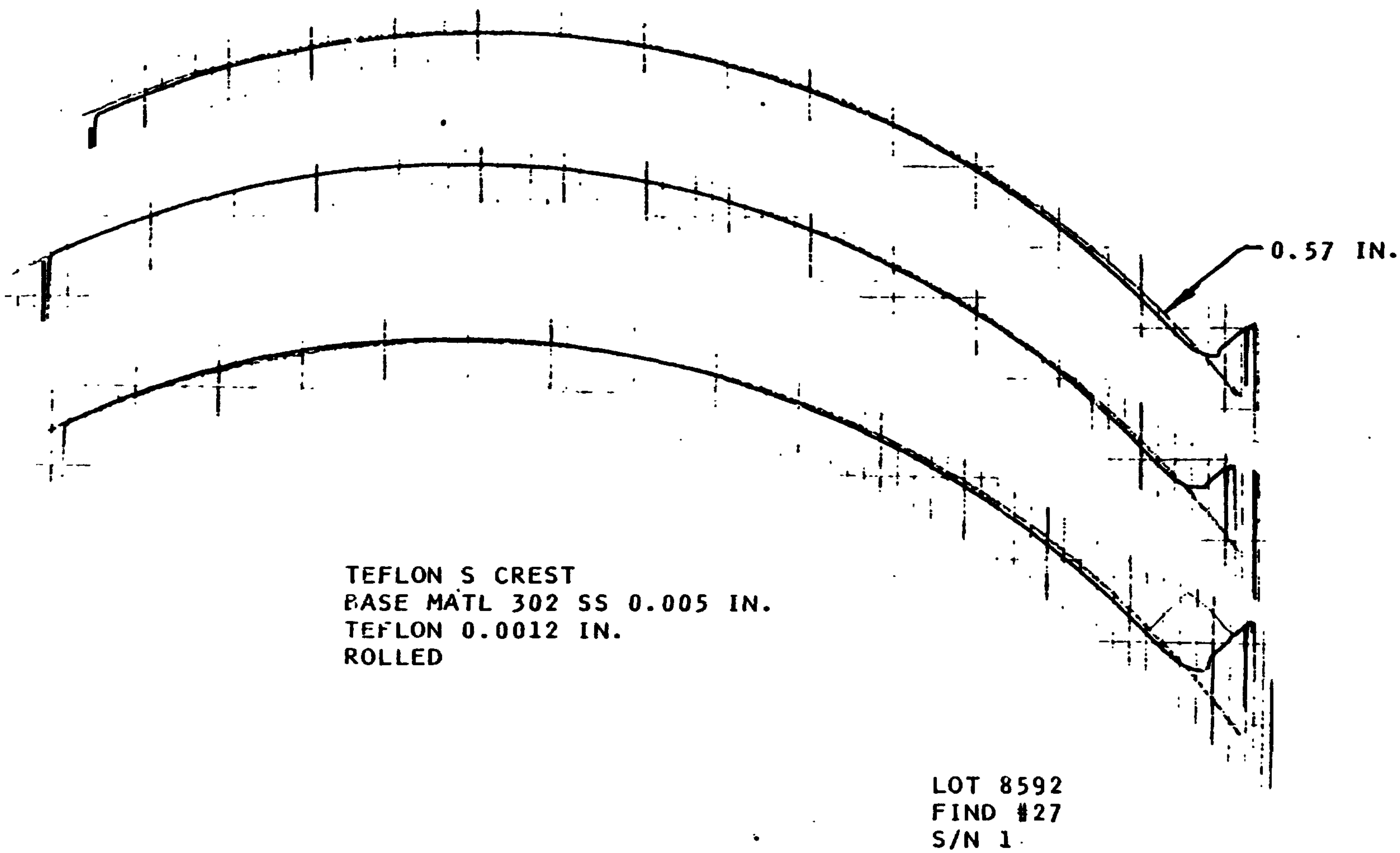


Figure 39. - Rolled Foils.

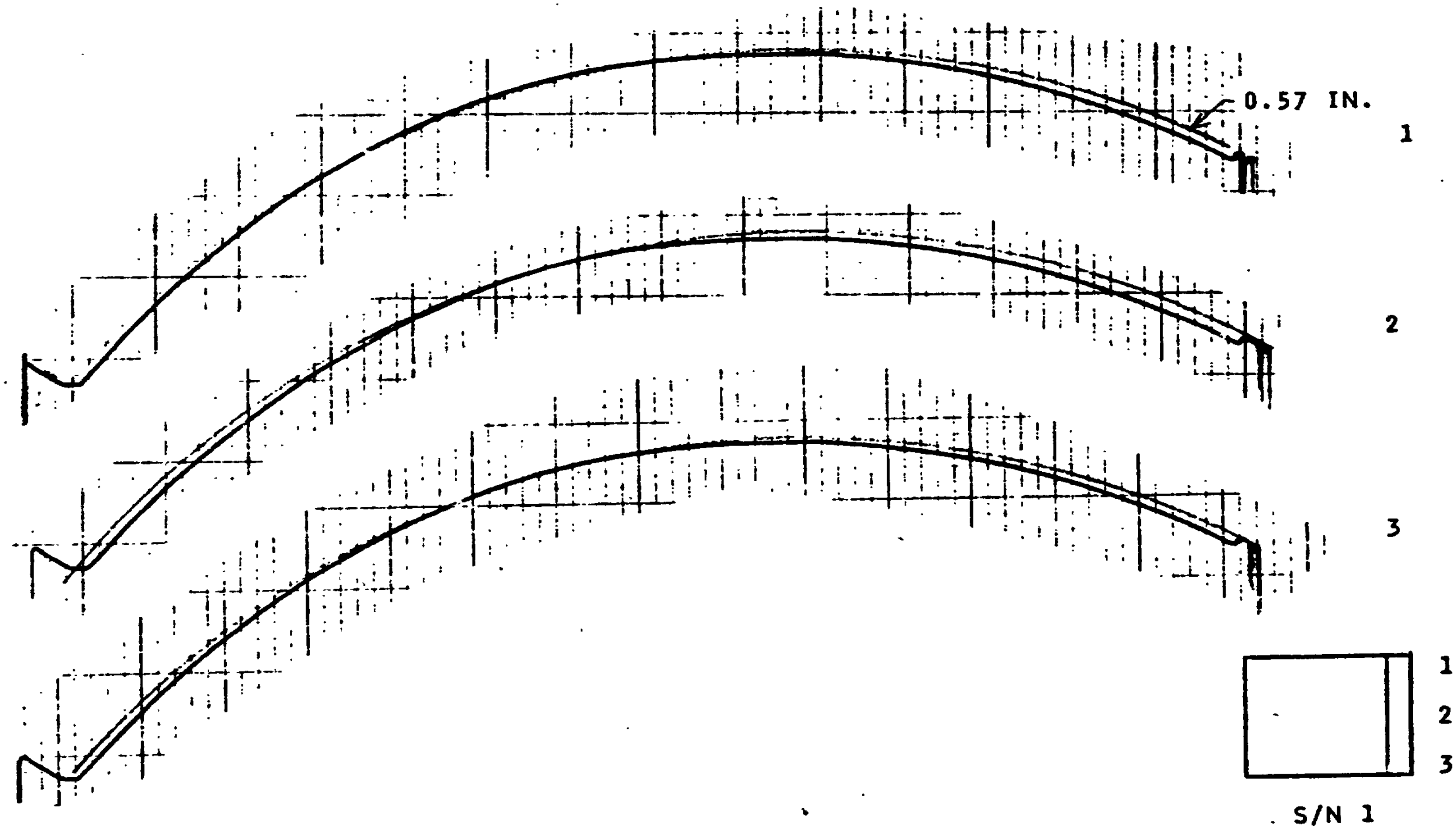


Figure 40. - First Samples From Forming Die.

TABLE XV. - CONTOUR READER INSPECTION

Rolled foils (radius changed)		
1.	Maximum edge-to-edge variation	10 mils
2.	Maximum variation from true radius	8 mils
Rolled foils		
1.	Maximum edge-to-edge variation	2 mils
2.	Maximum variation from true radius	10 mils
Forming die		
1.	Maximum edge-to-edge variation	1 mil
*2.	Maximum variation from true radius	14 mils

*Should improve when arbor press with "stop" is used.

Base material background and traceability
Base material type
Base material thickness
Base material heat treat and condition
Coating vendor
Coating type
Coating thickness
Bearing radius of curvature
Bearing size
Retainer material
Bearing test history

Inspection methods. - In addition to the 10:1 size profile traces described in the preceding section, a number of inspection techniques were implemented. The major contributions are shown in Figure 41.

In addition foils were dimensionally inspected in detail to the inspection record shown in Figure 42. This provided a record, keyed to each foil by etched serial number, that could be used for before and after test comparison.

Thermal Analysis and Test

Additional thermal analysis was conducted to determine if overtemperature was a contributor to the bearing failures. This analysis consisted principally of extending and refining the thermal analyses conducted earlier in the program by utilizing measured temperatures in the unit. In particular the compressor and turbine journal bearings were modeled in detail.

Figures 43 and 44 show the predicted temperature distribution for the two bearings.

A special workhorse loop test was designed to verify the predicted temperatures. A thermocouple was attached near the trailing edge of a compressor end journal foil as shown in Figure 45.

Thermal paint was applied to the alternator end bells, the turbine backface shroud, the tie bolt, the inside surfaces of the alternator rotor and the outside of the turbine end bearing carrier. (The compressor carrier did not provide enough exposed area to warrant thermal paint).

(1) RADIUS OF CURVATURE

- 10:1 PROFILE TRACING ADAPTED
- SEE ATTACHED SAMPLE TRACE

(2) SPRING RATE

- REPEATABILITY OF EXISTING METHOD VERIFIED
- NEW FIXTURE DESIGNED AND IN FABRICATION – WILL TAKE BOTH + AND - SPRING RATE AND LOCATE ZERO POINT

(3) ROUTINE CMR OF ALL MATERIAL/COATING COMBINATIONS

(4) INSPECTION LOG SHEET FOR ALL MINI-BRU/SIMULATOR/PBTR BUILDS – SEE FIGURE 42

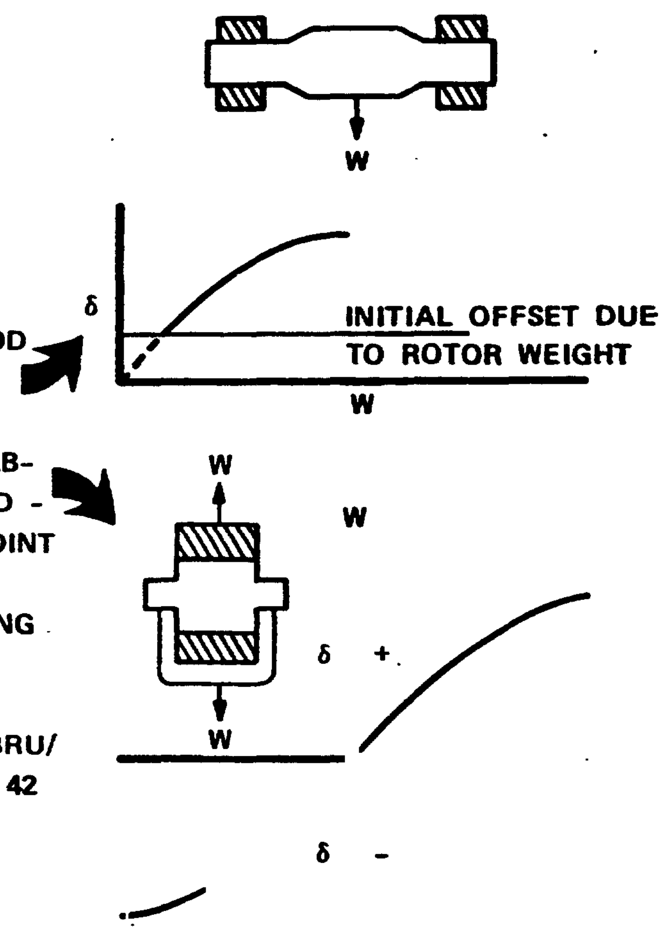


Figure 41. - Mini-BRU/STR Bearing Inspection Techniques.

BUILD FOR: ____________ BUILD DATE ____________ TEST DATE ____________

ROTOR - P/N ____________ S/N ____________

SHAFT O.D. COMPRESSOR END ____________ TURBINE END ____________

COMPRESSOR CARRIER - P/N ____________ S/N ____________

I.D. ____________ SLOT WIDTH ____________ (MIN.)

TURBINE CARRIER - P/N ____________ S/N ____________

I.D. ____________ SLOT WIDTH ____________ (MIN.)

JOURNAL FOILS

LOT NO. ____________ S/N ____________ R_C = ____________

BASE MATERIAL ____________ COATING ____________ STRESS RELIEVE TIME/TEMP °F ____________

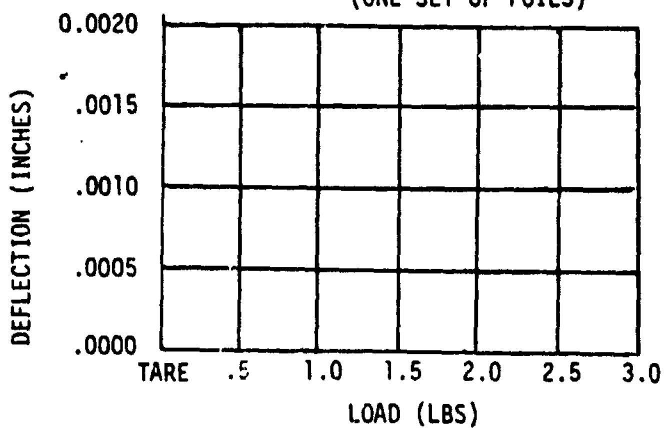
PINS ____________ MAG. ______ NON-MAG. ______ LENGTH ____________

FOIL THICKNESS: BASE MATERIAL ____________ COATING ____________ TOTAL ____________

"SWAY SPACE" = I.D. - O.D. - 4T = ____________

FOILS CLEANED WITH ____________

SPRING RATE — SINGLE ASSEMBLY (ONE SET OF FOILS)



LOAD (LB)	DEFLECTION (INCHES)
TARE ______	______
TARE + 1	______
TARE + 2	______
TARE + 3	______
TARE + 4	______
TARE + 5	______
TARE + 6	______

ROTATING GROUP BALANCE + RUNOUT (ATTACH DATA SHEET) ____________

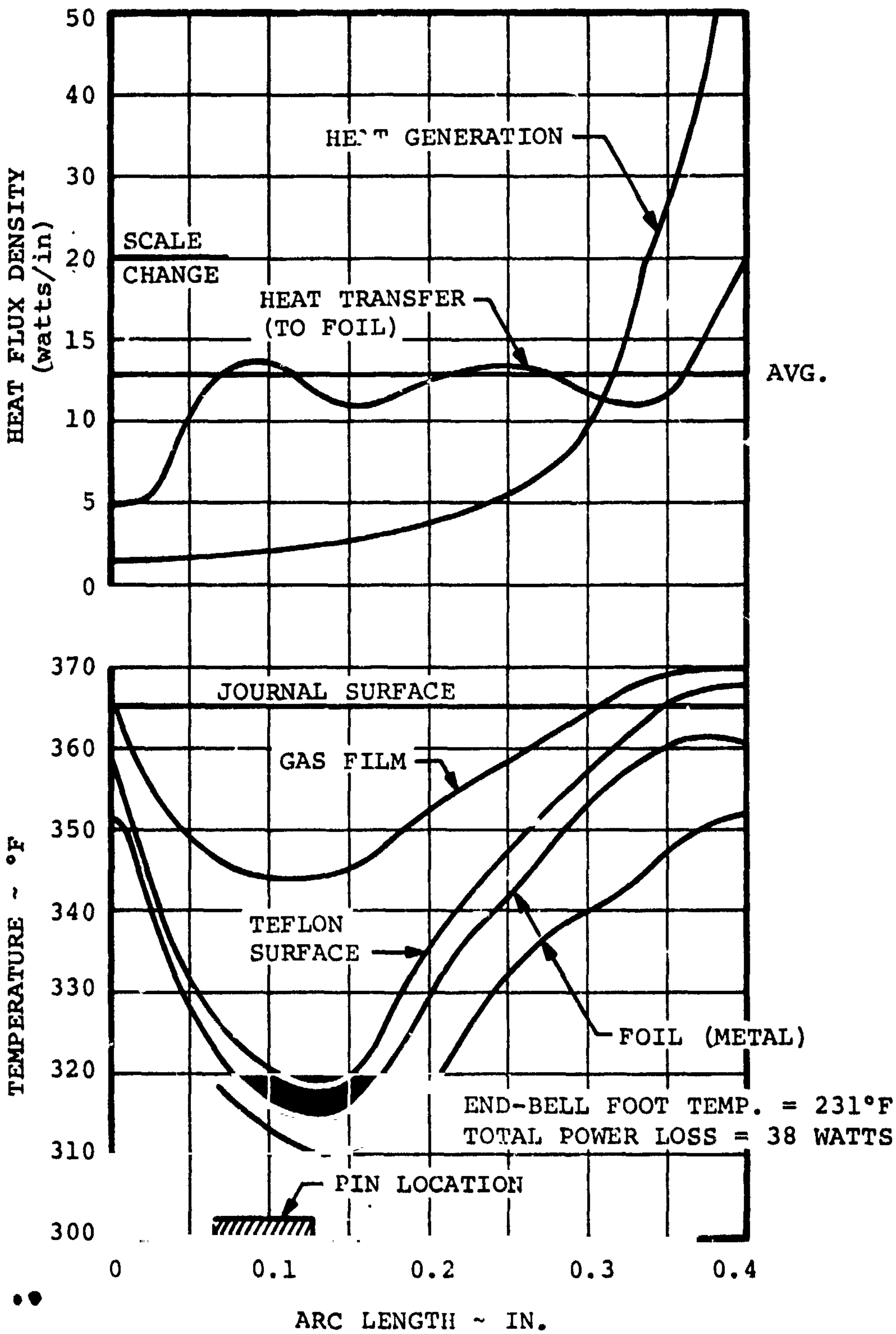
COMMENTS ON BUILD: ALL PINS LOOSE IN SLOTS? ____________

____

____

____

Figure 42. - Bearing Data Sheet.



LOCAL VALUES AT CENTER OF BEARING

Figure 43. - BIPS Comp-End Journal Bearing With Journal Thermally Isolated.

END-BELL FOOT TEMP. = 303°F
COOLING GAS FLOW RATE = 2.16 PERCENT W_c
COOLING GAS INLET TEMP. = 320°F
MINIMUM FILM THICKNESS = 0.000139 IN.
TOTAL POWER LOSS = 41.86 WATTS
9.4 WATTS DUE TO ROUGHNESS NEAR
TRAILING EDGES

NOTE: SHAFT CONDUCTION PER THERMAL ANALYSIS
OF MINI-BRU ALTERNATOR

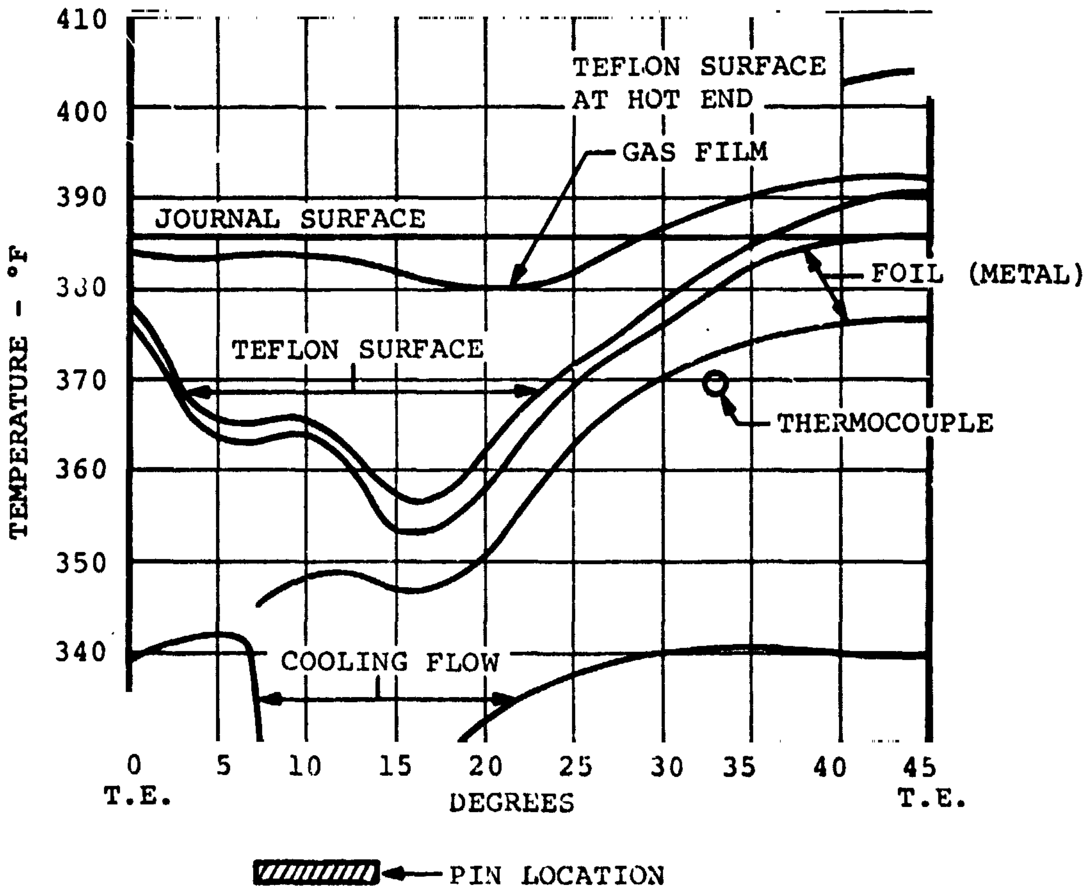
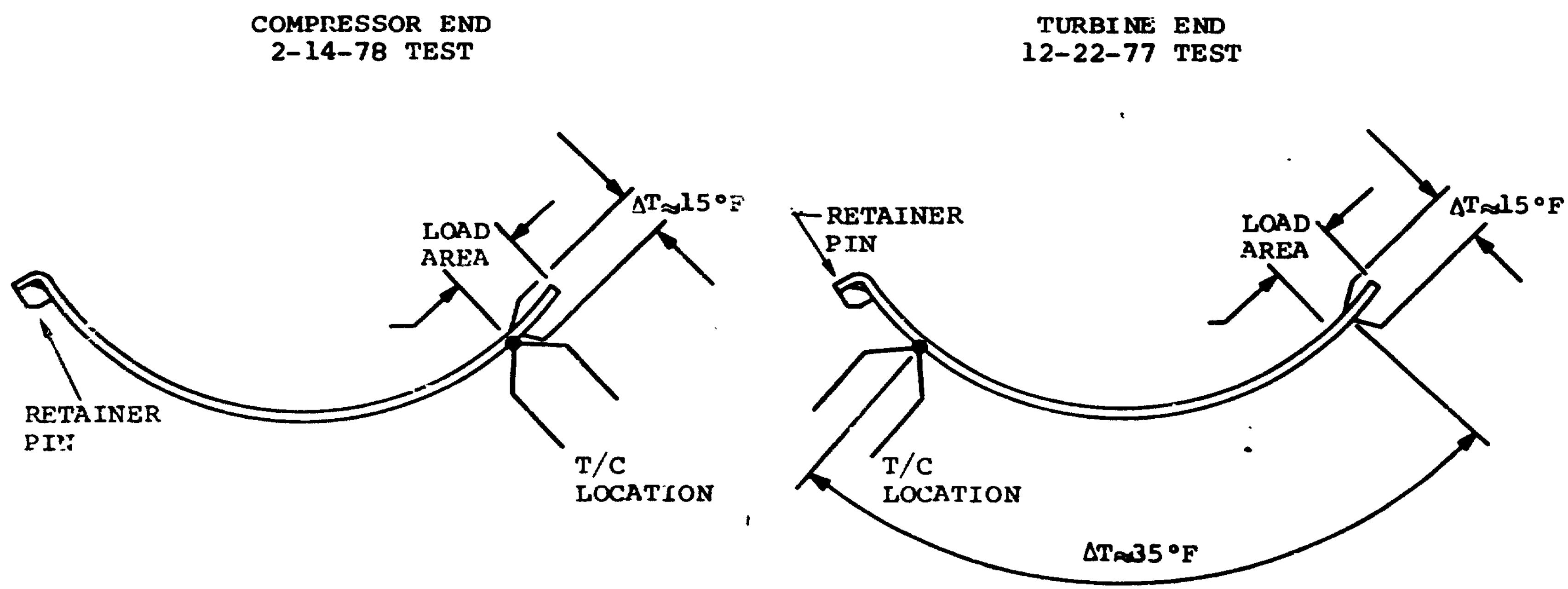


Figure 44. - BIPS Mini-BRU Turbine-End Journal Bearing Thermal Analysis.



TEMP MEASURED BY T/C	=	260°F
ΔT ACROSS METAL AND TEFLON	=	15°F
TEFLON SURFACE TEMP	=	275°F

TEMP MEASURED BY T/C	=	310°F
ΔT ALONG FOIL LENGTH	≈	35°F
ΔT ACROSS METAL AND TEFLON	≈	15°F
TEFLON SURFACE TEMP	=	360°F

Figure 45. - Teflon Surface Temperature Measurement.

This unit was installed in the workhorse loop and operated for 6 hours. Disassembly revealed all temperatures either equal to or less than the predicted temperatures.

This data along with data acquired during the December WHL test provided data to allow a determination of the Teflon surface temperature. These temperature predictions are shown in Figure 45. This data was used to establish predicted vaporization rates as discussed in the "Materials Analysis" section.

In addition to foil temperatures, the thermal analysis predicted that the difference in temperature between the bearing journal and the bearing carrier would result in a 0.0008 inch loss of sway space during operation. This was judged to be significant and led to an adjustment in cold sway space during future tests to compensate.

The conclusion reached by this analysis was that temperature was not a factor in material degradation but that it caused a decrease in sway space which might be significant.

DC-10 Charge/Continuity Test

There were a number of uncertainties involved in the questions of electrical charge buildup and rotor/foil continuity (touching) during operation. A test was setup to evaluate this phenomena relative to the DC-10 air cycle machine. The DC-10 machine has a history of long life operation in an environment much more abusive than the BIPS.

The details of this test are shown in Figures 46, 47, 48 and 49. The conclusion was that even at conditions of full film lubrication there may be asperity contact between the shaft and foil due to the conforming nature of the foil and the relative roughness compared to the minimum film thickness.

Thermistor Design

When it became evident that means would have to be provided for measuring the foil temperatures near the trailing edge, thermistors were considered as a candidate.

Foils were especially designed and fabricated by chemical etching for utilizing 0.005 inch diameter thermistors. The thermistors were attached to the foils and checked out.

Several bearing carriers were modified with slots for 4 thermistors on each bearing.

- CONTINUITY TESTS WERE CONDUCTED ON RELIABLE DC-10 FOIL BEARINGS, KNOWN TO OBTAIN AND MAINTAIN SATISFACTORY HYDRODYNAMIC FILM THICKNESS. THROUGHOUT SERVICE LIFE.

- PURPOSES OF TESTS WERE:

  1. TO EVALUATE SET-UP WITH BEARINGS KNOWN TO DEVELOP SATISFACTORY FILM.

  2. CORRELATE MONITOR VOLTAGE, V_O, WITH FOIL BEARING LIFT OFF* CHARACTERISTICS. (PARAMETERS: SPEED, SIDE LOAD)

- TEST SET-UP WAS AS SHOWN IN FIGURE 1.

* LIFT-OFF → DEVELOPMENT OF FULL FILM THICKNESS.

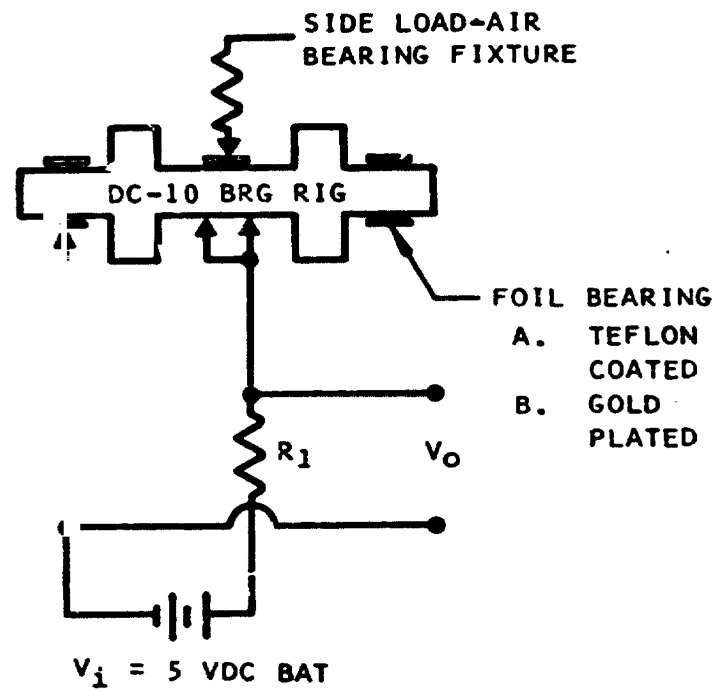


FIGURE 1. TEST SCHEMATIC

Figure 46. - DC-10 Bearing Continuity Tests.

- FULL FILM WAS DEVELOPED AT 30,000 RPM
  - NO LOAD
  - DESIGN SPEED ~42,000 RPM
  - OPEN CIRCUIT INDICATED, V_O = 5V
  - TRACE (3), FIGURE 2.
- FULL FILM MAINTAINED THROUGHOUT VARIOUS LOAD RANGES AT SPEEDS ABOVE 30,000 RPM.
- GOLD PLATED FOILS
  - TESTS INDICATED THE PRESENCE OF ASPERITY CONTACT AT FULL FILM
- TRACES (1), (2), (3) WERE IN AGREEMENT WITH TORQUE TRACES

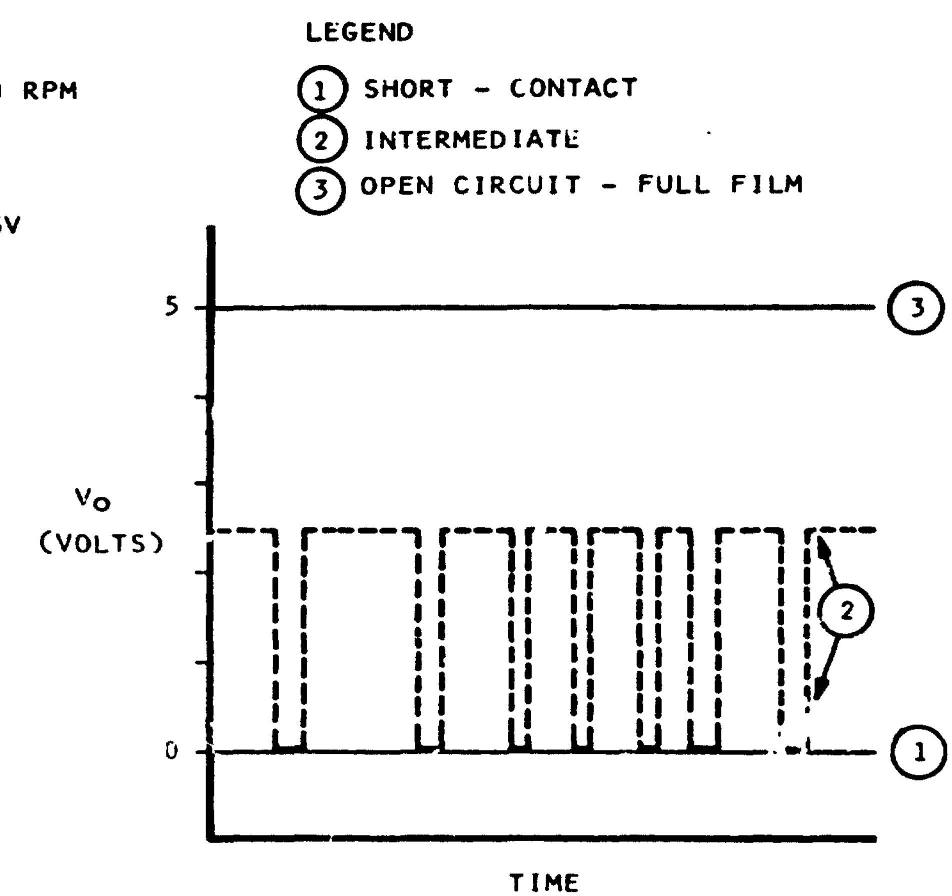


FIGURE 2. TYPICAL OSCILLOSCOPE TRACES, V_O

Figure 47. - Test Result - DC-10 Bearing Continuity Tests.

- FIGURE 3 SHOWS THE RELATIONSHIP BETWEEN PERCENT AREA CONTACT, MINIMUM FILM THICKNESSES, AND COMBINED SURFACE ROUGHNESS.

NOTE ASYMTOTE PORTION
$hf/\delta = 4$

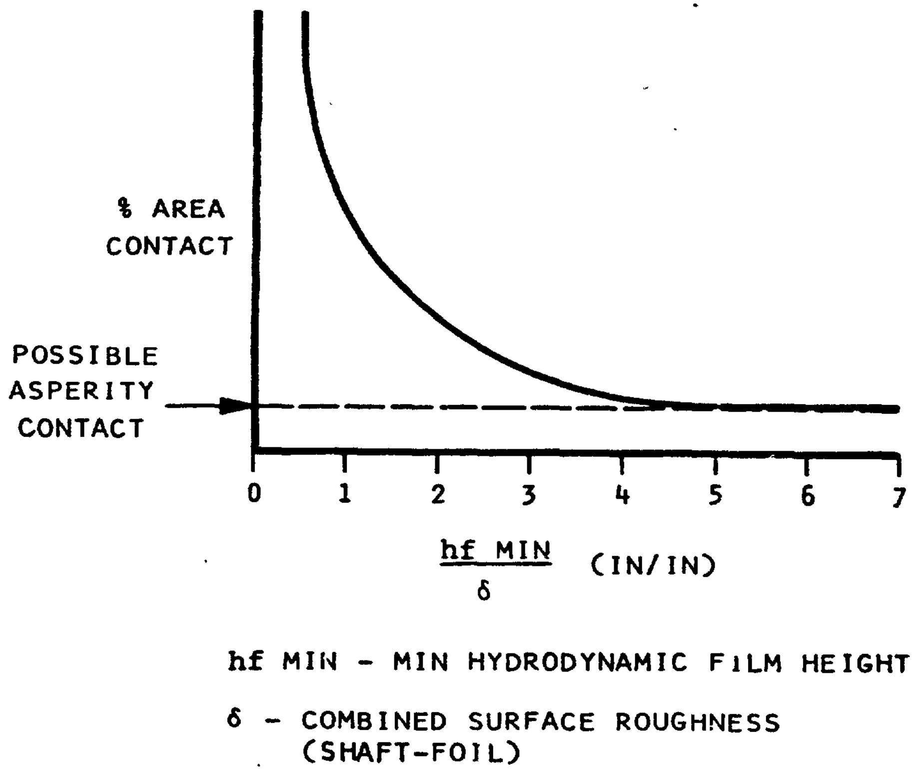


Figure 48. - DC-10 Bearing Continuity Tests.

CONCLUSIONS

- TEST SET-UP CAN GIVE VALID INDICATIONS OF THE DEVELOPMENT OF FULL FILM.
- AT FULL FILM THERE COULD BE ASPERITY CONTACT.
- TEST RESULTS CORRELATE WELL WITH PREVIOUS TEST DATA UTILIZING TORQUE MEASUREMENTS.

Figure 49. - Conclusions - DC-10 bearing continuity tests.

This technique was not implemented in tests because of success with ultra-small thermocouples and methods of attachment.

Shaft Displacement Probes

The original design of the Mini-BRU specifically excluded shaft displacement probes to aid in compacting the turbomachinery package. With the necessity to check every failure contributor, the monitoring of rotor dynamics was necessary.

Two types of probes were designed. A fiber optics probe was designed to fit on the compressor impeller inlet extension and a set of miniaturized capacitance probes were designed to fit between the compressor impeller and the thrust rotor.

Hardware to implement these probes into the Mini-BRU was not available in time for the 1000 hour test so the plan was carried no further than procurement of probe hardware.

WHL Blowdown Test

The suspicion of foreign object damage to the bearings was dispelled by conducting a WHL blowdown test. Argon gas was blown through the loop in quantities simulating the loop throughflow.

The gas was filtered at the compressor inlet and the results were examined by 30X microscopy. The interior of the duct was also wiped and the residue examined.

No debris larger than 5-10 microns was discovered.

Foil Bearing Analysis

A foil bearing analysis method was developed under a contractor sponsored program. This technique was applied to the Mini-BRU journal bearings so as to gain insight into such factors as dimensional sensitivity and minimum film thickness.

The analysis utilizes a geometry subroutine to represent the foil deflections and a hydrodynamic routine to calculate the pressure profiles and individual foil loads.

Thus far the program is only applicable to zero eccentricity (no side load) configurations.

Discussion of Analysis - The geometry routine utilizes the basic elements of foil bearing geometry, shown in Figure 50, to calculate the height of the individual foils relative to the bearing carrier.

In general, the bearing comprises (N) identical foils of arc breadth B, axial length L, metal thickness t, total geometrical thickness, T, (which accounts for the presence of a coating), and initial curvature radius, R_C. Attached to the underside leading edge of each foil is a pin which is inserted into one of (N) equally pitched axial slots machined into the inside diameter surface of the bearing carrier, whose inside diameter is d_H. The journal of diameter, d_J, is inserted into the bearing housing, (N) foil subassembly to comprise the bearing system.

One term applicable to foil bearing geometries is Sway Space, which is defined as:

$$\text{Sway Space} = d_H - d_J - 2\ (T)$$

The sway space is a measure of the diametrical movement freedom of the journal with respect to the bearing carrier.

The initial foil radius, R_C, always is greater than that of the housing, d_H; thus, before the journal is inserted, each foil bottom surface is in contact with the housing at its upstream leading edge and with the downstream adjacent foil at its trailing edge. Correspondingly, the upstream foil bottom surface trailing edge contacts the subject foil top surface, Figure 51. Considering now the local height of the foil relative to the bearing surface inside diameter, H (X) is maximum, the height at that value X defines the diameter of that journal that could be inserted into the assembly to establish line contact among all foils in the absence of preloading each foil.

By progressively applying equal line loads to each foil at the locations where the heights are maximum, orientations and line contact loads, corresponding to journals of increasing diameters, are determined. With sufficient applied load, each foil is brought into contact with the downstream foil at the downstream foil leading edge. With this additional contact, each foil has "bottomed" on the underside foil, Figures 53 and 54.

Hence, the free body diagram of each foil is as given in Figure 55. In general, each foil experiences an externally applied load, Q, which is reacted by force, P, and, under sufficient deflection, force, S. It also withstands force, P_2, applied by the upstream foil bottom trailing edge. The foil elastic deflection is determined using the strain energy method,

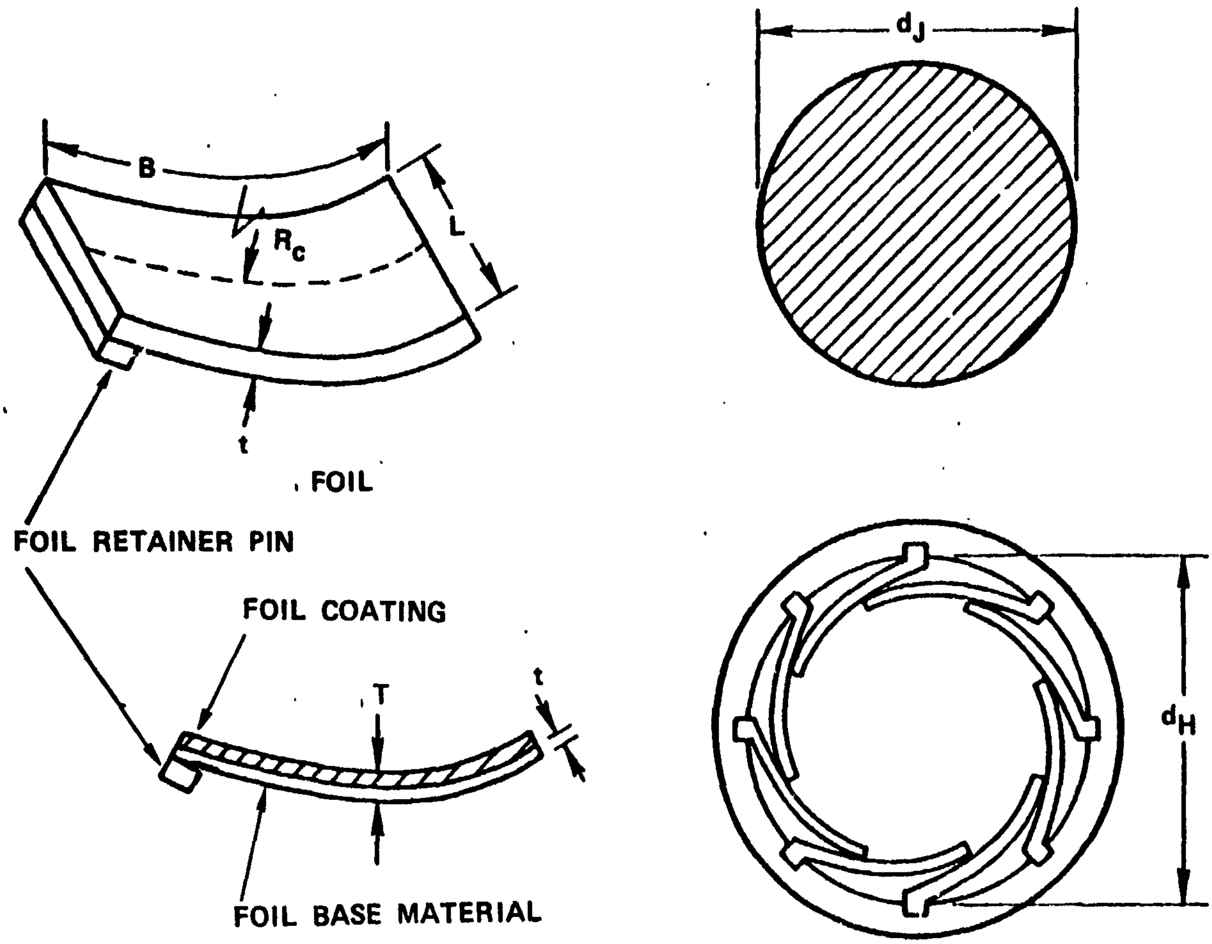


Figure 50. - Conventional Foil Bearing Geometry and Parameters.

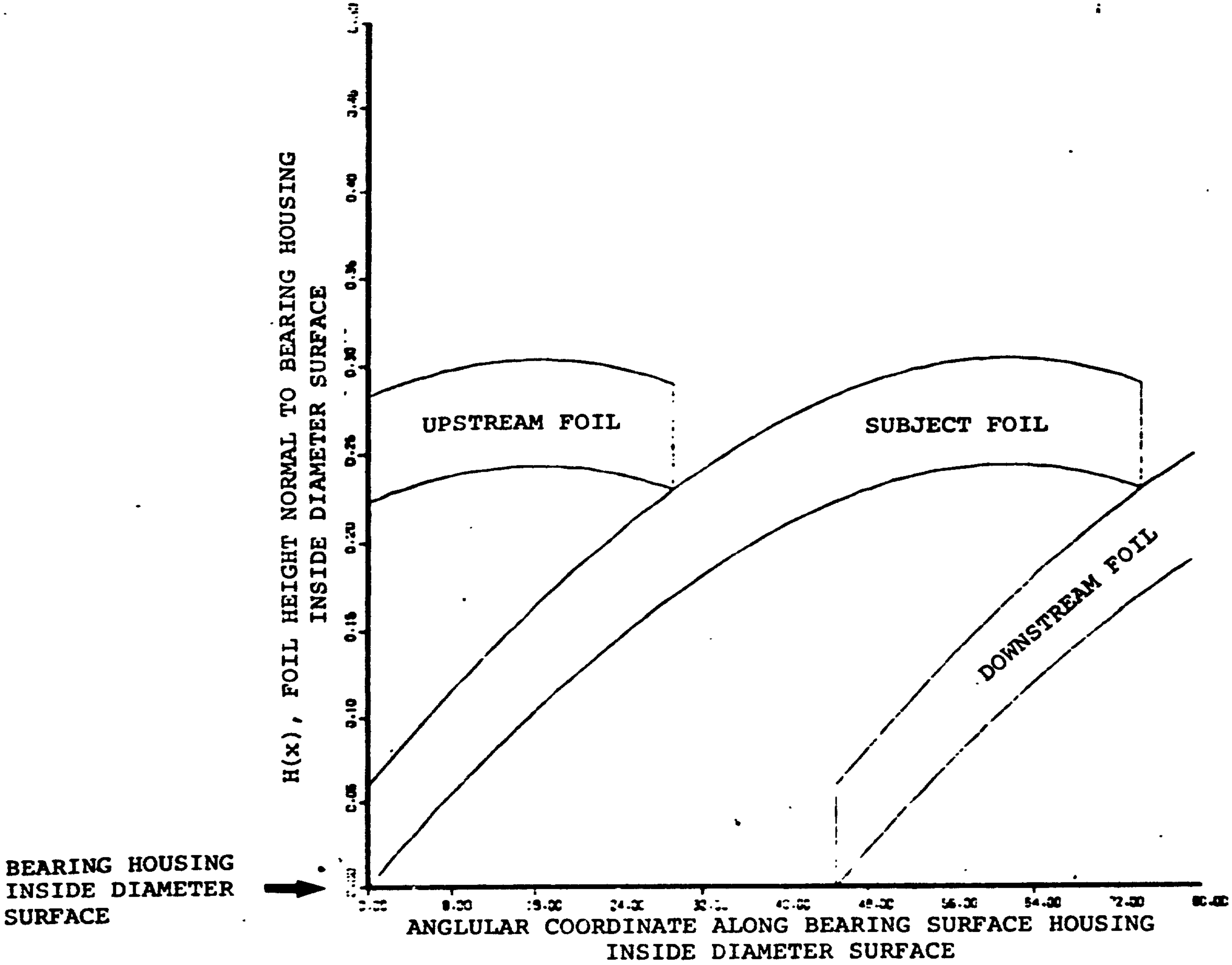


Figure 51. - Analytical Representation of Foil When Loaded to Point of Initial Contact With Adjacent Foils.

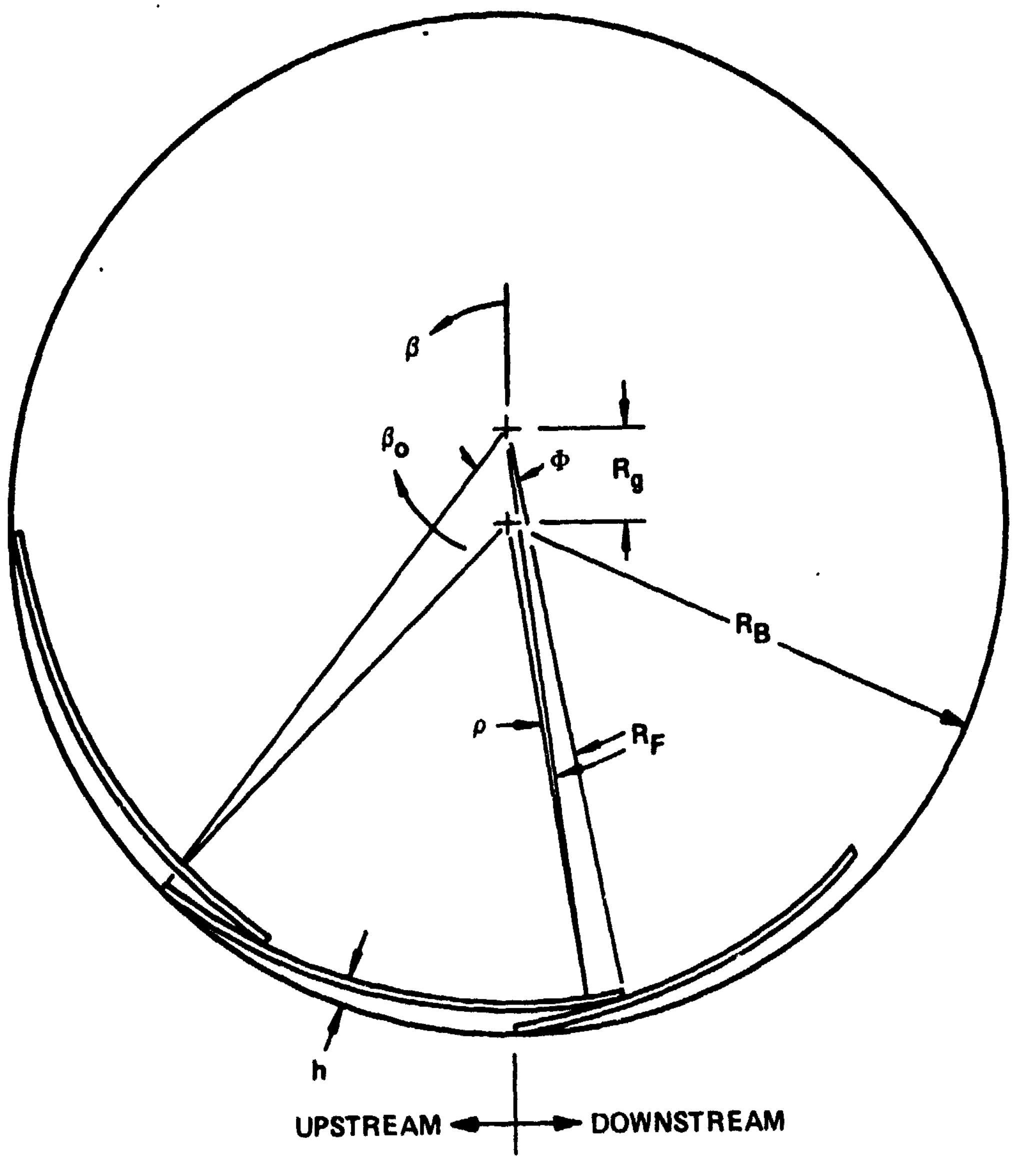


Figure 52. - Foil Bearing Prior to Inserting Journal.

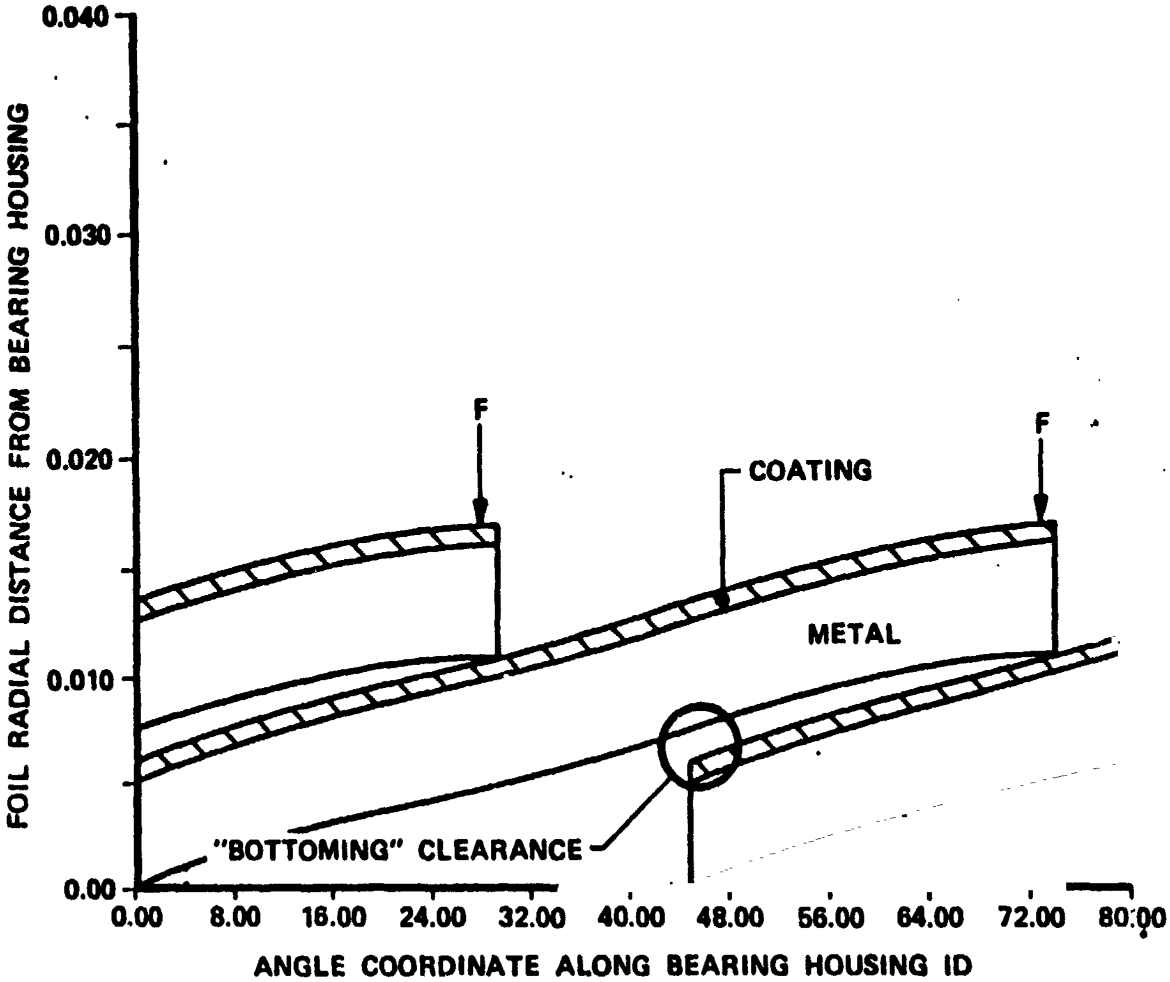


Figure 53. - Foil Orientation Prior to "Bottoming."

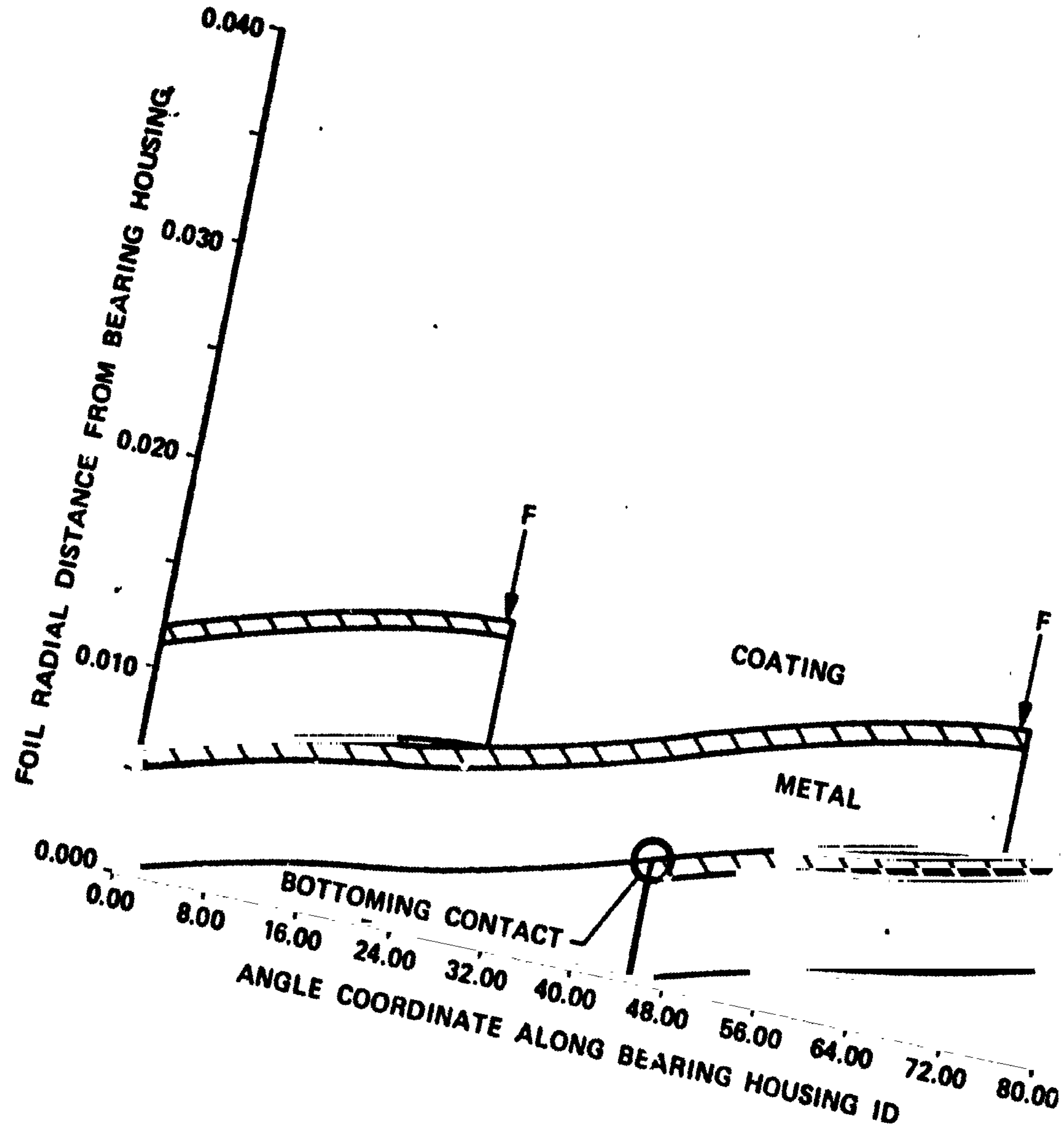


Figure 54. - Foil Orientation After "Bottoming."

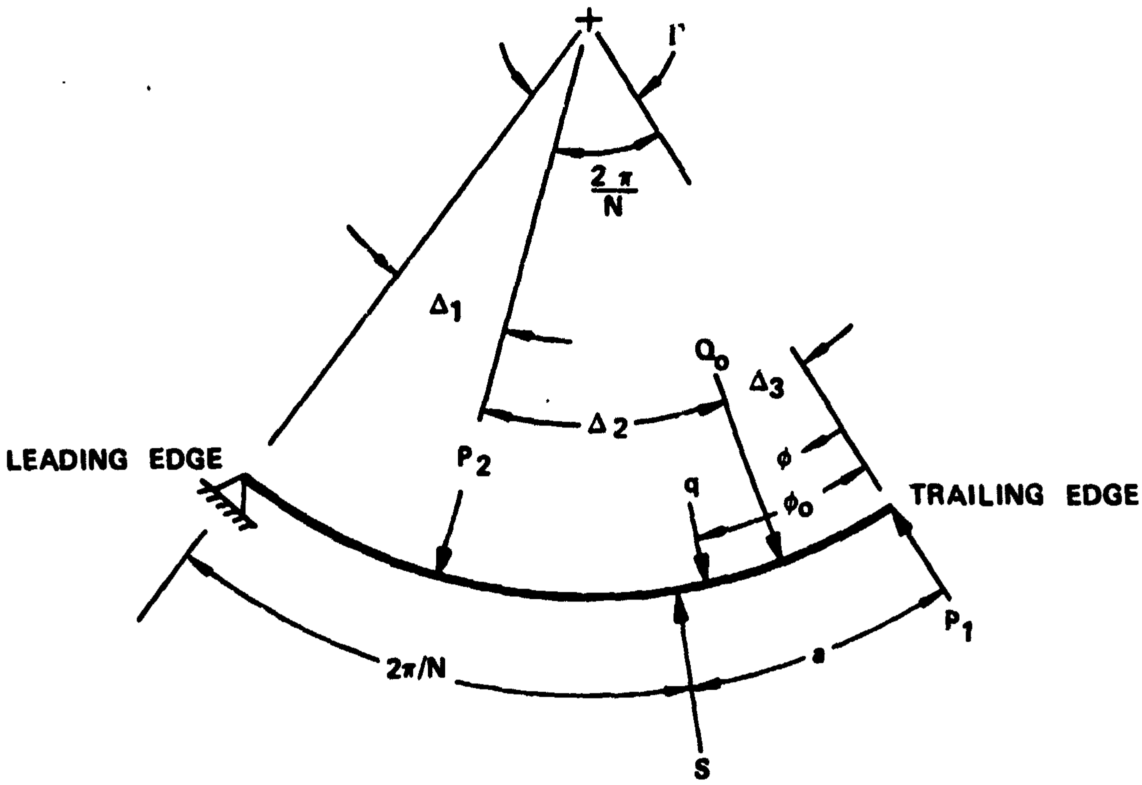


Figure 55. - Foil Bearing Nomenclature Used in Analysis.

$$U = \int_0^{\delta} \frac{R_c M^2 d\phi}{2ED}$$

where:

U is the strain energy

R_c = foil radius

M = moment distribution as function of (P_1, P_2, Q, S, ϕ)

ϕ = angular coordinate along foil

δ = foil arc breadth

D = foil flexural rigidity

E = foil material elastic modulus.

The local elastic deflection is determined by considering additionally that a virtual force, q (ϕ), is applied, and

$$\eta(\phi) = \left.\frac{\partial U}{\partial q}\right|_{q = 0}$$

Finally, the resulting foil height H (X) is determined from $\eta(\phi)$ and the constraints that; once the foil "bottoms", the height at the bottoming point remains fixed by the thickness of the underside foil; the foil at the trailing-edge remains in contact with the downstream neighbor; and the upstream foil remains in contact with the subject foil at the upstream foil trailing-edge.

Presence of the pressure distribution loading imposed by self acting gas film is then accounted for by representing the pressure field as discrete line loads, Figure 56.

The determination of these pressure induced loads is made using the classical Reynolds equation.

Side leakage effects are accounted for by applying boundary layer corrections to the foil edges. For most foil bearings, $L/B \gg 1$, so that these corrections are of second order influence.

The coupled hydrodynamic solutions and foil deflection solutions start by applying a load, Q, sufficient to separate each foil from the journal and computing h (x). Given h (x) and the bearing operating speed, viscosity and ambient pressure, p (x), is then computed. This process is continued until the minimum gas film thickness from Q is the same

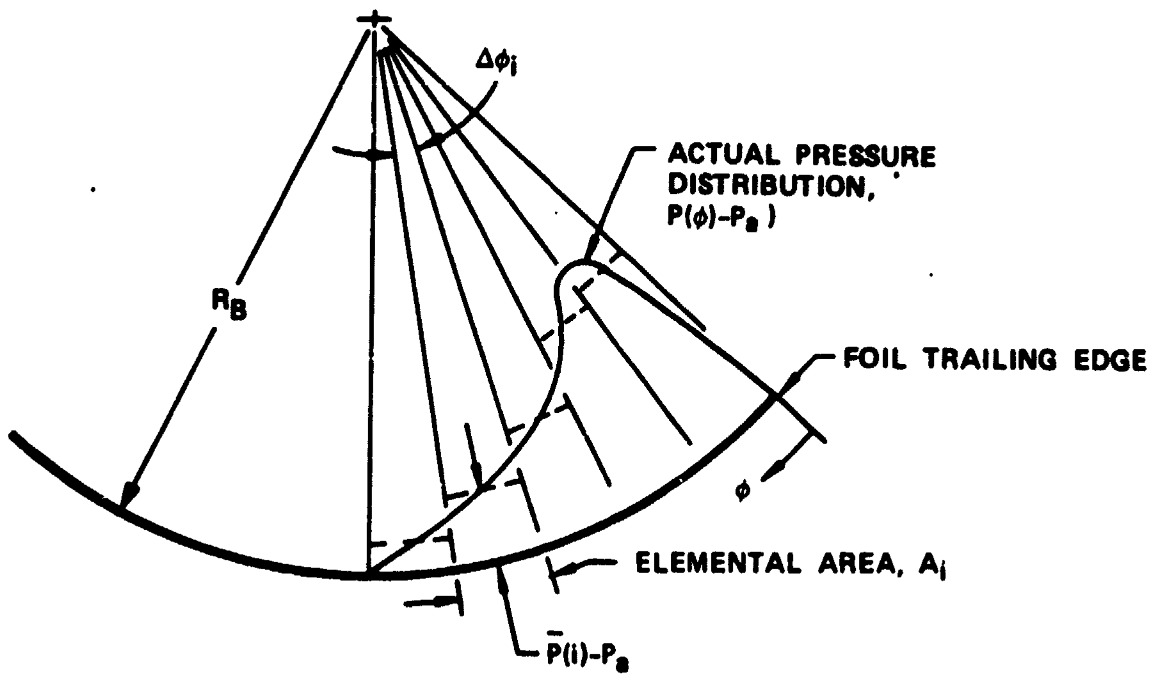


Figure 56. - Pressure Field Representation.

as that resulting from the corresponding pressure field. This pressure field is then scaled in normalized fashion to obtain the second order improvement pressure solution. This process is carried forward until the assumed and actual pressure fields cause the same resulting foil deflections to within a pre-specified error limit.

This analysis is used to optimize bearing geometrical parameters and establish bearing performance properties. Examples of successive ordered solutions to pressure fields, obtained from a closed Brayton cycle system, are given in Figures 57 through 60. The same bearing stiffness properties are given in Figure 61. Figures 62 and 63 are examples of minimum film thickness-versus-sway space predictions, and gas film load-versus-minimum film thickness of this bearing.

Note that the analysis rigorously treats each foil load with respect to its neighbors. This allows prediction of foil damping properties associated with journal radial loads with respect to the housing.

Other Tasks

Several other minor design tasks were completed in support of the bearing investigation.

A dimensional stacking analysis was completed. The object of this was to determine if the tolerance buildup of the component parts would cause too much lateral or angular misalignment. The result was that the tolerance stack was within the limits of good design practice.

The lateral misalignment of the bearing carrier bores was measured in the assembled condition. An offset of 0.0007 inch was measured. This was judged not to be excessive.

Hardware was modified for use of the compressor impeller as a pump to recirculate gas in the compressor bearing compartment. This was not implemented because the bleed flow was increased to accomplish the same end.

A design was completed for an extended thermal shunt inside the rotor to conduct heat from the alternator rotor to the compressor impeller (an existing shunt conducts heat from the thrust runner to the compressor impeller). This also was not implemented when analysis and test subsequently indicated high temperature of the alternator rotor was not a problem.

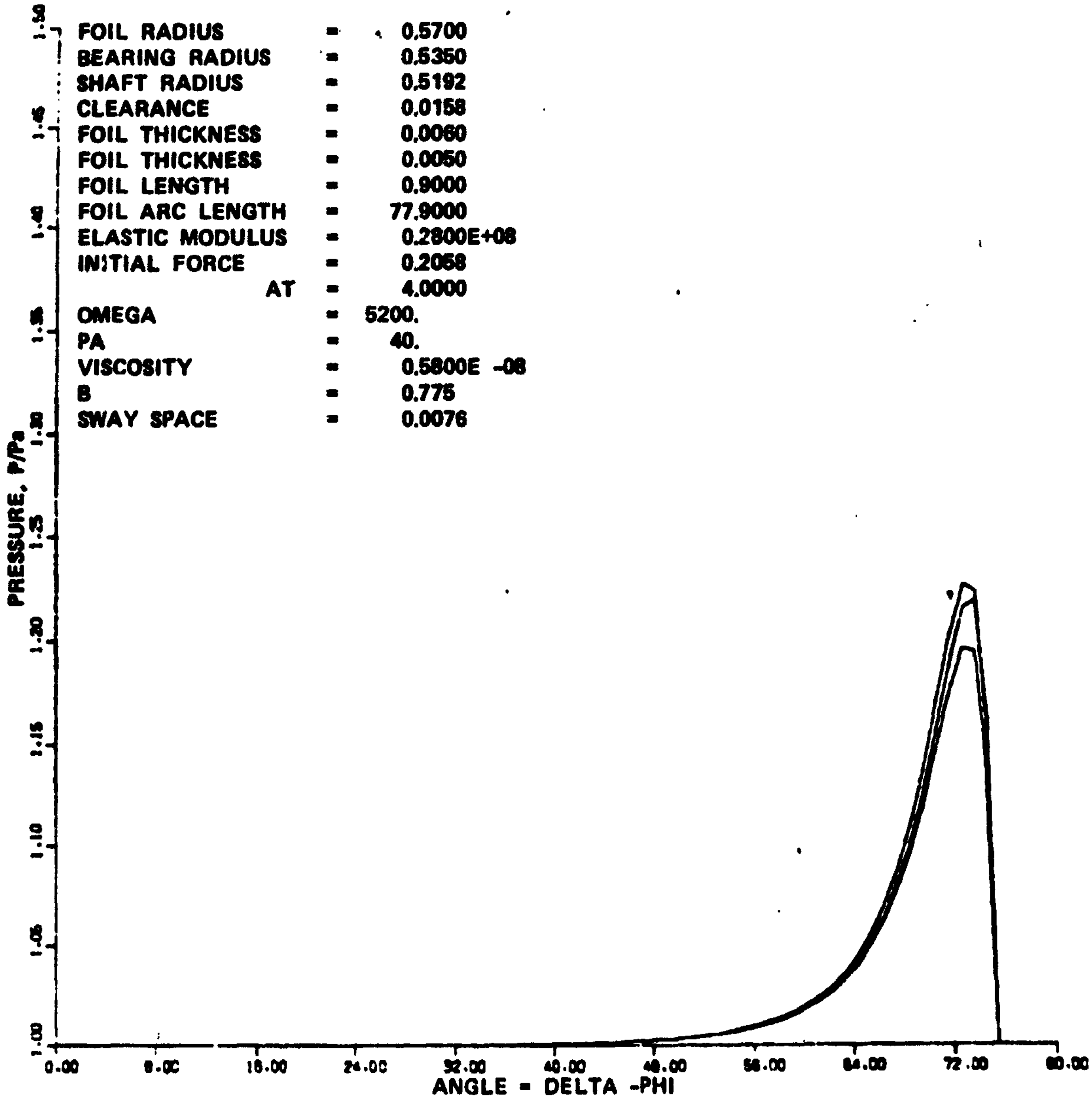


Figure 57. - Foil Pressure Profile.

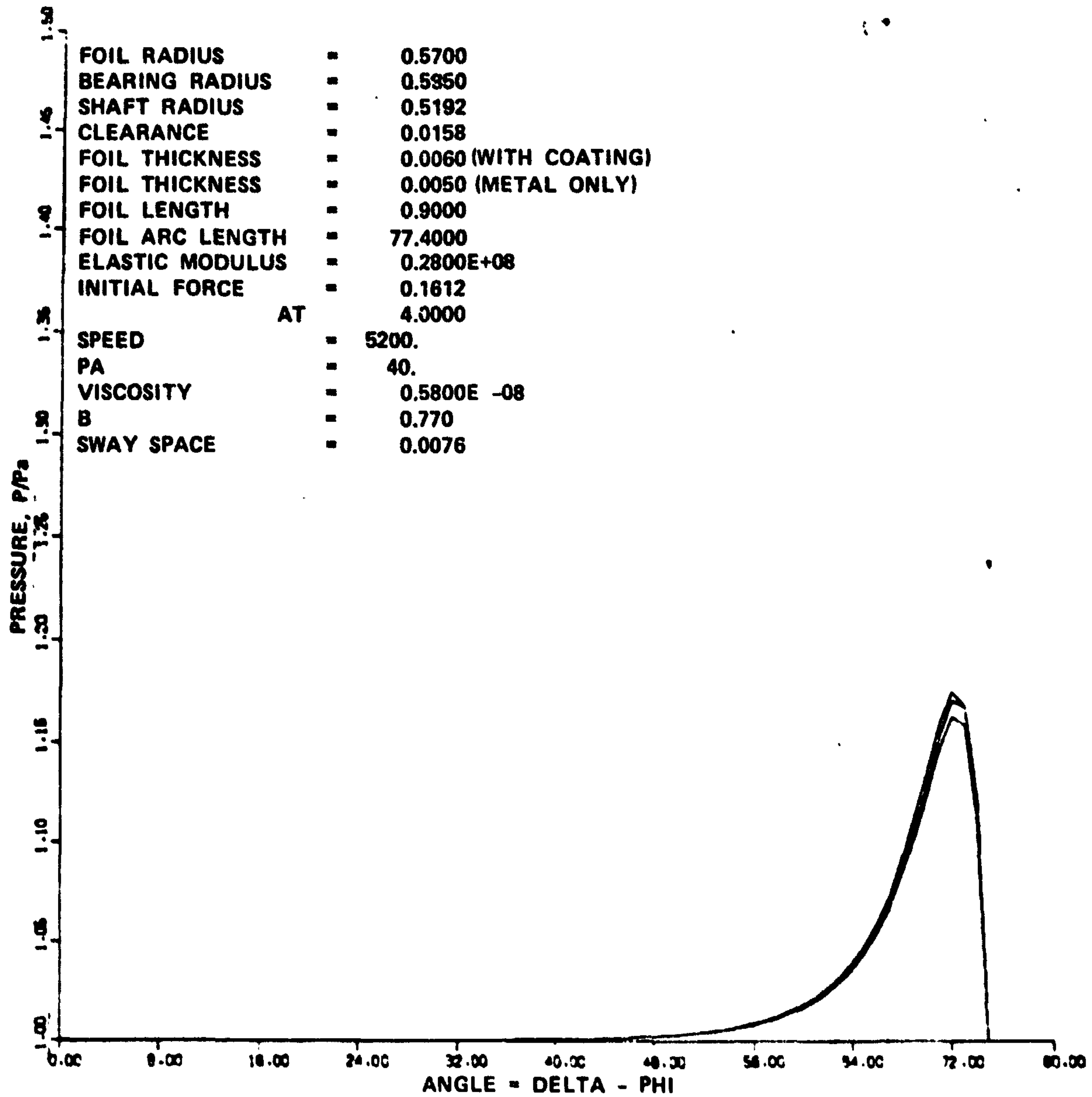


Figure 58. - Foil Pressure Profile.

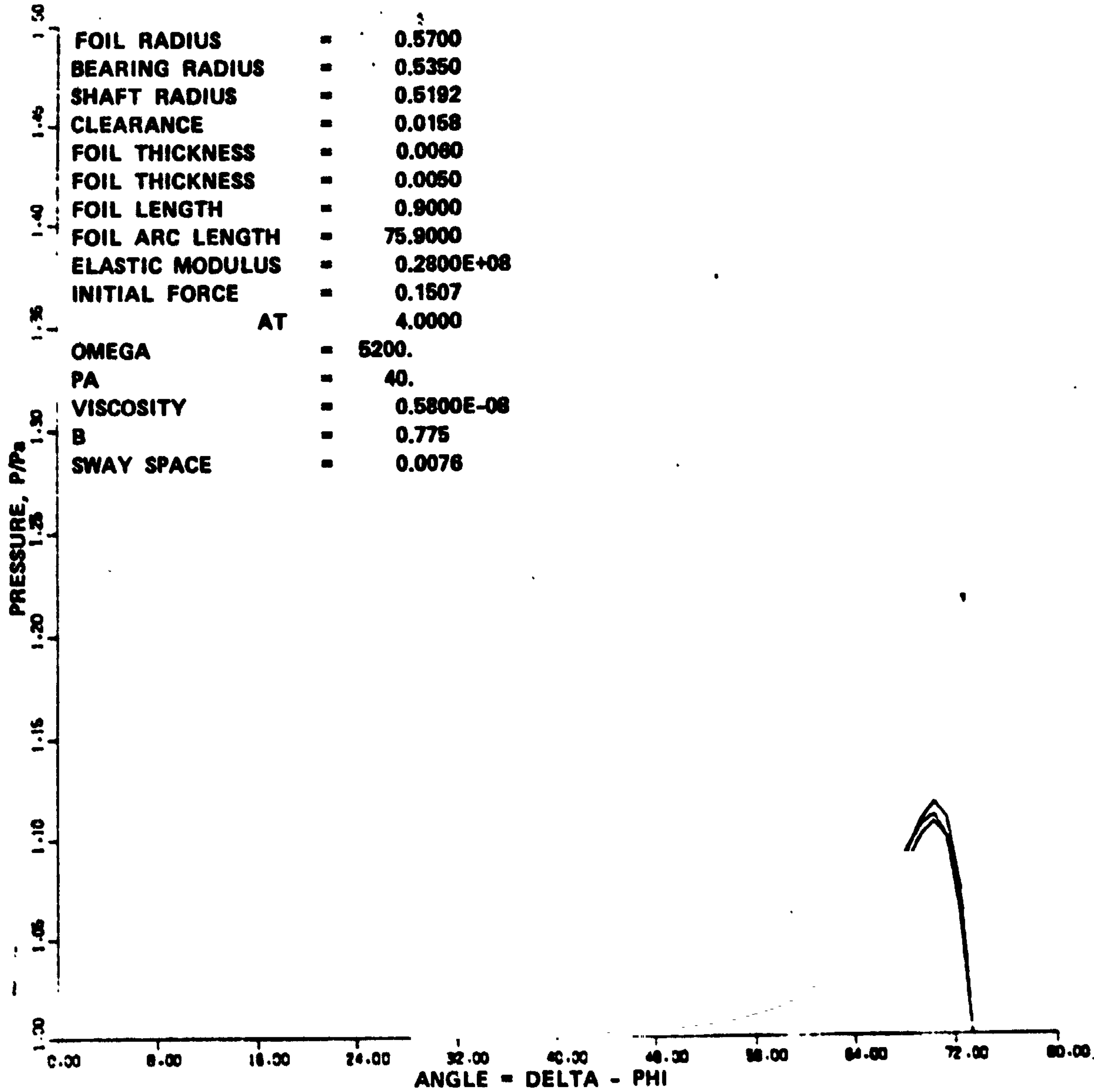


Figure 59. - Foil Pressure Profile.

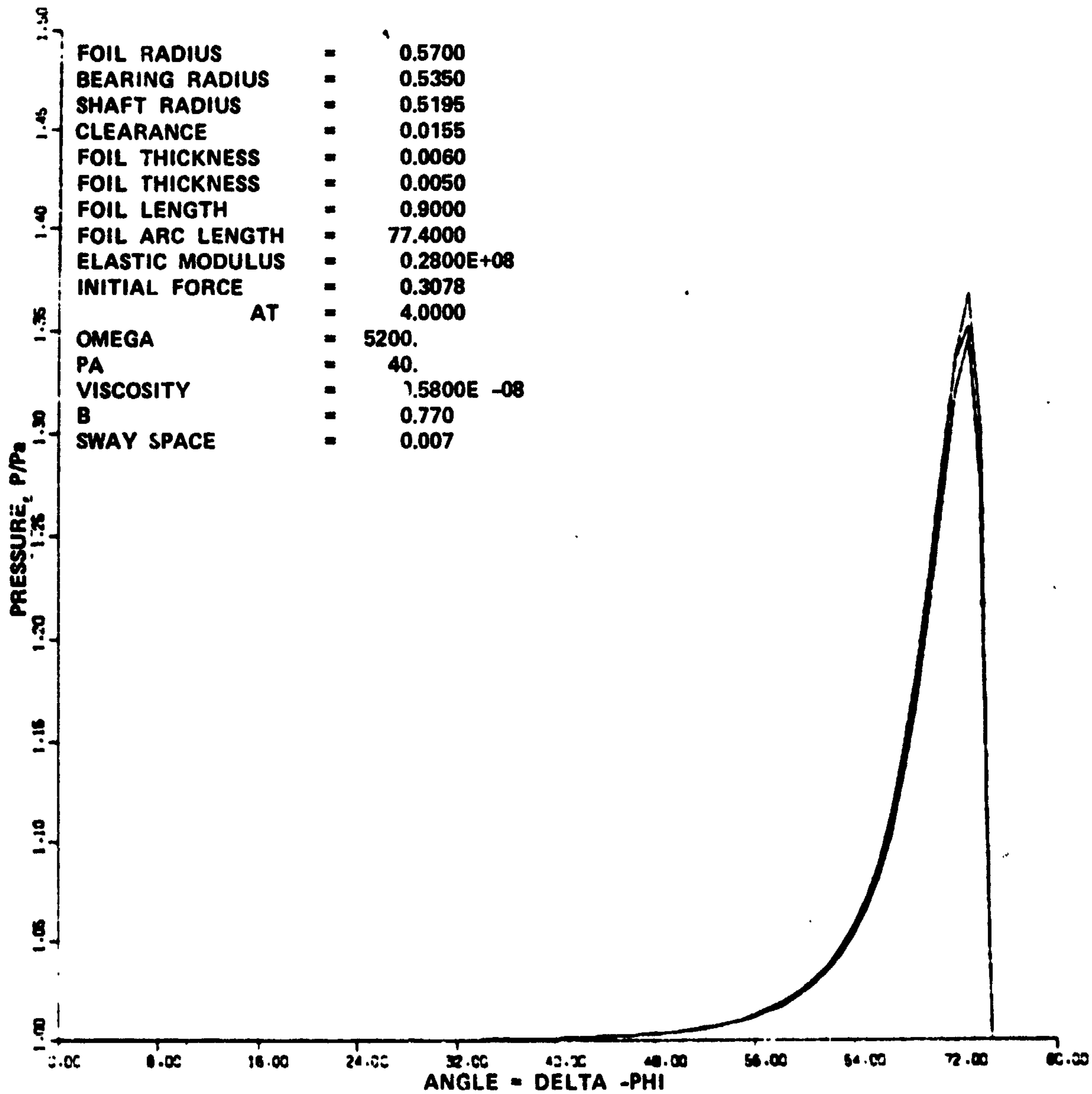


Figure 60. - Foil Pressure Profile.

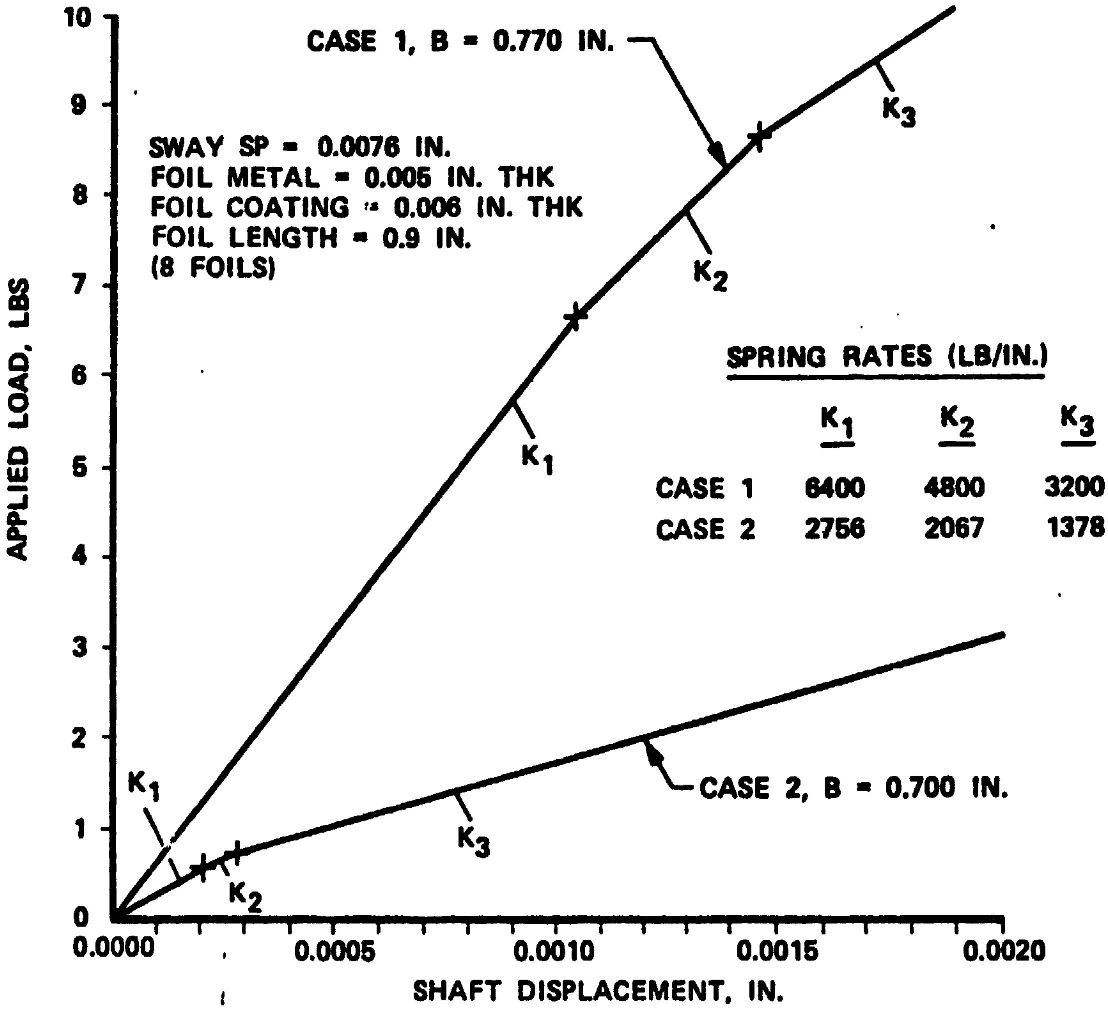


Figure 61. - Foil Bearing Load Versus Deflection Influence of Foil Breadth.

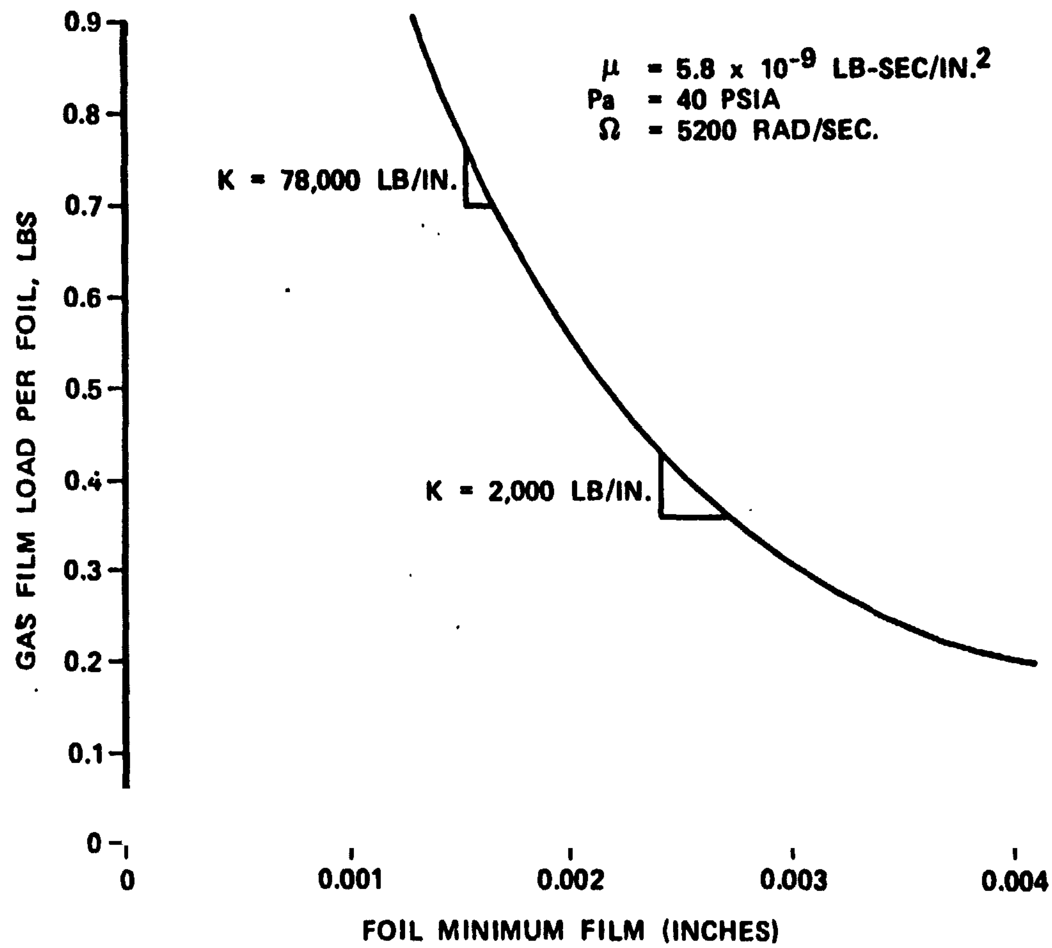


Figure 62. - BIPS Mini-BRU Foil Bearing Gas Film Load Versus Minimum Film Thickness.

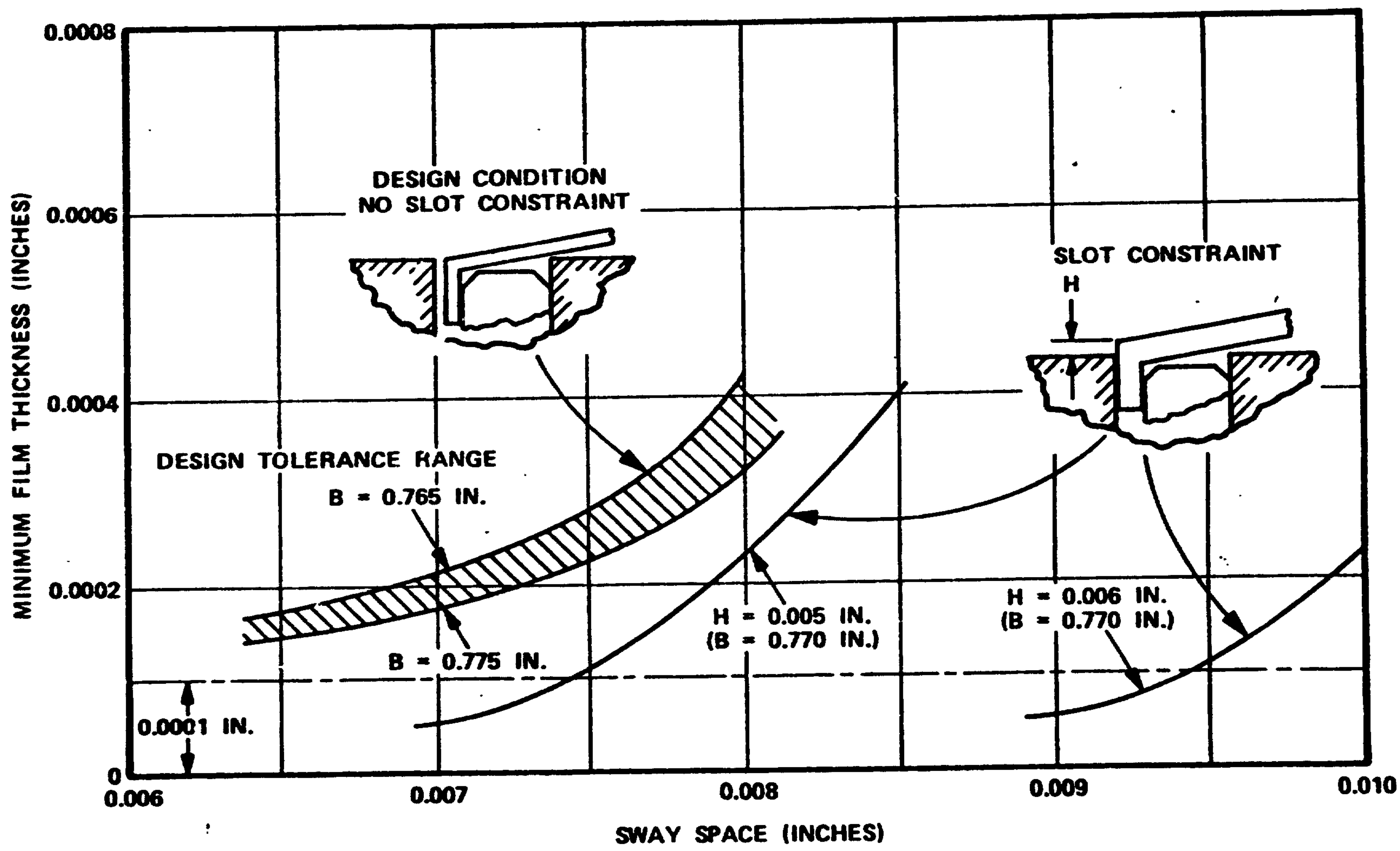


Figure 63. - Foil Bearing Film Thickness Versus Sway Space.

A design was initiated, but not completed, to mount the thrust bearing on a strain gage ring for the purpose of measuring the engine rotor axial thrust during operation. This action was prompted by concern when a thrust bearing failed in the MBTR during cold testing. This problem was diagnosed as the result of adverse aerodynamic backface pressure distributions during cold operation under heavy electrical loads. The problem was subsequently controlled by limiting the magnitude of electrical load during cold operation.

CONCLUSIONS

Although no single factor could be identified as the failure mode , certain key elements could be deduced:

- o High temperature was not a factor contributing to coating degradation (no high foil temps; no excess power loss)
- o The failure could not be simulated outside the WHL environment no matter how abusive the test schedule (low speed motoring, start/stop, high loads, tight sway space etc.)
- o Electrical arcing did not appear to be a factor because it was not clear that the foil pads ever totally lost contact with the shaft (asperity contact)
- o Evidence was found to substantiate non-adherence of the original Teflon coating (a random material coating phenomena)
- o Magnetic excitation of the unit could cause a dramatic instability threshold for certain bearing configurations (very low spring rate)
- o The temperature difference between the shaft and the carrier could cause a 0.0008 inch decrease in the compressor end bearing sway space.
- o Bearing performance and ruggedness seemed to improve as fabrication and inspection methods were improved (December test failure in 3 hours; February test no distress in 6 hours; subsequent cold tests with no serious distress after very abusive testing)
- o The compressor end bearing, because of its design for no cooling flow, could cause entrapment of self-generated debris whereas the turbine bearing could cleanse itself by virtue of its 2 percent bleedflow cooling.

These factors suggested that loss of sway space, lack of flushing flow, poor coating quality and surface finish were the principal contributors to the bearing failures. In addition better fabrication techniques and inspection

MINI-BRU MODIFICATIONS

The results of the bearing development program and the conclusions reached therein pointed the way toward the logical design modifications that were integrated into the Mini-BRU.

Table XVI tabulates the changes implemented in the unit for the next (and final) Workhorse Loop Test.

In addition, a standard procedure was established for tests conducted on the unit prior to installation in the loop. The elements of these preparatory tests are shown in Table XVII. These tests were designed to assure that all functional requirements were satisfactory without exceeding operational limits that might overtemperature the unit or overload the bearings.

TABLE XVI. - MINI-BRU DESIGN CHANGES FOR 1000 HOUR WHL TEST.

- Increased bleed flow for bearing cooling (∿50 percent increase to 3 percent bleed flow)
- Slotted retainer on compressor end journal bearing
- Increased sway space

  0.0099 compressor cold (0.0091 hot)

  0.0092 turbine cold (0.0087 hot)
- Crest coated journal foils

  8 RMS surface finish

  630°F cure
- Continuity/ground probe
- Bearing cavity ΔP instrumentation
- Provision for assuring retainer pin is always wider than foil.

TABLE XVII. - MINI-BRU WHL PREPARATORY TESTS

Prior to installation in the loop the unit is subjected to the following tests:

1. Acceleration to 52,000 rpm - monitor shaft stability.
2. Apply magnetic field excitation to 2.4 amps - monitor stability.
3. Apply 100 Watts output load.
4. Motor start to 20,000+ rpm.

1000 HOUR TEST

In early April, 1978, the Mini-BRU was installed in the BIPS WHL with the initial goal of attaining 100 hours of ope   on to verify the bearing problem resolution.

During the initial leak checking, the pressure probes added for measuring the compressor bearing cavity pressure differential were found to be seriously leaking and were abandoned.

The test was initiated on April 6, 1978. During the initial 100 hour period readings from the continuity probe indicated an apparently improving situation. Bearing temperatures were stable throughout the period.

At the 100 hour milestone, a decision was made to continue the test to achieve the 1000 hour goal.

On May 22, 1978, the system completed 1006.9 hours of operation with no engine problems. The run was interrupted three times by facility problems which were all resolved. The longest continuous run, 402 hours, was achieved at the end of the test. Four starts to 20,000 rpm for checkout purposes; 3 starts with the loop at design point temperatures and 3 normal operating type starts with the heat source at 1200°F were accomplished during the test.

When the unit was disassembled after the test, the bearings were found to be in excellent condition. The post test inspection is documented in Reference 2.

It was found that the continuity probe had worn itself out. This accounted for the apparent change (improvements) in continuity experienced during the initial 400 hours. No evidence was found of electrical arcing damage.

REFERENCES

1. Mini-BRU Final Report NASA CR 159441, October, 1978
2. Mini-BRU 1000 Hour Inspection Report, AiResearch Report No. 31-2938, August 1, 1978.

APPENDIX

MATERIALS ANALYSIS DOCUMENTATION

RELEASED

APR 4 1978

AIRESEARCH MANUFACTURING COMPANY
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

MATERIALS ANALYSIS 13344

MATERIALS ENGINEERING

Date Submitted 1-9-78 Date Required 1-23-78
Outline No. 240610-1
Charge No. 3409-249626-04-0704
Material Spec. MIL-S-5059/AF5467
Equip. Name BIPS-WHL
Equip. S/N Part S/N
Vendor

Name of Part BEARING, FOIL
Part No. 3604338
Material 302/, EFLON
Part Condition EV, WR ABRAS COAT TFE
Requested By J. Hadley Ext. 3445
Investigator M. Inzana Date 1-16-78
Reviewed By Date
Reviewed By R E Stark Date 3-8-78

Product Status ☒					
FAA	TSO☐ Type Certified☐	DOE	Qualified ☐Yes ☐No Production ☐ Research & Development☒	Industrial Commercial	Production ☐ Development☐

BACKGROUND: No similar MA's this part number.

Operating Media Xenon - Helium Environment
Operating Time 1st <100 Hrs, 2nd <10 Hrs Temperature Range 150°F to 450°F
Additional Information:
Bearings from journals on two builds. Shutdowns accompanied by load shedding indicating problem with bearings. First group had a much longer suspected time of running at speed below aerodynamic film. Second set should have been running on film, except for brief time during start and stop. Summary memo to follow.

SUMMARY AND CONCLUSIONS:

1. The damage to the foil surfaces was characteristic of abrasive wear. The most severly worn foils were from the first run compressor bearing.
2. EDX analysis indicated that all particles and debris found on the foils was from the immediate working area of the parts. Some particles, found in the wear track, may be from the rotor and some were probably stainless steel. A pimpled appearance on some bearing surfaces were believed to be dichromate particles, the black streaks were debris filled holes. Nothing in the debris area indicated other than teflon shavings. Fret lines, point of overlap, showed teflon coating still present.
3. The actual hardness (HRC-38) of the foils was slightly higher than that described by the ASM metals handbook (HRC-32).
4. The material chemistry of the foils was verified as type 302 stainless steel. The material chemistry of all of the bar stock was not the

INVESTIGATION REQUESTED:

(1X) Macroexamination Etched Unetched Photo
(2X) Microexamination Etched Unetched Photo
(3X) Hardness
(4X) Chemistry Verify Complete
(5) NDT Fluor. Pen. Magnetic Particle X-Ray
(6X) Other: SEM exam to survey surface topography of all zones and identify foreign material.
1. Document full foil surface. Representative photos of each zone on foils.
2. Look for heat effects, contamination, material structure.
4. Confirm foil material and teflon coat.

DISTRIBUTION	DEPT. NO.
J. McCormick (20)	93-171-3U
H. Longee	93-171-3U
F. Dobler	93-171-3U
M. Miller	93-391-4V
J. Hadley	93-391-4V
L. Matsch	93-335-4K
B. Heath	93- [illegible] -3U
R. VonFlue	93-070-3U
M. Inzana	93-392-114

SUMMARY AND CONCLUSIONS (CONTD.)

specified Type 347 stainless steel. Bar material was believed to be a low alloy steel (magnetic).

FINDINGS:

1. Four foils from the first and second run compressor and turbine bearings were submitted for evaluation. Representative photos of each bearing foil were shown in Figure 1. The heaviest wear appeared on the first run compressor bearing (Figure 1-I) and was documented in seven areas. The least wear appeared on the second run turbine bearing (Figure 1-IV).

   The trailing edge of the foils showed abrasive wear in the form of distinct scoring grooves. Most of the grooves were filled with debris. All of the foils exhibited a dark line down the center caused by the trailing edge of the overlapping foil.

   The variety of the wear that appeared on the first run compressor bearing was shown in Figure 2. Deep scoring grooves and complete removal of the teflon coating along the trailing edge, Figures 2(A), (B), and (C). The trailing edge of the overlapping foil left a scuffed pattern in the middle of the foil as shown in Figure 2(D). The unaffected teflon coating was shown in Figure 2(E). A dark colored teflon area was noted in the overlapping section of the foil as shown in Figure 2(F) This progressed into a black colored area which had numberous surface cracks and inclusions as shown in Figure 2(G).

   The severity of wear on the other three bearing foils was much less than the first run turbine bearing. Representative areas were shown in Figures 3, 4, and 5.

2. Scanning Electron Microscope (SEM) analysis of the foil surface began in Figure 6. High magnification photomicrographs of the foil surface showed that the scoring grooves were filled with debris (Figure 6(D)). EDX analysis of the area indicated by the black arrow in Figure 6(A) was shown in Figure 7 and was identical to the particle indicated by the black square in Figure 6(C).

   Although the wear on the first run turbine foils was confined to a smaller area, the characteristics were similar to the other bearings. This was shown in Figure 8.

   Wear on the trailing edge of the second run compressor foil was more pronounced than on the first run turbine bearing foil. The trailing edge wear appeared to be in the form of scoring grooves with particles imbedded in the teflon coating. EDX analysis of the areas shown in Figure 9(e) was reproduced in Figure 10. Areas three and four had evidence of silicon while area two did not show evidence of titanium.

   The representative microstructure of the foils was shown in Figure 11 and was typical of heavily worked Type 302 stainless steel in the half hard condition.

3. Hardness:

	Actual	Specified
	* RC-38	** RC-32

* Converted tukon microhardness.
** 1/2 hard per ASM metals handbook, Volume 1, Pg. 414.

P5821-1A

AIRESEARCH MANUFACTURING COMPANY
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

MATERIALS ANALYSIS 13344

MATERIALS ENGINEERING

FINDINGS (CONTD.)

4. The material chemistry of the foils was verified as Type 302 stainless steel per MIL-S-5059. The material chemistry of the bar stock was only verified as Type 347 stainless steel per QQ-S-763 in one out of four specimens.

J. R. Hadley

M. J. Inzana

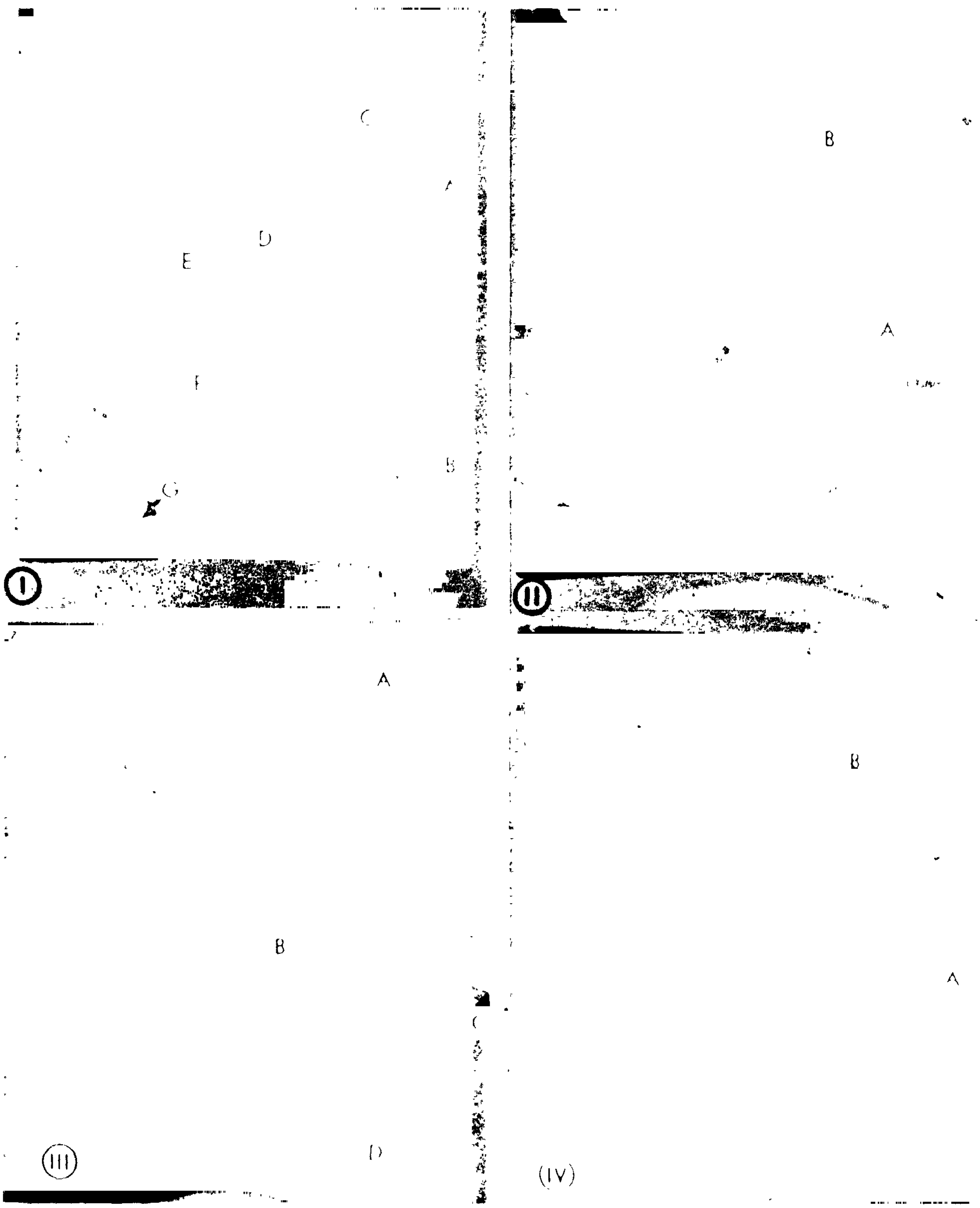


FIGURE 1 (I). FIRST RUN COMPRESSOR FOIL S/N 336 L/N 7491, 4½ X MAG.
FIGURE 1 (II). FIRST RUN TURBINE FOIL S/N 332 L/N 7491, 4½ X MAG.
FIGURE 1 (III). SECOND RUN COMPRESSOR FOIL S/N 440 L/N 7517, 4½ X MAG.
FIGURE 1 (IV). SECOND RUN TURBINE FOIL S/N 555 L/N 7517, 4½ X MAG.
LETTERED ARROWS CORRESPOND TO THE FOLLOWING FIGURES.

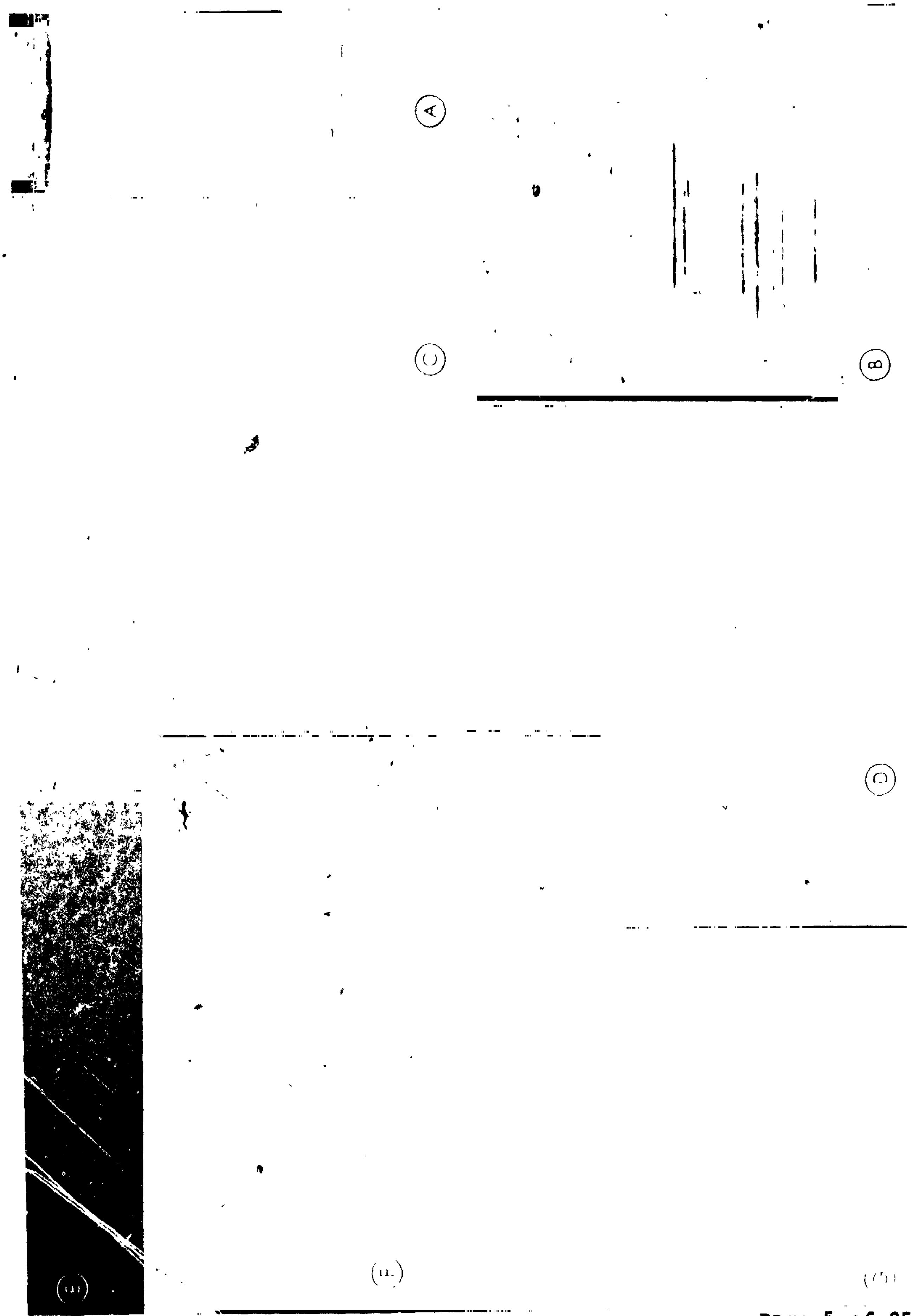


FIGURE 2. FIRST RUN COMPRESSOR FOIL. 20X MAG.

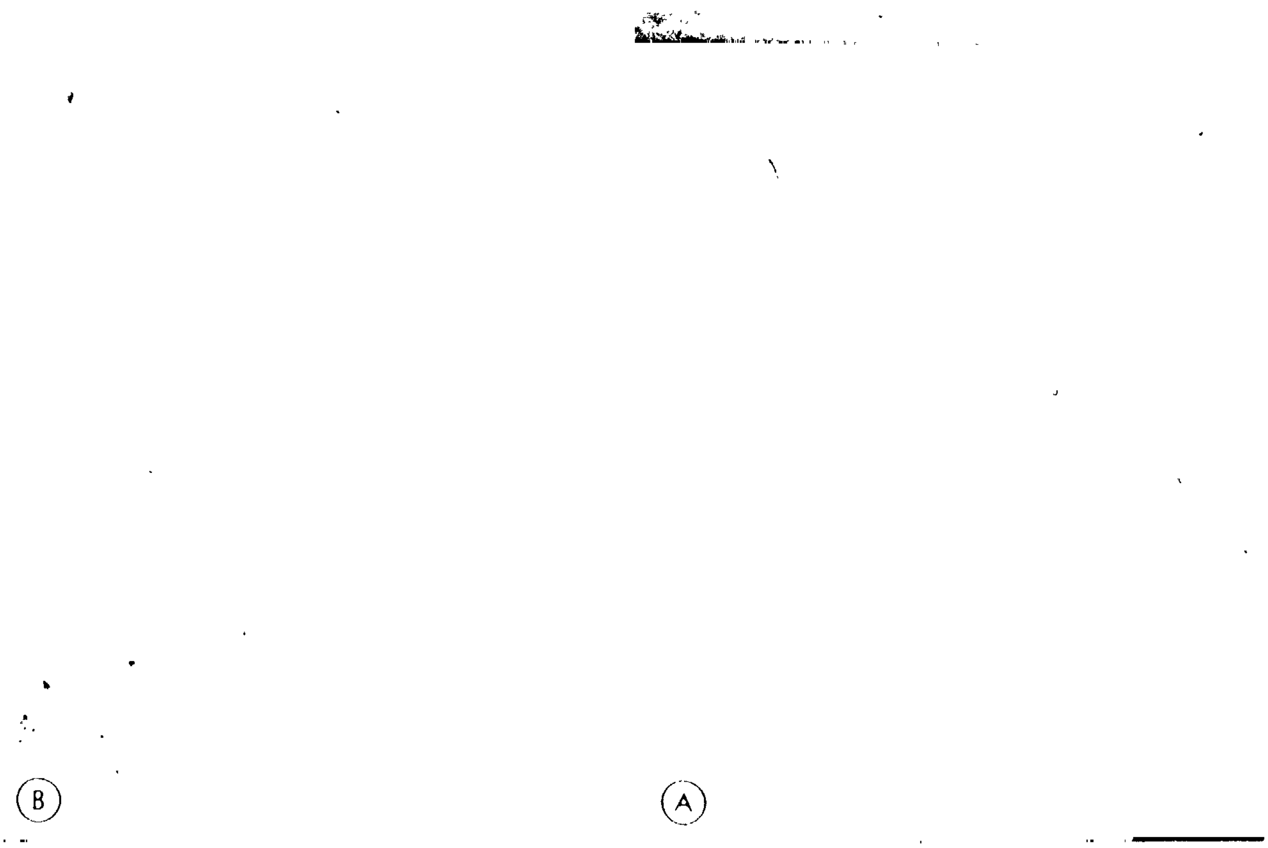


FIGURE 3. FIRST RUN TURBINE FOIL . 20X MAG.

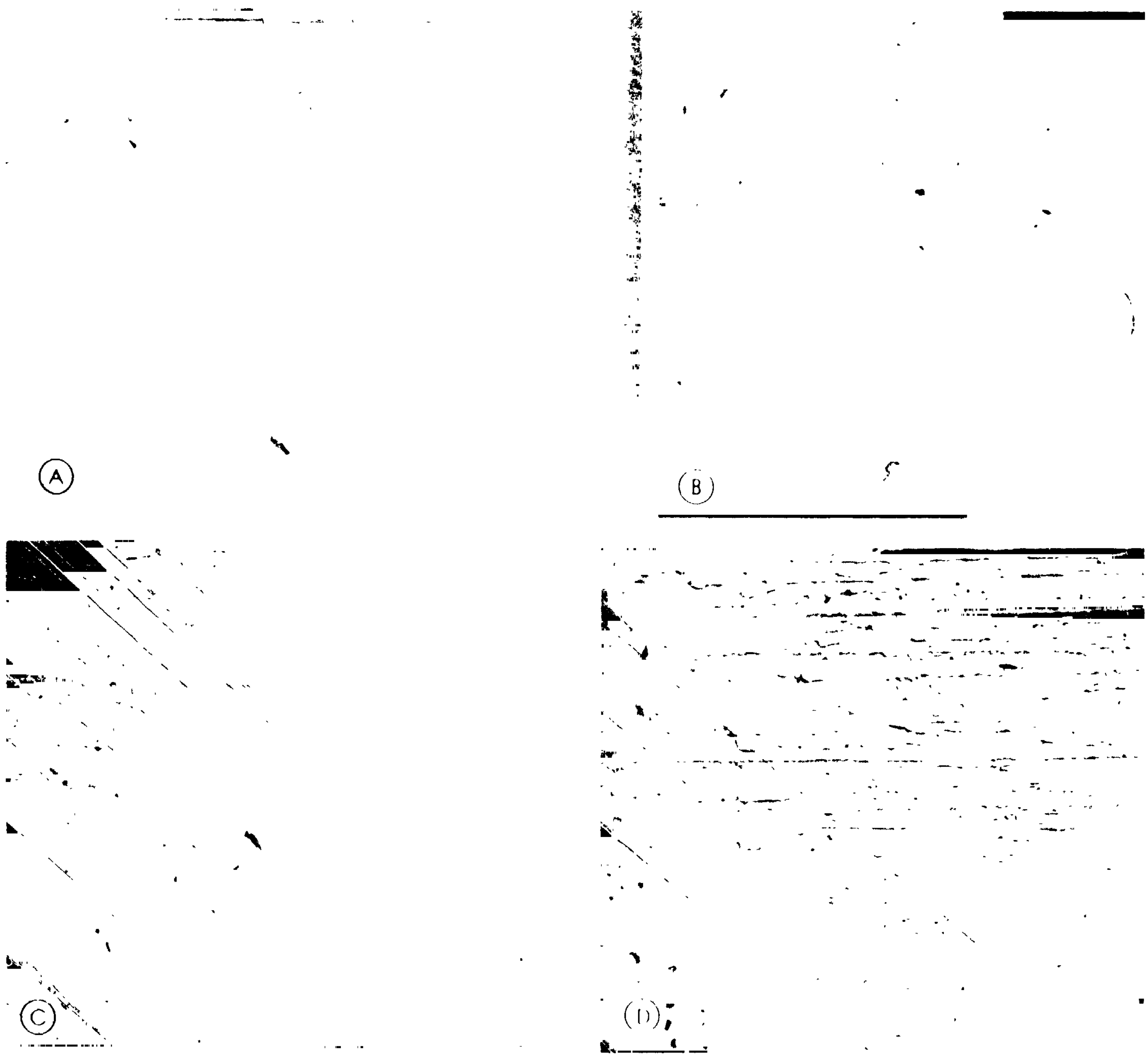


FIGURE 4. SECOND RUN COMPRESSOR FOIL. 20X MAG.

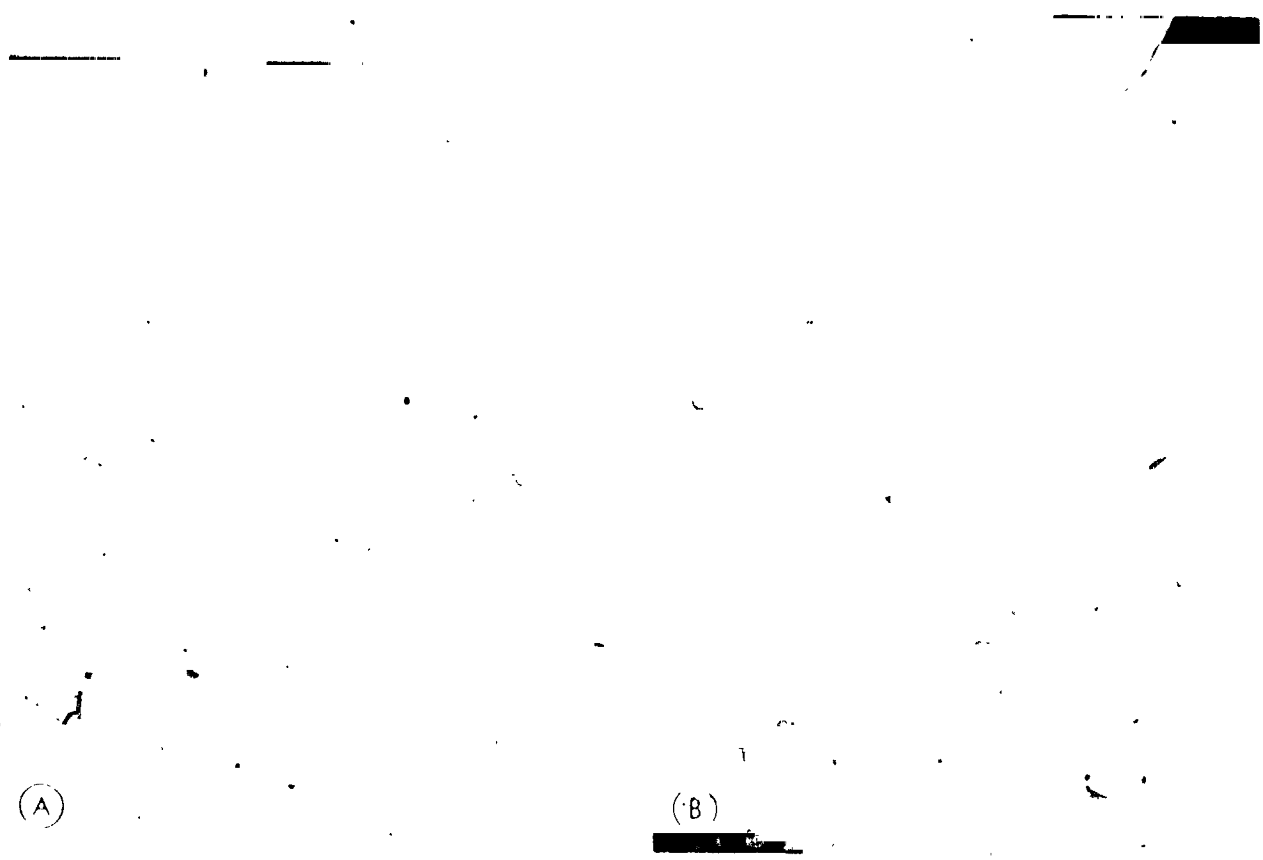


FIGURE 5. SECOND RUN TURBINE FOIL . 20X MAG.

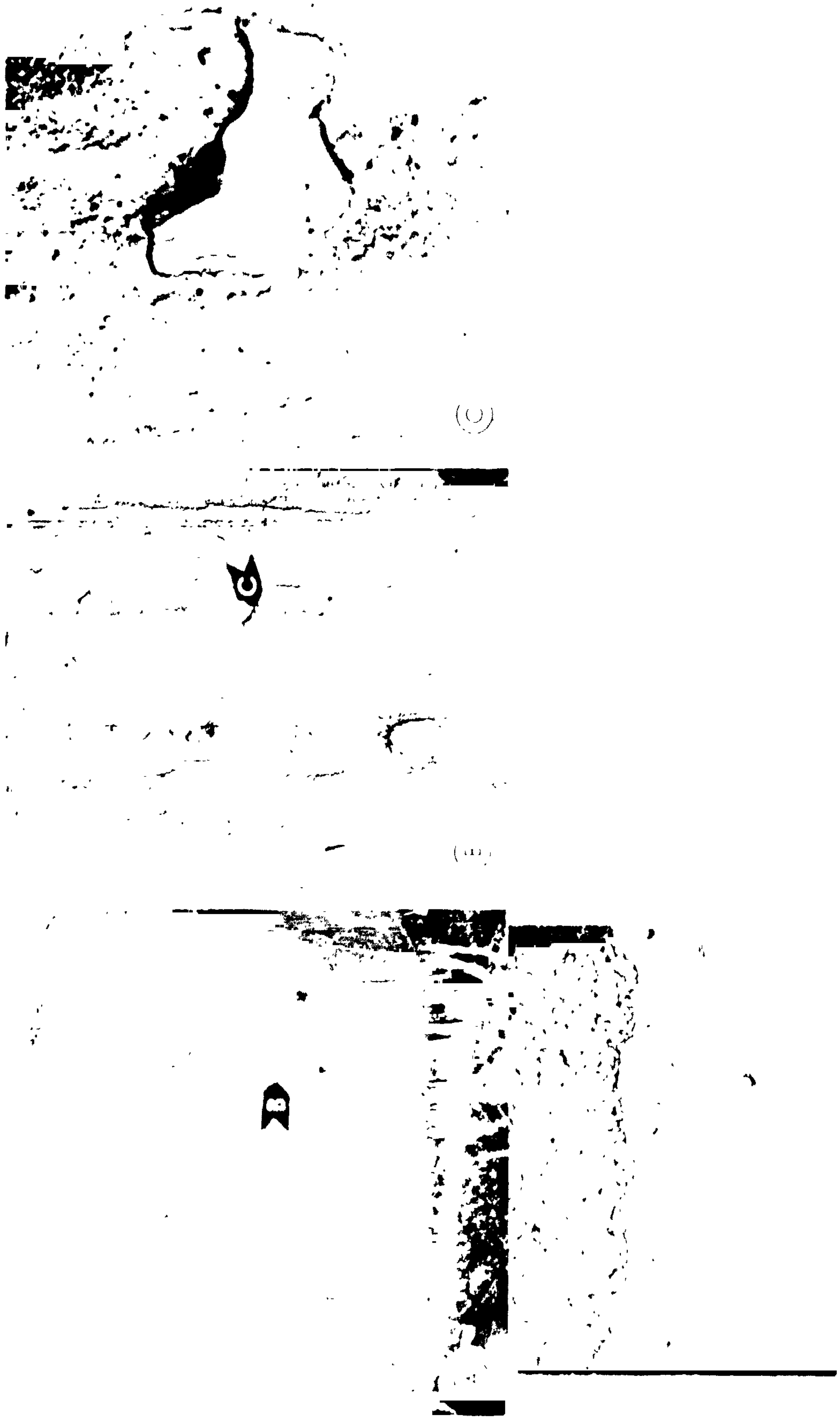


FIGURE 6. FIRST RUN COMPRESSOR FOIL (A). 10X MAG EDX ANALYSIS AT BLACK ARROW. (B) 100X MAG. (C) 1000X MAG. (D) 150X MAG. EDX ANALYSIS AT BLACK SQUARE.

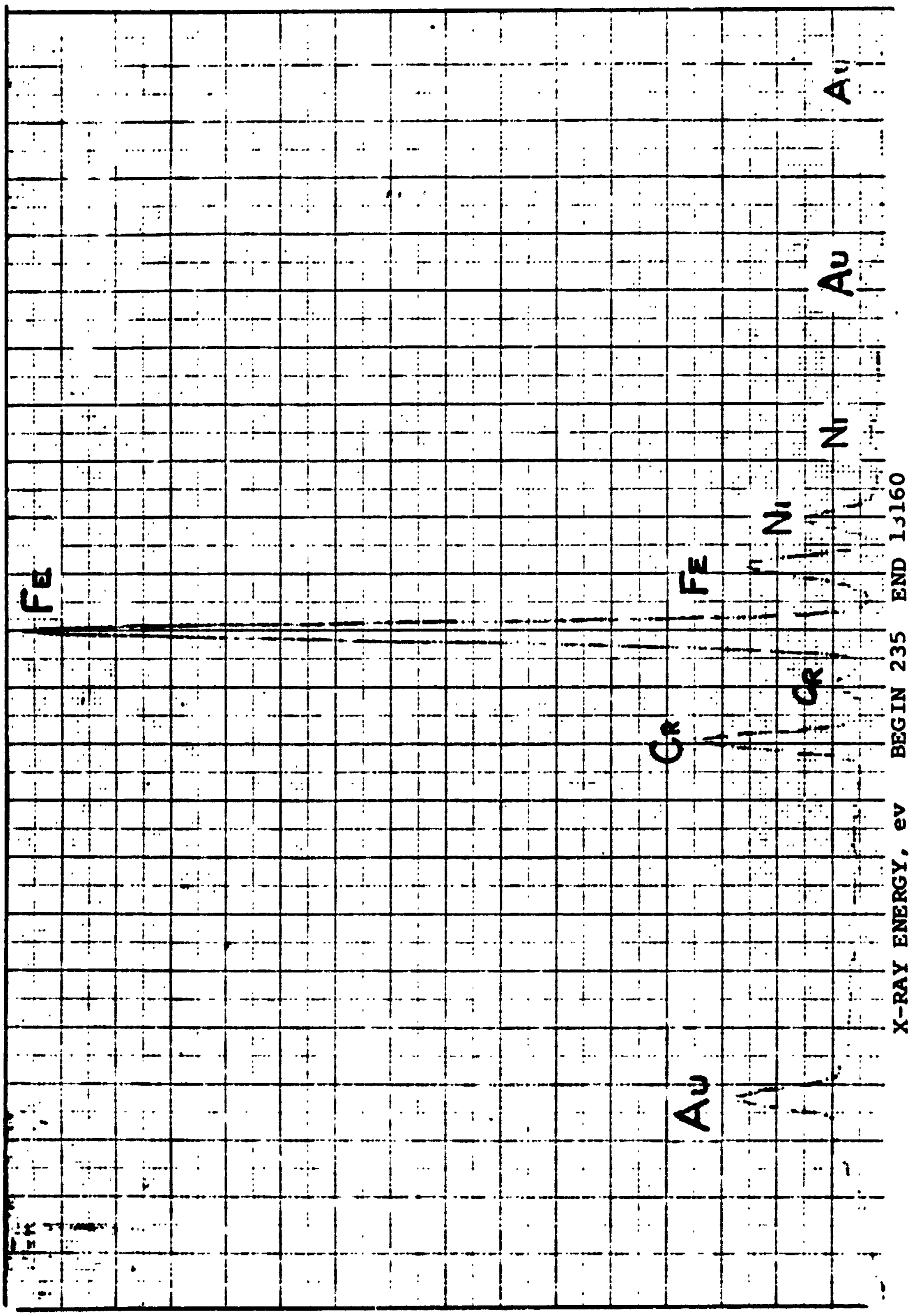


FIGURE 7. ENERGY DISPERSION X-RAY (EDX) ANALYSIS OF AREAS INDICATED IN FIGURE 6.

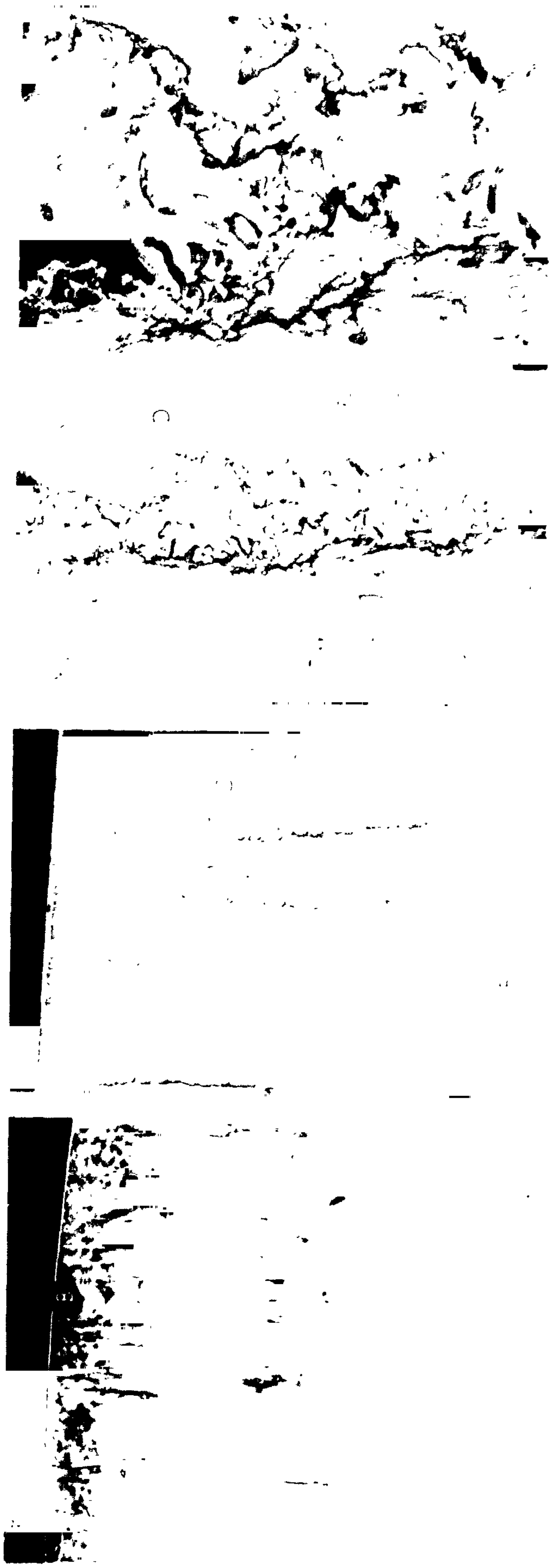


FIGURE 8. FIRST RUN TURBINE FOIL (A) 10X MAG. (B) 50X MAG. (C) 200X MAG. (D) 500X MAG.

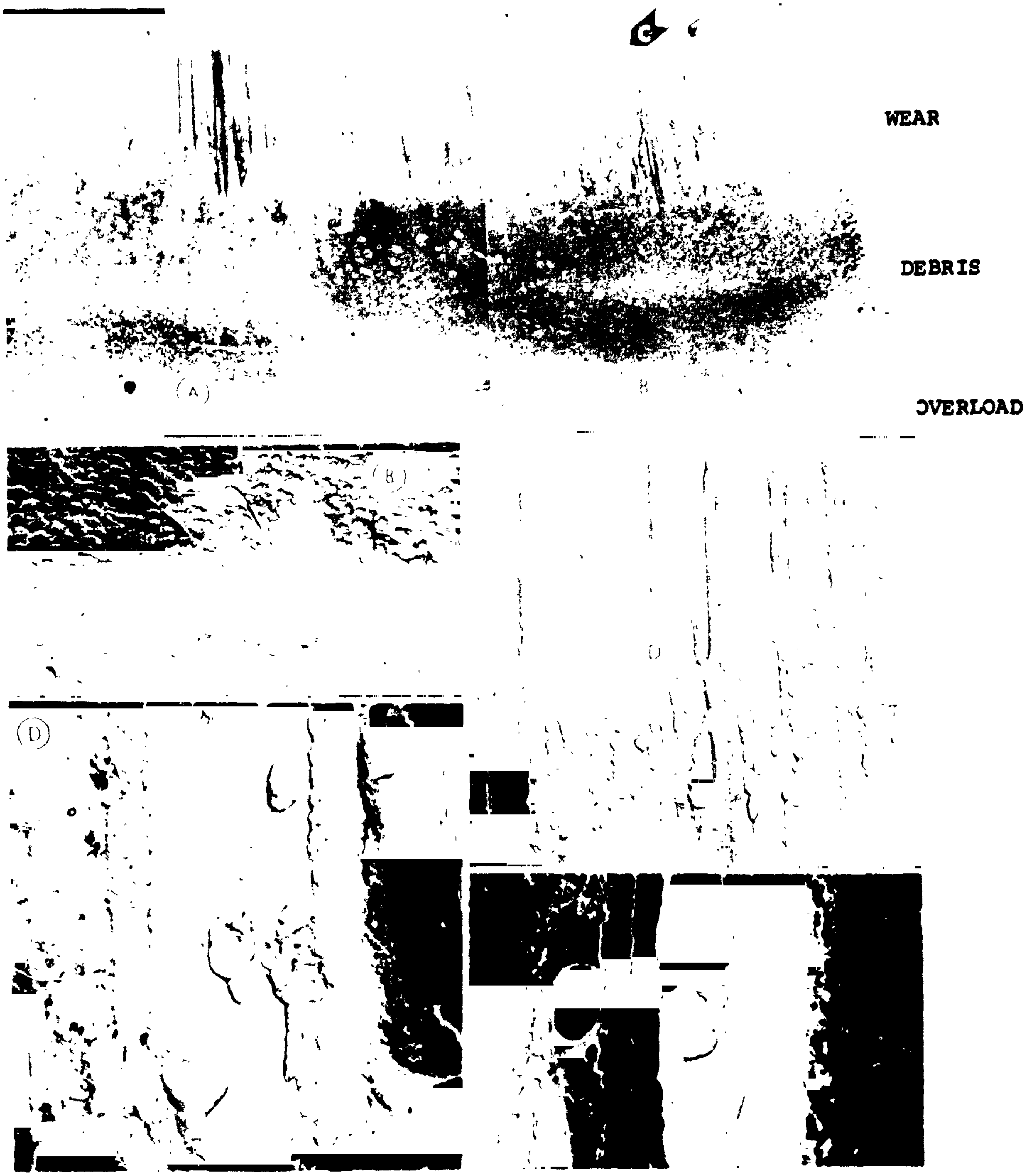


FIGURE 9. SECOND RUN COMPRESSOR FOIL. (A) 10X MAG. (B) 150X MAG. (C) 20X MAG. (D) 200X MAG. (E) 200X MAG. SEE FIGURE 10 FOR EDX ANALYSIS OF INDICATED AREAS.

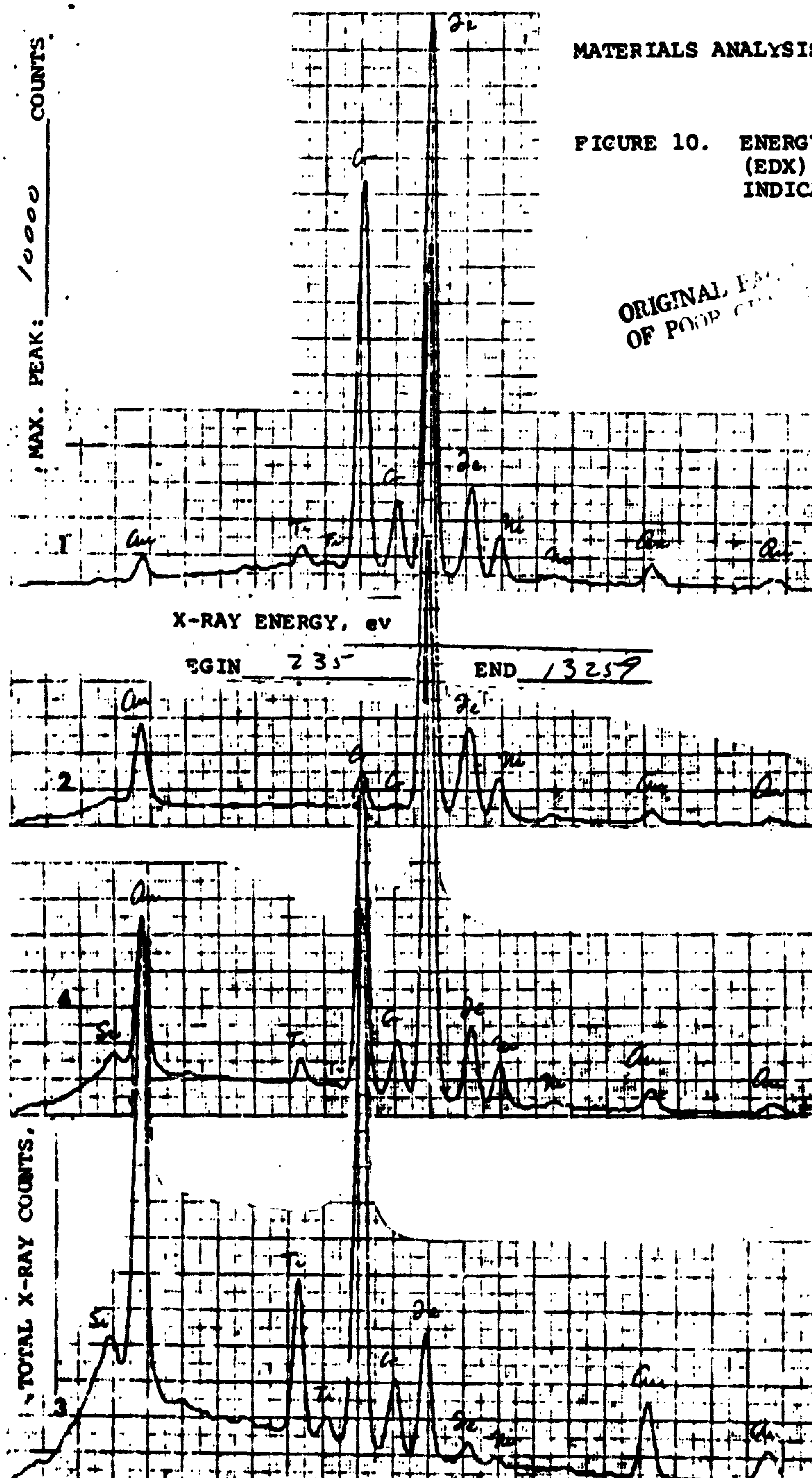


FIGURE 10. ENERGY DISPERSION X-RAY (EDX) ANALYSIS OF AREAS INDICATED IN FIGURE 9(E)

ORIGINAL PAGE IS OF POOR QUALITY

FIGURE 11. REPRESENTATIVE MICROSTRUCTURE
OF THE FOIL BEARINGS. 500X MAG.
ETCH: 10% OXALIC ACID.

APPENDIX A

MBTR ARGON RUN

The foils from the MBTR (Mini-BRU Turbine Rig) Argon Test Run were examined after a series of simulation runs in the MBTR under Argon atmosphere.

The compressor journal foils, Figure A1, showed typical wear areas with debris filling the depressions. In addition, a black, shiny particle was noted in the surface. The wear on the turbine bearing, journal foil, Figure A2, was minimally visable in the SEM and was photographed using the macro-camera. A built-up ridge of material was also noted. In addition, the debris on the surface of the thrust bearing, turbine side, foils was analyzed.

The compressor journal bearing debris was high in chrome with the typical Ti, Fe, and Ni small peaks, indicating primarily teflon. The black spot analyzed as almost pure sulfur and appeared to be integral with the coating. The built-up debris on the turbine journal foil analyzed typically of teflon with a little less iron, Al and Si, than the teflon base material.

The pad surface on the thrust bearing showed a highly etched surface. There was definitely more iron in the particle than has been noted in other debris. The judgement is that this debris may contain more metallic substance than any other debris.

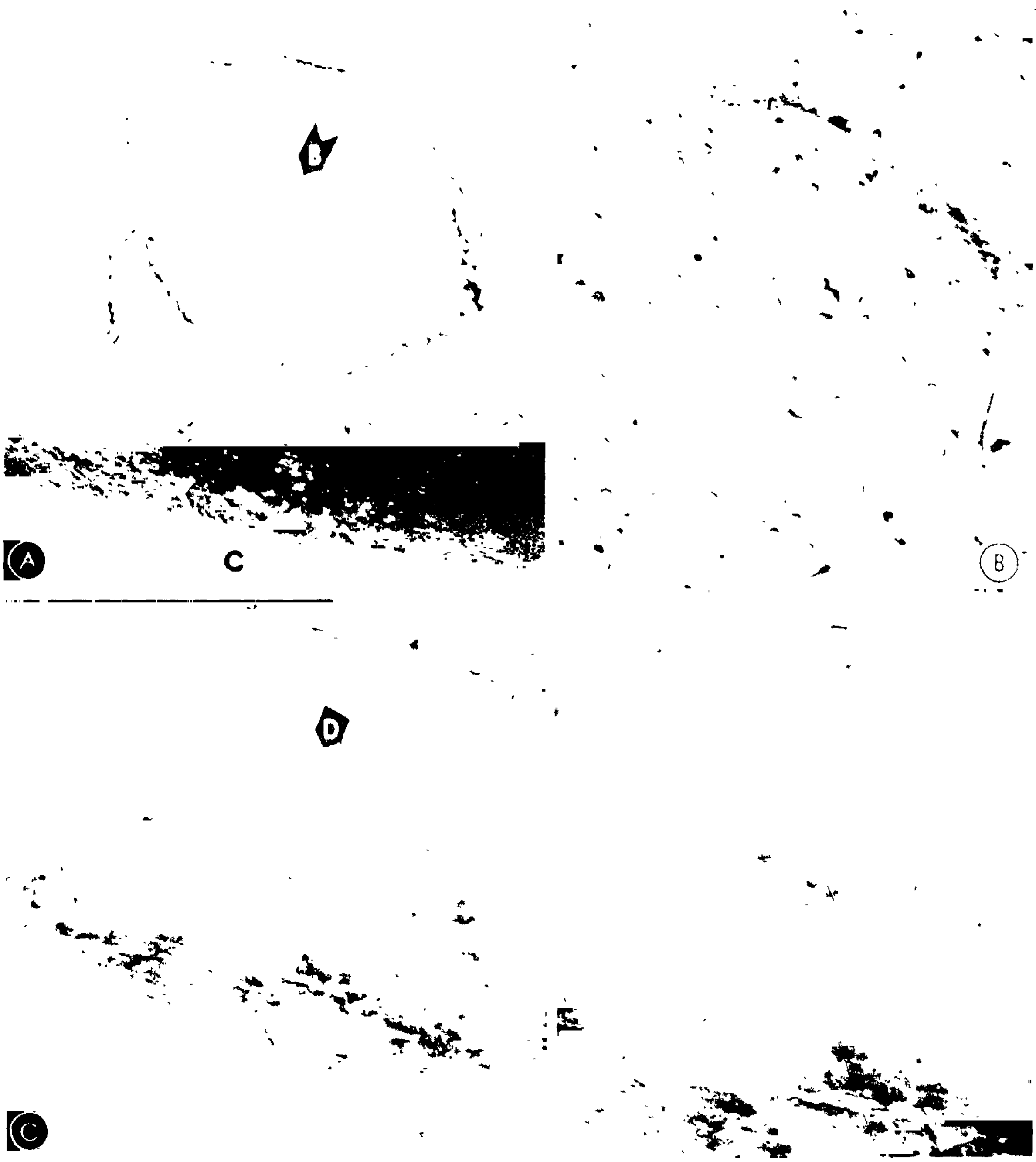


FIGURE A1. TYPICAL AREA FROM MBTR ARGON RUN. AREAS NOTED ARE: (A) DEBRIS (ARROW C). 20X MAG. (B) BLACK SHINY PARTICLE. 500X MAG. (C) WEAR AREA. 50X MAG. (D) ENLARGEMENT OF C. 100X MAG.

(NOTE: RING IN FIGURE A WAS PUT ON FOIL TO LOCATE SPOT.)

A

FIGURE A2. TURBINE JOURNAL FOIL FROM MBTR ARGON RUN. (A) LIGHT PHOTOMICROGRAPH OF WEAR AREA. 15X MAG. (B) SEM PHOTOMICROGRPAH OF BUILT-UP AREA. 60X MAG. S/N610.

APPENDIX B

APPENDIX B STR RUNS 1/21 & 1/23/78

On January 21 and 23, 1978, the STR (Simulator Test Rig) was run to check the effect of unloading one phase of the alternator during power generation. When the rig was torn down, the journal bearings were in the condition noted in Figure B1. The black, wiped area was typical of bearings run in the rig tests and was thought to be incipient failure of the teflon coating. The alternator shaft, shown in Figure B2, had a wiped area and the material appeared as a build-up under oblique lighting. The thrust bearing also had indications of wear at the top and bottom of the pads, and evidence of debris between the pads, as shown in Figure B3.

The pattern on the turbine and compressor journal bearings is similar, with the damage sustained by the turbine bearing being much less than the compressor bearing, as shown by SEM photographs, Figure B4. (The particle outlines are accentuated by charging of the particles in the electron beam) EDX analysis revealed that the area around the particles was similar to the virgin teflon and contained mostly Cr with minor amounts of Fe, Ni, Ti, Al and Si. The particle contained mainly Fe with almost as much Cr. In addition to Al, Ti, Si and Ni, the particles also had smaller amounts of Ca, K, Na, S, Cl and Zn. The more highly charged particle in Figure B4-a, had the same constituants as the flatter particles. This indicates that contaminated (not deionized) water, a fingerprint or dirt are mixed into these particles along with some ferrous material.

The thrust bearing shows signs of break-away of teflon on the trailing edge, as shown in Figure B-5. Although the wear on the turbine side is heavier, the greatest break-away is on the compressor bearing side. A large particle was noted in one pad surface with two streaks in the direction of rotation. The only identifiable flourescence from this particle was of silicon.

The evidence indicates that there was much more contamination in these bearings than any others which have been analyzed. Whether this contamination occured during fabrication or assembly is not clear. The nature of the contaminant being only on the particles, however, indicates it may be ingested dirt or dirt on the rotor. There is no evidence to indicate that the damage in the bearing is other than that which would be caused by rubbing of the alternator shaft on the bearing surface.

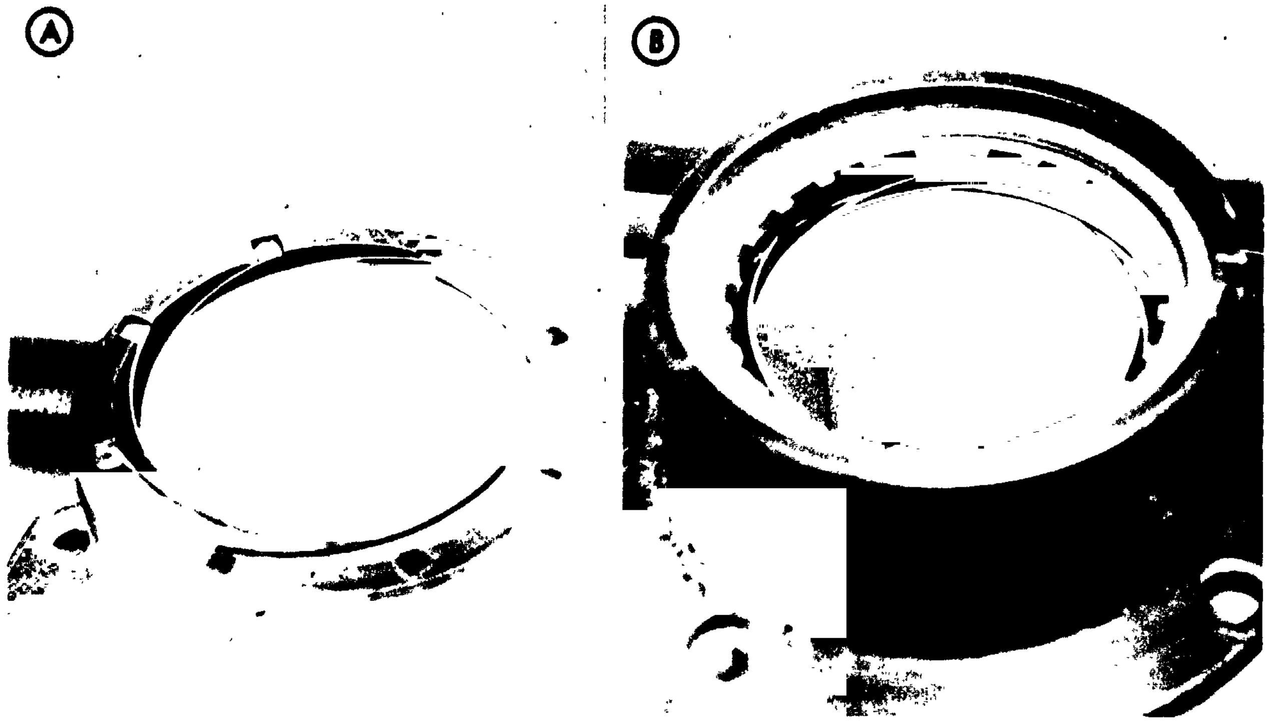


FIGURE B1. OVERALL VIEWS OF (A) COMPRESSOR AND (B) TURBINE BEARINGS AFTER STR RUNS OF 1/21/78 AND 1/23/78. 1X MAG.

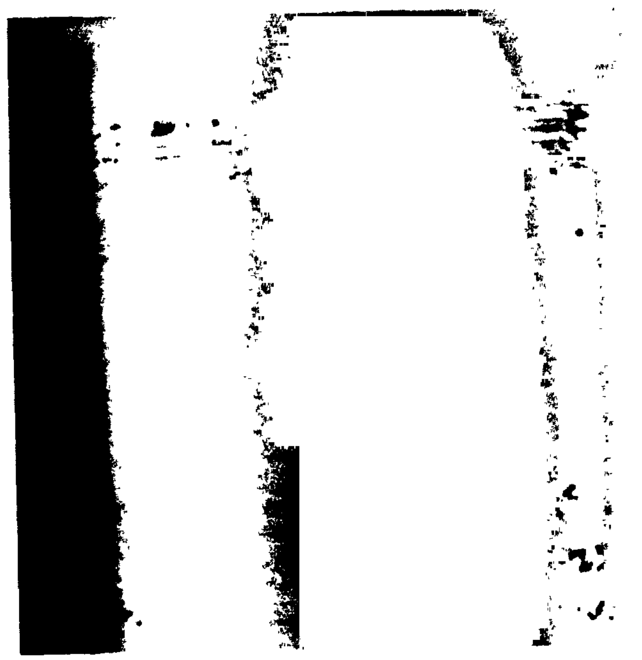


FIGURE B2. RUBBED AREA OF ALTERNATOR SHAFT AT COMPRESSOR JOURNAL BEARING. 5X MAG.

FIGURE B3. THRUST BEARING PADS FOR STR RUNS OF 1/21 AND 1/23/78. (A) COMPRESSOR SIDE. (B) TURBINE SIDE. 5X MAG.

FIGURE B4. (A) WEAR AREA OF COMPRESSOR JOURNAL BEARING. 10X MAG. (B) ENLARGED VIEW OF COMPRESSOR BEARING. 60X MAG. (C) TURBINE JOURNAL BEARING FROM STR RUNS OF 1/21 AND 1/23/78. 50X MAG. EDX ANALYSIS. (I) SAME AS II. (II) Fe, Cr MAJOR Ca, K, Na, Al, Si, S, Cl, Ti, Ni, Zn (III) Cr MINOR, Fe EQUAL Ti, OTHERS MUCH LESS. TURBINE BEARING, PARTICLES SAME AS (II), BACKGROUND HAS Cr MAJOR, Fe VERY MINOR, LITTLE Al AND Si.

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FIGURE B5. TRAILING EDGE OF COMPRESSOR SIDE THRUST BEARING PAD. (A) 50X MAG. (B) 300X MAG.

APPENDIX C

SUMMARY OF MA-13344 AND APPENDICES A & B

In reference to the teardown inspection E:FAD:0335:012578, the following descriptions of debris in the bearing areas appear applicable.

Burnish Pattern - Normal wear between rotating part and bearing.

Whitish Deposit - Material looks like finely divided smeared teflon. Analysis indicates a high iron content meaning transfer from the alternater motor or thrust bearing rotor to the teflon particles.

Black Spots - These appear to be of two classes, either an uncontrolled particle, integral with the coating, or a sulfur particle.

Black Streaks - These are either gouged out areas filled with teflon debris or highly smeared particles of teflon. Some of these larger particles appear shiny and metallic to the eye.

Metallic particles - The smaller, rounded, particles contain iron as the major ingredient They are,most probably, shaft and thrust rotor material with varying amounts of teflon associated with the metal. The flatter areas are highest in iron, but with almost as high a chrome peak and appear to be highly smeared teflon with rotor or shaft material smeared in.

Scratches - The scratches, primarily the second WHL failure, have both sharp and broken edges. The primary indications are that the shape depends on both the particle geometry and the nature of mechanical movement through the scratch.

General Color - The whitish areas are generally finely divided debris. The black areas are mostly highly smeared teflon particles and, in a few cases, debris packed gouges. The continuous, black areas are teflon, most probably exposed to higher temperature and, apparently, coked.

The flourescent patterns from all the areas were compared to a standard pattern for AISI 302 stainless steel. Although the conditions were not calibrated, the following conclusions can be drawn:

1. No area exactly matched the AISI 302 pattern.
2. Almost all particles in the teflon showed the iron contents to be predominant. Varying amounts of chrome appeared with the patterns,

APPENDIX C (CONTD.)

indicating varying mixes of iron base particles with teflon. The thrust bearing debris was significantly higher in Fe content than the journal bearing debris.

3 All background and unworn areas in the teflon, show very high Cr content with minimal Fe and Ni and some Ti.

The primary method of breakdown, based on these results, indicates direct rub of the shaft and bearing as the most probably cause. The journal bearings, having less iron content than the thrust bearings, may just mean that the debris was generated over a longer period of time and/or was a more "gentle" rub condition.

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