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SURVIVABILITY OF SILICON NITRIDE BEARING.(U)
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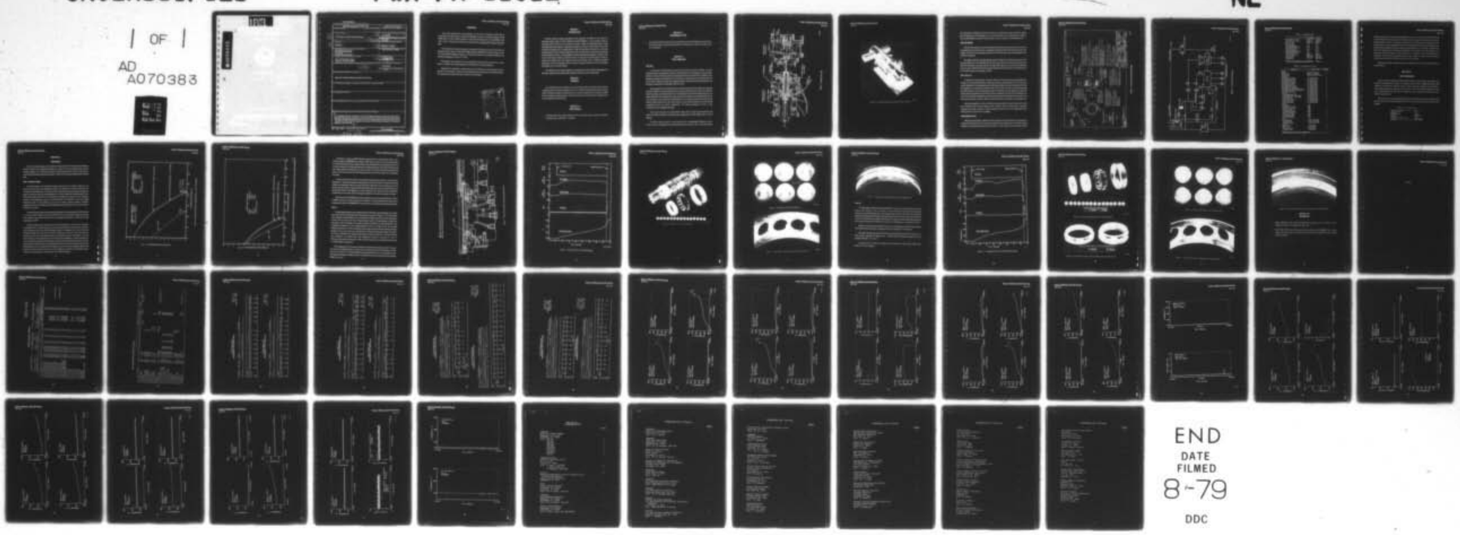

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An oil shutoff test was conducted on a 35 mm bearing with silicon nitride balls. The time to bearing failure was 90 sec compared to 45 sec for an M-50 steel bearing which was similarly tested. This result compares favorably with the 1.74 factor as predicted by an analytical model. Post-test inspection found the silicon nitride balls with minor surface distress compared to the extreme spalling of the M-50 balls.

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FOREWORD

This report describes the work performed by the Pratt & Whitney Aircraft Group, Government Products Division of United Technologies Corporation, West Palm Beach, Florida 33402 under U.S. Navy Contract N00140-77-C-0974 which incorporates U.S. Army MIPR No. RN 719-77. This is a final report covering work conducted from 1 August 1977 through 1 December 1978.

The Government technical manager for this program was Raymond Valori of the Naval Air Propulsion Center, Trenton, New Jersey 08628 (telephone (609) 882-1414). Walt Thompson of the U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland 21005 was the technical representative for the U.S. Army.

The program was conducted at Pratt and Whitney Aircraft under the direction of John Miner, Component Technology Manager and William Grace, Program Manager.

Appreciation is extended to the following Pratt and Whitney Aircraft personnel for their assistance on this program. Jorge Alcorta and Edward Kichura assisted in the analytical effort. The experimental bearing tests were conducted by James Mohn.

SECTION I
INTRODUCTION

Previous ceramic bearing development work sponsored at P&WA by the Naval Air Propulsion Center under Contract N00140-75-C-0382 (Reference 1) was primarily aimed at evaluating silicon nitride as a low mass ball material to offset the detrimental effect of high centrifugal ball loads expected of high speed bearings in future gas turbine engines. The results of tests with bearings with hot pressed silicon nitride rolling elements compared to an all-metal bearing showed 10 to 20% lower heat generation, 30% less axial load at the inception of ball skid, and an apparent reduction in ball temperature. These characteristics suggested a longer survival time for the ceramic bearing in situations where the lubricant flow had stopped. Should an aircraft lose lubricant flow, the bearing survival time becomes crucial to finding a suitable landing site. It is in this situation that the ceramic bearing is believed to offer a survivability advantage over an all metal bearing.

The objective of the present program is to determine the survivability characteristics of bearings containing silicon nitride balls compared to those of an all metal bearing.

SECTION II
SUMMARY

An oil shutoff test was conducted on a 35 mm bearing with silicon nitride balls. The time to bearing failure was 90 sec compared to 45 sec for an M-50 steel bearing which was similarly tested. This result compares favorably with the 1.74 factor as predicted by an analytical model. Post-test inspection found the silicon nitride balls with minor surface distress compared to the extreme spalling of the M-50 balls.

SECTION III
CONCLUSIONS

1. A bearing with silicon nitride elements will survive longer under conditions of lubricant starvation than an all M-50 steel bearing.

SECTION IV
RECOMMENDATIONS

1. An optimized ball bearing with silicon nitride elements should be designed and tested in the 100-165 mm range to assess the characteristics of a bearing more suited for an engine main shaft application.

SECTION V
TEST HARDWARE

TEST RIG

A cross section of the bearing test rig with the drive turbine is shown in Figure 1. A roller bearing inner race was installed as a spacer to locate the silicon nitride bearing at the proper axial position in the rig. A bearing preload of approximately 90 lb was obtained by recording critical bearing and assembly dimensions and by machining the shaft spacers to a dimension that was shorter than the distance between the housing shoulders. Additional axial load was applied to the bearings by pressuring the diaphragm (load to the left).

Oil was supplied to the test bearing from a probe that jetted oil into the shaft bore under the bearing. Channels in the shaft pumped oil to the annuli that fed the ball contact and cage land lubrication holes in the bearing inner race. Oil was supplied to the steel slave bearing by a jet (not shown) directed into the axial scoop on the rig drive shaft. Channels in the shaft pumped the oil from the scoop to annuli under the bearing inner race, which were similar to those for the test bearing. Slinger-type seals on the shaft inboard of each bearing separated the ball bearing compartments from the central compartment. The bearing discharge oil flows of each compartment were scavenged separately.

The test rig was driven by a radial inflow steam turbine through a small diameter quill shaft. The shaft is capable of absorbing small misalignments without adding load to the test bearing.

The drive turbine assembly is self-contained with an independent lubrication system. Figure 2 shows a photograph of the assembled bearing rig and drive turbine. The bearing rig is

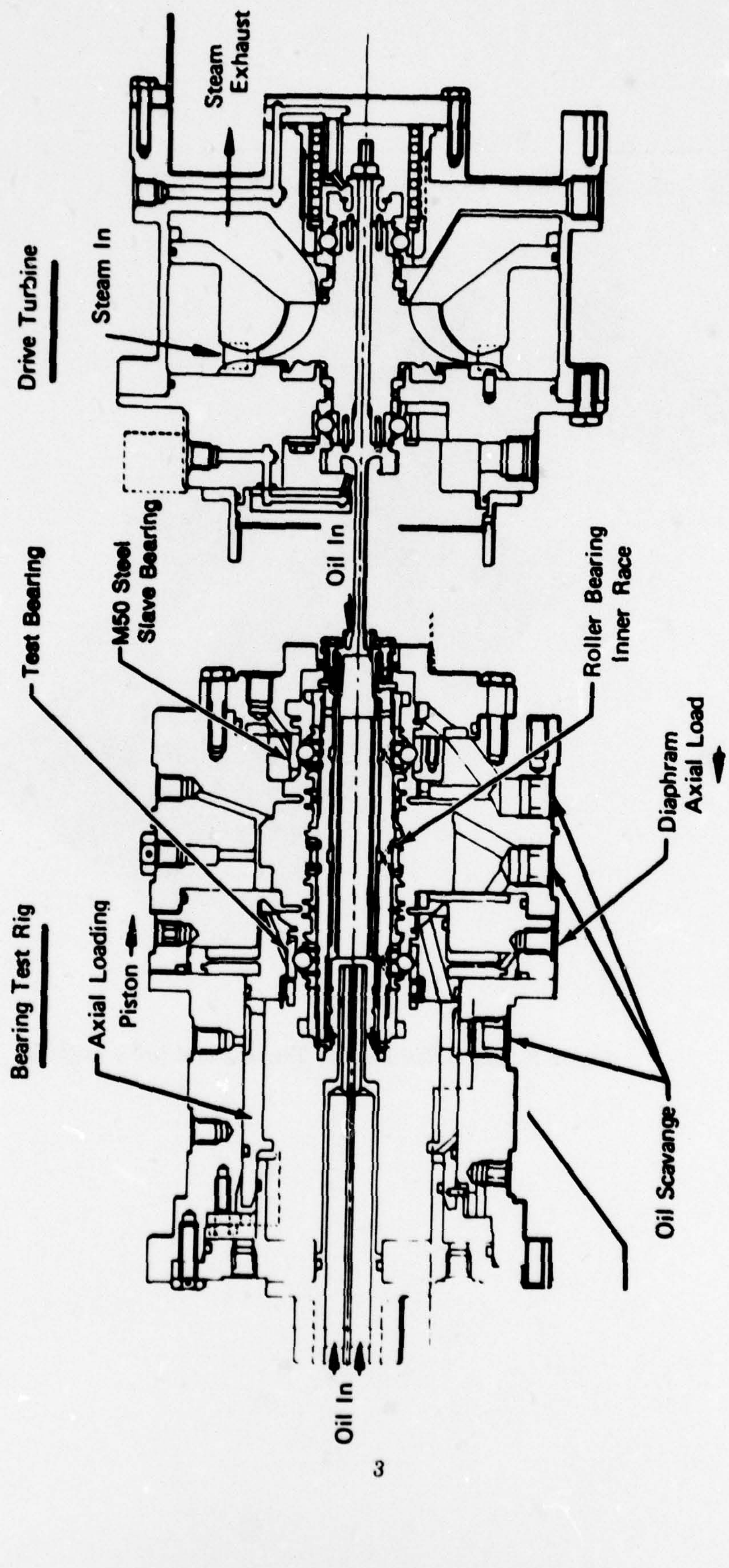

Figure 1. Bearing Test Rig

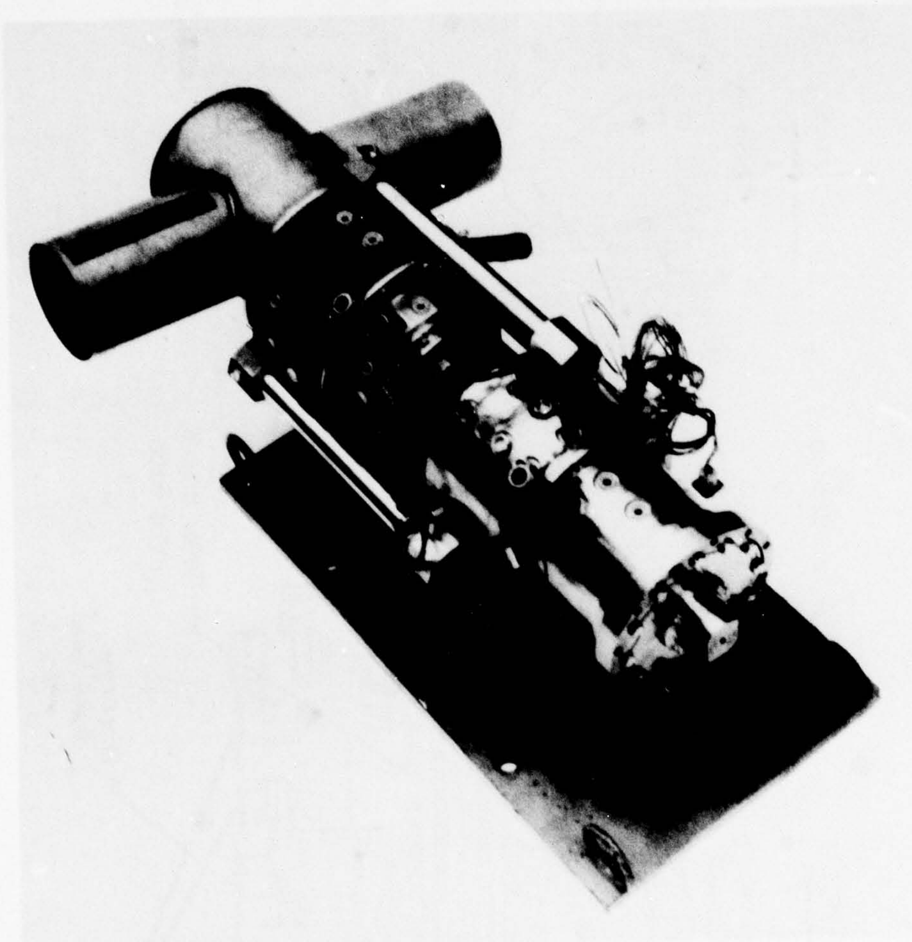

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Figure 2. Assembled Bearing Test Rig and Drive Turbine

hard mounted to a baseplate and the drive turbine is supported from three pins which extend from the bearing rig. Three bushings on the drive turbine allow the turbine assembly to slide on the pins preventing the transfer of axial load from the drive turbine to the bearing test rig.

TEST BEARINGS

A 35 mm bore angular contact ball bearing having M-50 tool steel races and Norton NC132 hot pressed silicon nitride balls, and a comparable bearing with M-50 steel balls were used in the program. The silicon nitride bearing is identical to the steel bearing, which was designed for a 2.5 million DN operation.

The design of the silicon nitride bearing is shown in Figure 3. The bearing inner race is split and contains grooves in the unloaded half for ball contact lubrication. Holes are provided in the lands for lubrication of the cage journals. The cage which rides on the inner land, was machined from one piece of AMS 6414 and silver plated. Design details for the silicon nitride bearing, and for the steel bearing, are presented in Table I.

TEST FACILITY

A schematic of the test facility is shown in Figure 4. Oil was pumped from a 25 gal reservoir through a 10μ filter and distributed to both test and slave rig bearings as well as to the drive turbine bearings. Oil for pressurization of the bearing load piston was also pumped from the tank and supplied to the rig through individual control valves. The test, slave, and turbine bearings had individual flow control valves and flow meters. In addition, the test bearing oil supply line had an electrically operated on-off solenoid valve for stopping the oil flow to the test bearing. The oil from each bearing compartment was scavenged with individual pumps and returned to the tank through a water-oil cooler. A steam coil was immersed in the oil reservoir for heating the oil.

Steam was supplied to the drive turbine from an area system through a large control valve and a parallel vernier valve for precise control of speed. The steam supply had a manually operated abort system to prevent a turbine overspeed in the event of a drive shaft failure when bearing seizure occurred after oil stoppage.

INSTRUMENTATION

Bearing instrumentation, listed in Table II, was identical for each bearing in both the silicon nitride and steel bearing tests. Outer race temperature was measured with four thermocouples installed in each bearing housing so that they were in contact with the outer races. Axial load was

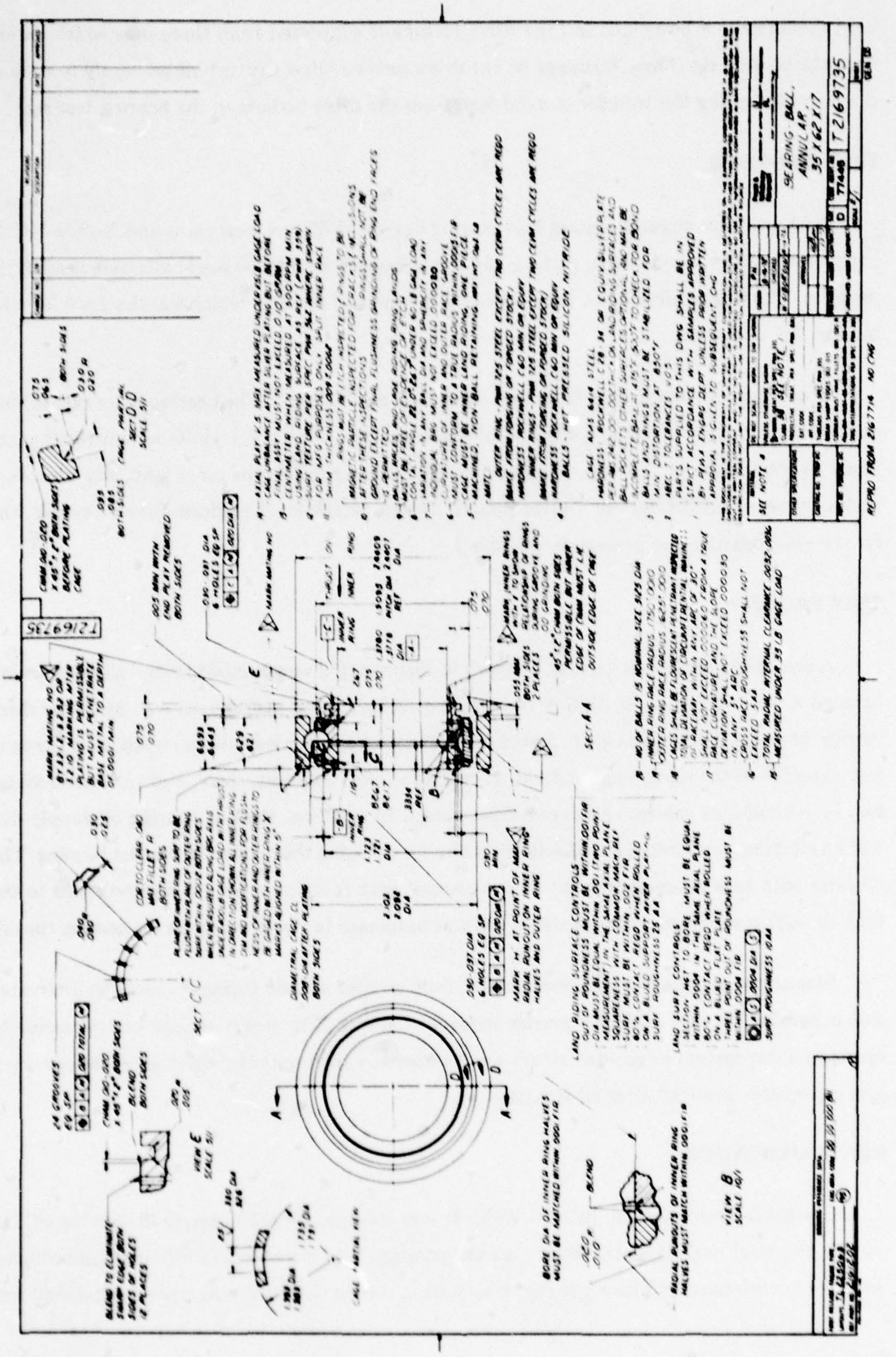

Figure 3. Silicon Nitride Bearing Design

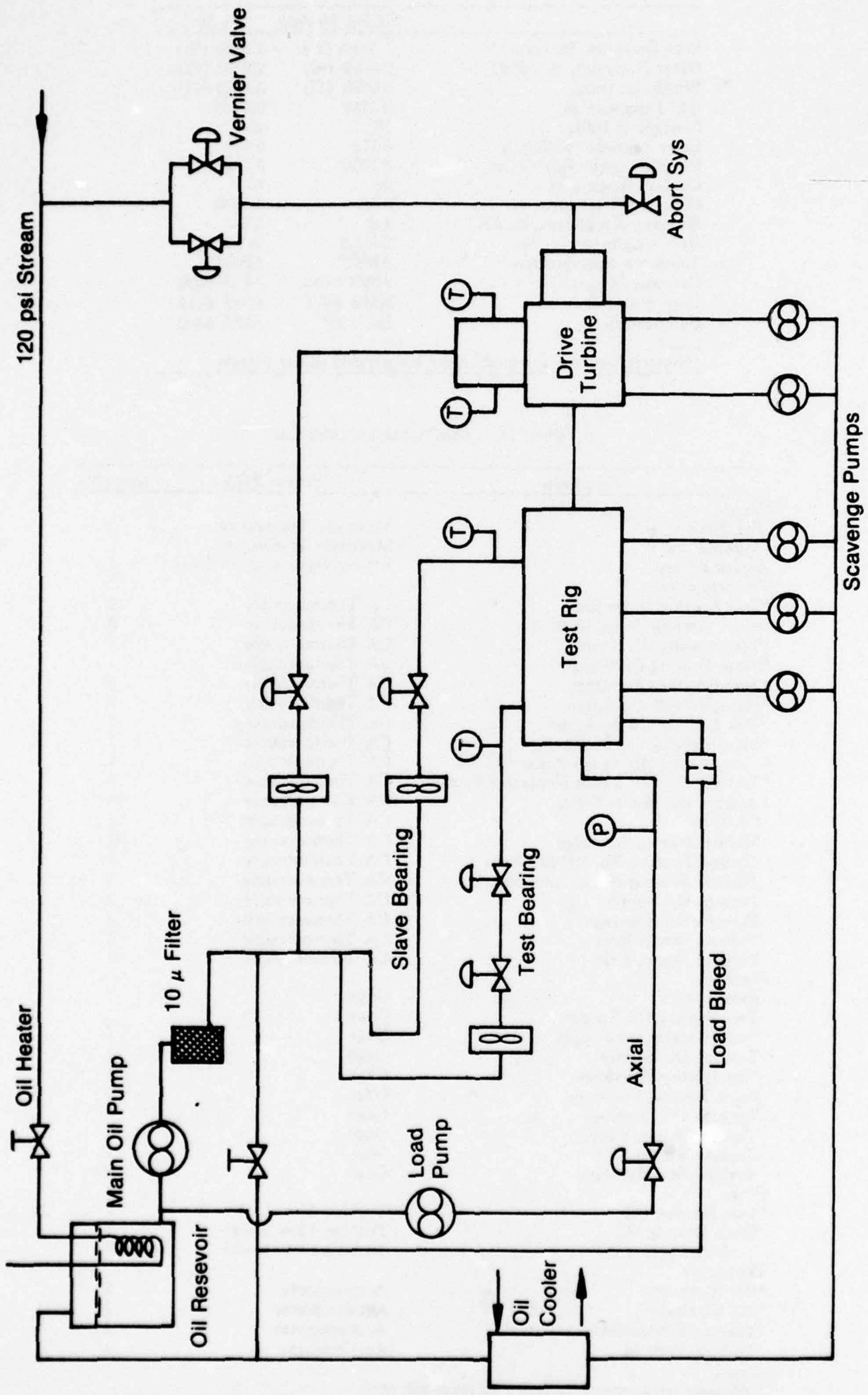

Figure 4. Test Facility Schematic

Table I. Bearing Design

	Silicon Nitride	M-50
Bore Diameter, in. (mm)	1.3780 (35)	1.3780 (35)
Outer Diameter, in. (mm)	2.4409 (62)	2.4408 (62)
Width, in. (mm)	0.6690 (17)	0.6679 (17)
Ball Diameter, in.	0.3119	0.3127
Number of Balls	15	15
Inner Raceway Radius, in.	0.175	0.175
Outer Raceway Radius, in.	0.1625	0.1625
Contact Angle, deg	25	25
Diametral Clearance, in.	0.0035	0.0036
Raceway Roughness, in. AA	4-6	4-5
Ball Roughness, in. AA	2.5-3.3	2.3-3.0
Tolerance Specification	ABEC7	ABEC7
Raceway Material	AMS 6490	AMS 6490
Cage Material	AMS 6414	AMS 6414
Ball Material	NC 132*	AMS 6490

*Norton Company designation for hot pressed silicon nitride.

Table II. Instrumentation List

Parameter	Sensor Type	Quantity
Speeds		
Rig Shaft	Magnetic Transducer	1
Turbine Shaft	Magnetic Transducer	1
Bearing Cage	Strain Gage on Outer Race	1
Temperatures		
*Test Bearing Outer Race	CA Thermocouple	4
Slave Bearing Outer Race	CA Thermocouple	4
*Test Bearing Oil Supply	CA Thermocouple	1
*Slave Bearing Oil Supply	CA Thermocouple	1
*Test Bearing Oil Sump	CA Thermocouple	2
*Slave Bearing Oil Sump	CA Thermocouple	2
*Test Bearing Oil Scavenge	CA Thermocouple	1
*Slave Bearing Oil Scavenge	CA Thermocouple	1
*Test Bearing Air Temp Puller Groove	CA Thermocouple	2
*Test Bearing Air Temp Nonpuller Groove	CA Thermocouple	2
*Internal Rig Metal Temp.	CA Thermocouple	14
Oil Tank	CA Thermocouple	1
Middle Bearing Scavenge	CA Thermocouple	1
Turbine Bearing No. 1 Outer Race	CA Thermocouple	2
Turbine Bearing No. 2 Outer Race	CA Thermocouple	2
Turbine Oil Supply	CA Thermocouple	2
Turbine Oil Scavenge	CA Thermocouple	2
Turbine Steam Inlet	CA Thermocouple	1
Turbine Steam Exit	CA Thermocouple	1
Pressures		
Axial Load	Gage	1
Test Bearing Oil Supply	Gage	1
Slave Bearing Oil Supply	Gage	1
Turbine Oil Supply	Gage	1
Test Bearing Scavenge	Gage	1
Slave Bearing Scavenge	Gage	1
Turbine Oil Scavenge	Gage	1
Turbine Steam Supply	Gage	1
Turbine Steam Exit	Gage	1
Turbine Seal Air Dam	Gage	2
Flows		
*Test Bearing Oil	Turbine Flow Meter	1
Slave Bearing Oil	Turbine Flow Meter	1
Turbine Bearing Oil	Turbine Flow Meter	1
Vibrations		
*Rig Horizontal	Accelerometer	2
*Rig Vertical	Accelerometer	2
Turbine Horizontal	Accelerometer	1
Turbine Vertical	Accelerometer	1

*Indicates parameter is recorded on magnetic tape.

determined as the sum of the estimated preload and the product of the pressure and the load area of the diaphragm. Thermocouples were immersed in the oil supply lines and rig sump to measure bearing supply and exit oil temperature. Cage speed was measured with strain gages on the bearing outer race, which sensed the dynamic strain resulting from ball passage. Shaft speed was measured with a magnetic transducer that sensed the passing of a 12-tooth cog on the shaft. Oil flows were measured with turbine-type flowmeters in the supply lines; rig vibrations were measured with accelerometers on the rig housing. A complete list of all instrumentation is presented in Table II; the parameters noted were also recorded on magnetic tape during the transient period when the oil flow was shut off to the test bearing.

Standards traceable to the National Bureau of Standards were used for the calibration of all instrumentation.

SECTION VI

TEST PROCEDURE

The test rig with the M-50 steel bearing was installed in the test facility. The oil system was serviced with approximately 25 gal of oil qualified under the MIL-L-23699B specification. Rig conditions as specified in Table III were set. After steady-state operation was achieved, a complete set of stand and rig data was recorded. The oil to the test bearing was then shut off. The time to bearing failure was recorded by a stopwatch and on magnetic tape along with other transient rig parameters.

After the test, the rig was disassembled and photographs were taken of the M-50 steel bearing. The rig was then reassembled with the silicon nitride bearing and the test program was repeated.

Table III. Test Conditions

Oil Inlet Temperature	150°F
Environment	Air
Bearing Bore Size	35 mm
Rig Speed	62,000 rpm
Thrust	135 lb
DN (Bearing bore mm × rpm)	2.2×10^6
Lubricant	MIL-L-23699B

SECTION VII

DISCUSSION

The silicon nitride program was conducted in three tasks. Task I consisted of developing an analytical model of the high-speed bearing rig to predict the time to bearing seizure (loss of internal clearance) for the M-50 and the silicon nitride bearings. Task II was an oil shutoff test on an M-50 ball bearing. Task III was a repeat of Task II with a bearing containing silicon nitride balls.

Task I Analytical Model

A thermal model of the high-speed bearing rig was used to simulate conditions of oil starvation in both 35 mm bore high-speed bearings. Two different test conditions were used with the silicon nitride ball bearing. The first set of test conditions assumed a bearing heat generation based on the results of previous testing (Reference 1) which showed that the heat generation from silicon nitride balls was 89.5% of the value with M-50 balls. The second set of test conditions assumed a heat generation equal to the M-50 bearing. The theoretical criteria for bearing malfunction used in these analyses is the loss of internal running clearance. Transient temperatures from the analyses and the P&WA Bearing Analysis Deck were used to determine clearance loss vs time.

Use of the thermal model and the originally specified oil inlet temperature of 250°F resulted in a loss of internal clearance of both the M-50 and silicon nitride ball bearings in less than 5 sec. Based on the results of this study, the test program was changed to reduce the oil inlet temperature to 150°F.

Using the thermal model and reducing the oil inlet temperature to 150°F prior to oil shutoff, the predicted time to bearing seizure due to loss of internal clearance was 43 sec for the silicon nitride bearing and 25 sec for the M-50 bearing (Figure 5). In addition to the time until loss of internal clearance, two other points are worthy of mention on this curve. One, the lower heat generation of the silicon nitride bearing did not significantly improve survivability. Two, the major contributor to the improvement in survivability was the difference in thermal expansion of the two materials. Although both bearings have the same internal clearance when cold, at steady-state operating conditions the silicon nitride bearing has nearly twice the internal clearance of the M-50 bearing. If both bearings had been designed to have the same operating clearance (see Figure 6), the silicon nitride, because of its lower coefficient of expansion, would still provide a benefit (35% improvement) in survivability over the M-50 steel ball.

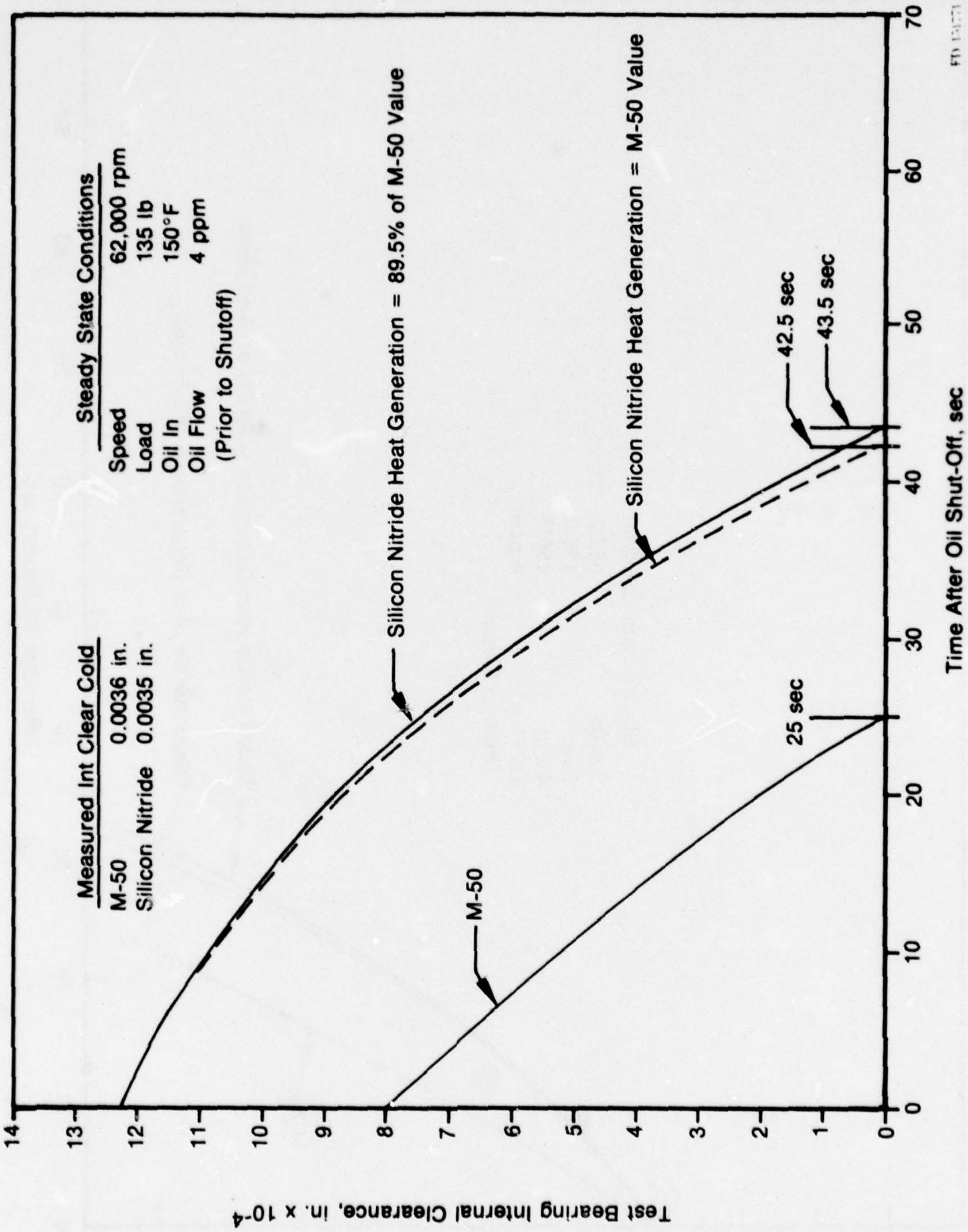

Figure 5. Analytical Prediction of Bearing Seizure After Oil Shutoff

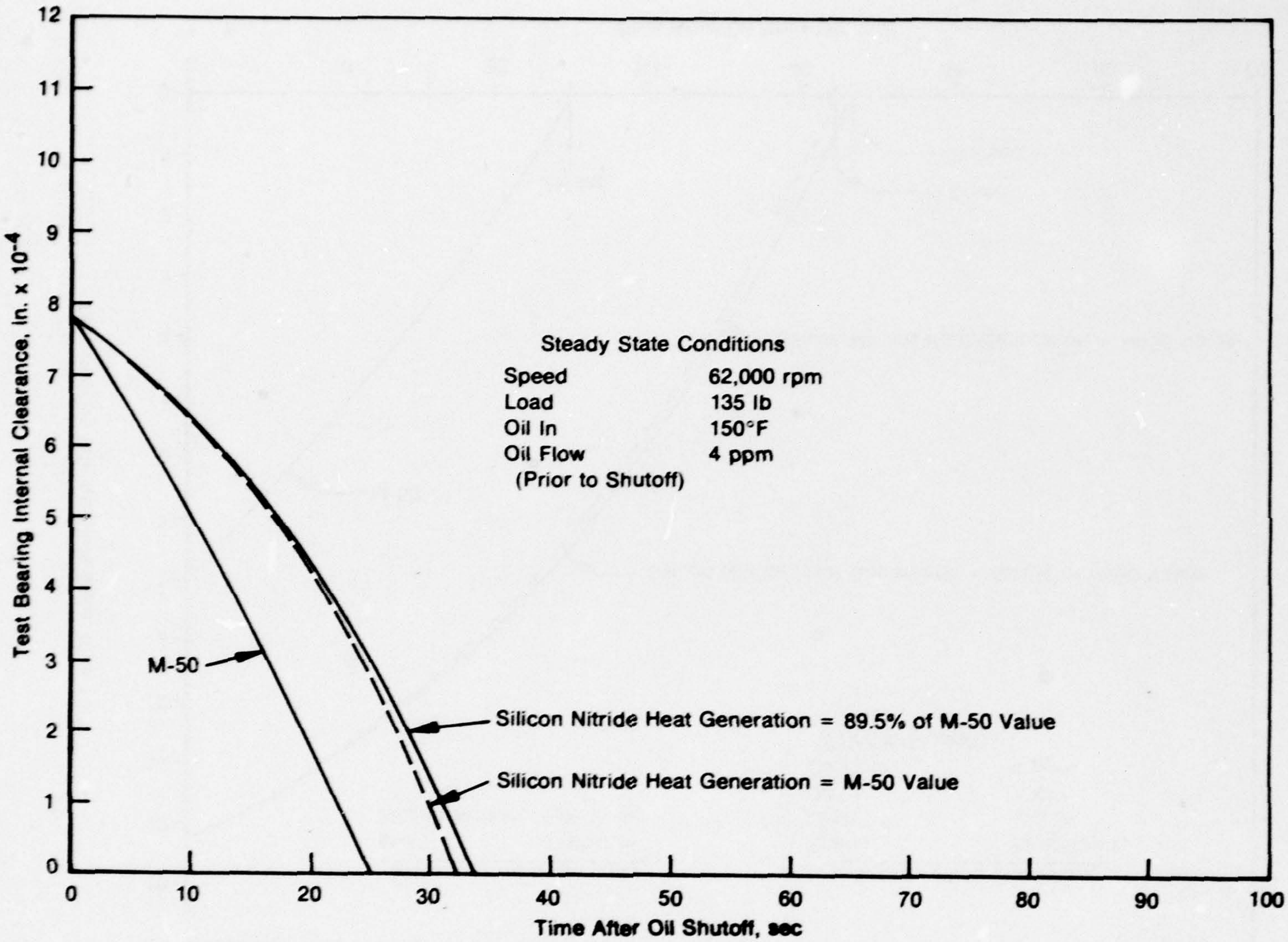

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Figure 6. Analytical Prediction of Bearing Seizure After Oil Shutoff Assuming Both Bearings Have the Same Internal Clearance at Steady-State

In addition to using the P&WA Bearing Analysis Deck, an attempt was made to use a computer program (SHABERTH) developed by SKF under contract to the Air Force (Reference 2) to analytically simulate the combined effects of bearing kinematics and thermal behavior of an oil-starved bearing in the high-speed bearing rig. Separate analyses were conducted for bearings with rolling elements of M-50 steel and silicon nitride. The analytical predictions showed that failure would occur faster for the M-50 bearing than with the silicon nitride, but the difference was slight.

A steady-state thermal analysis was undertaken using test data obtained in a previous test (Reference 1). The thermal response corresponded well with the test data. The M-50 or Si_3N_4 test steady-state temperature map was used for the initial conditions for the oil starvation runs. The results of the oil starvation analyses exhibited excessive heat generation and temperature rise for the starvation factors used (Reference 2), when compared to the current test data. Subsequent modifications to the model created convergence problems in the starvation region of interest.

Problems with the SHABERTH computer program were noted upon installation of the deck at P&WA, as well as in various variations in the model. It is recommended that further work in correlating this data with SHABERTH be done to reduce the convergence problems experienced.

Task II

The high-speed bearing rig was assembled with an M-50 slave and test bearing. An enlarged view of the test section showing internal instrumentation is shown in Figure 7. A 5-minute steady-state condition was established at the test conditions of 62,000 rpm and an oil inlet temperature of 150°F. The oil was shut off with a solenoid valve located in the test bearing oil supply line. Immediately after oil stoppage, the rig speed climbed to 72,000 rpm and the bearing outer race temperature increased at a rate of approximately 2.4°F per sec. After 45 sec, the rig speed dropped instantly from 72,000 to 30,000 rpm and all vibration meters showed maximum full scale readings. At this point the test was terminated by activating the steam abort system. The results of this test, as taken from the magnetic tape system, are shown in Figure 8. At the point the test was terminated, the bearing outer race temperature started to increase at a rate of 35°F per sec and reached a maximum of 425°F. The test rig was then removed from the test stand and disassembled for inspection.

Upon disassembly of the rig, severe distress of the M-50 test bearing was noticed. The inner race halves were welded together. In trying to pull one half of the inner race off the shaft, the other came with it (Figure 9). The balls exhibited severe spalling (Figure 10). (The dark spots on the photographs are shadows of adjacent balls.) The cage and outer race showed much metal transfer (Figures 11 and 12).

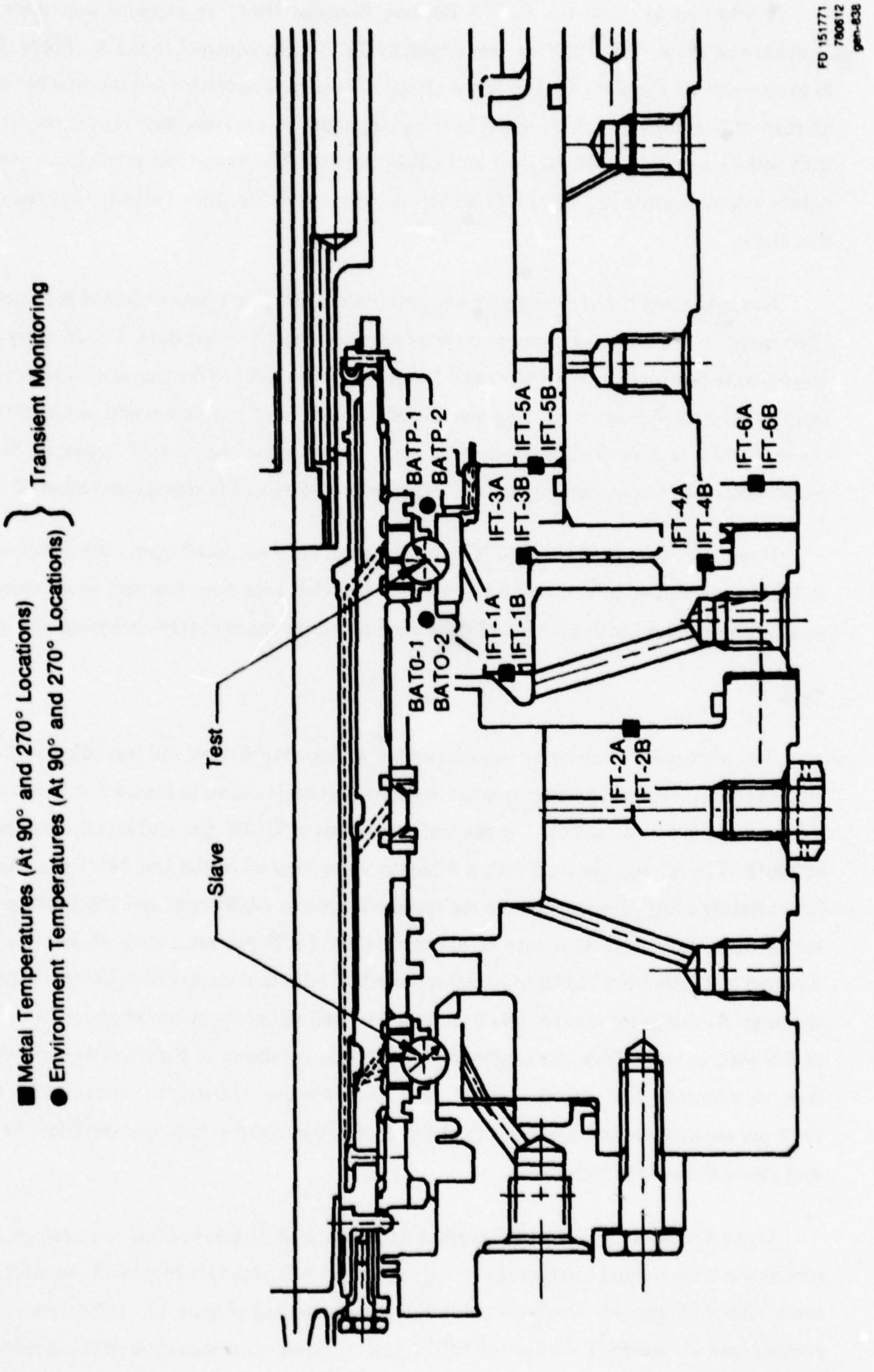

Figure 7. Temperatures Monitored During Shutoff Test

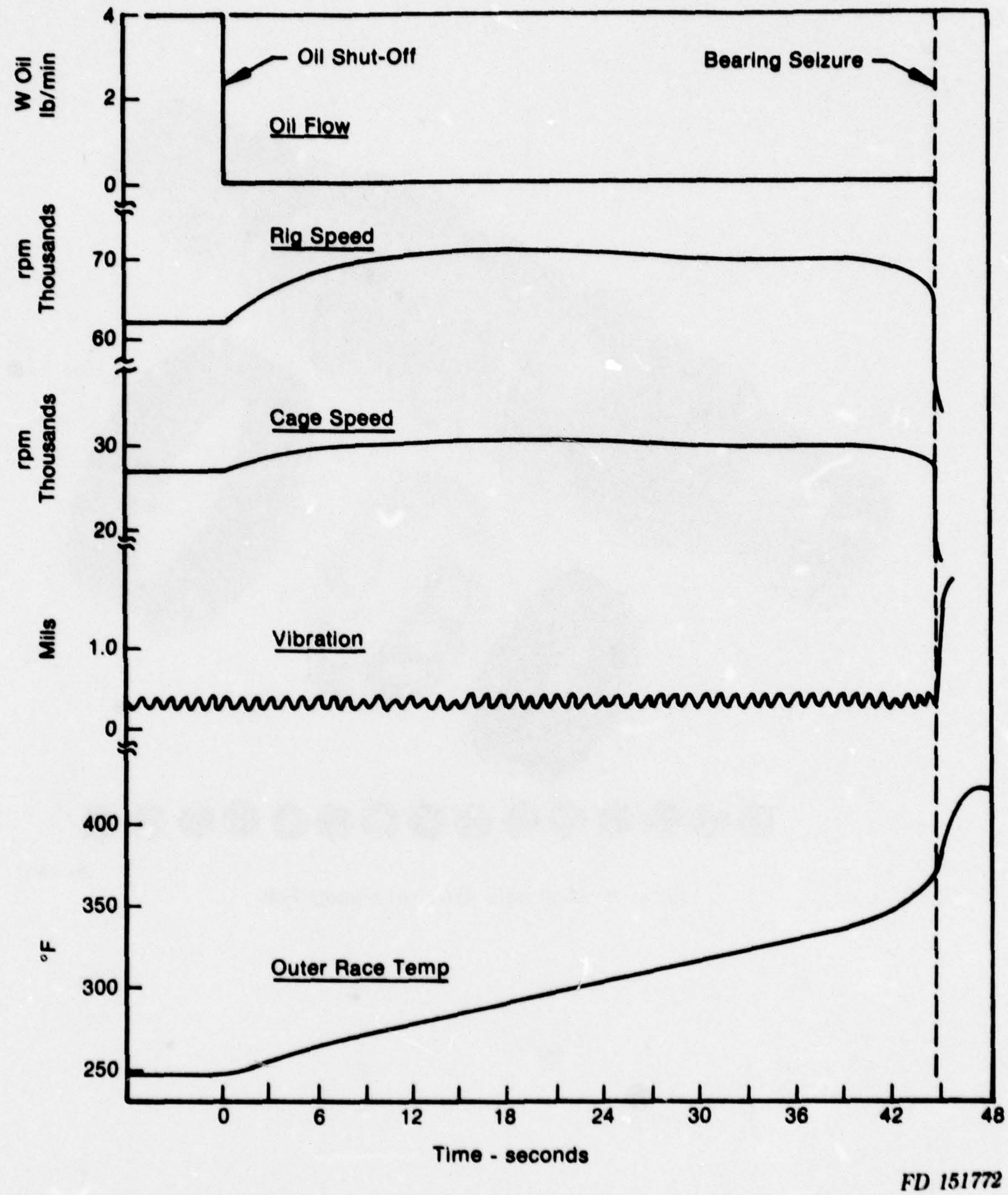

Figure 8. Oil Shutoff Test, M-50 Ball Bearing

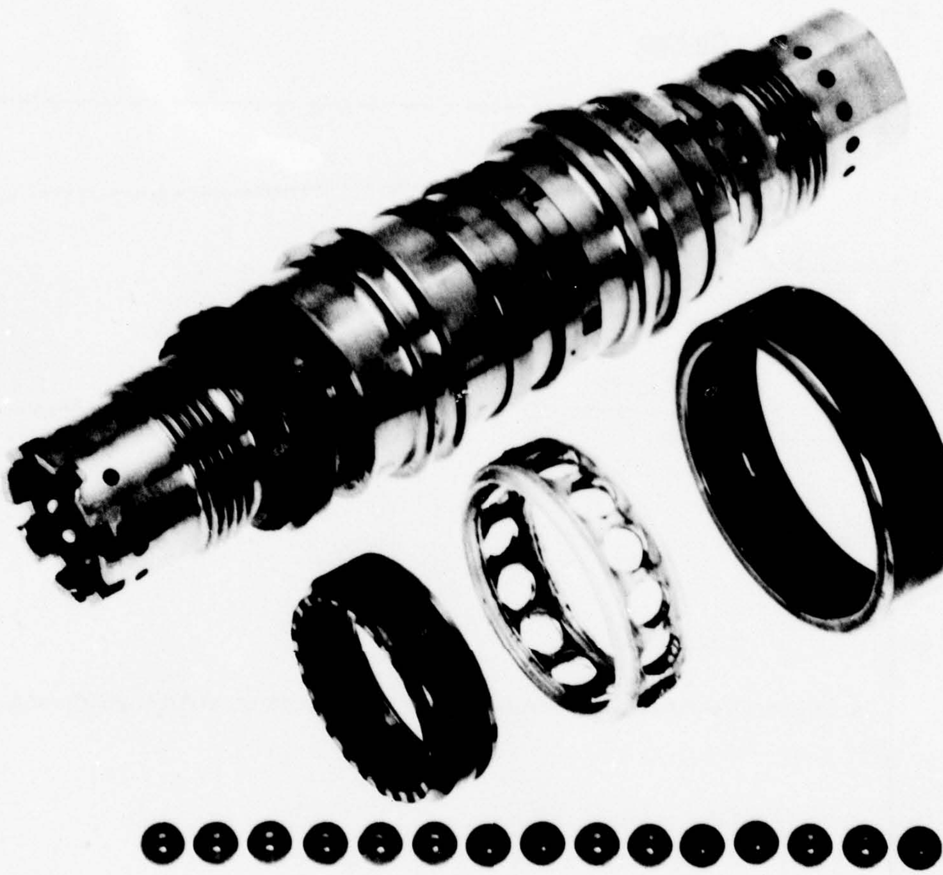

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Figure 9. M-50 Balls After Oil Shutoff Test

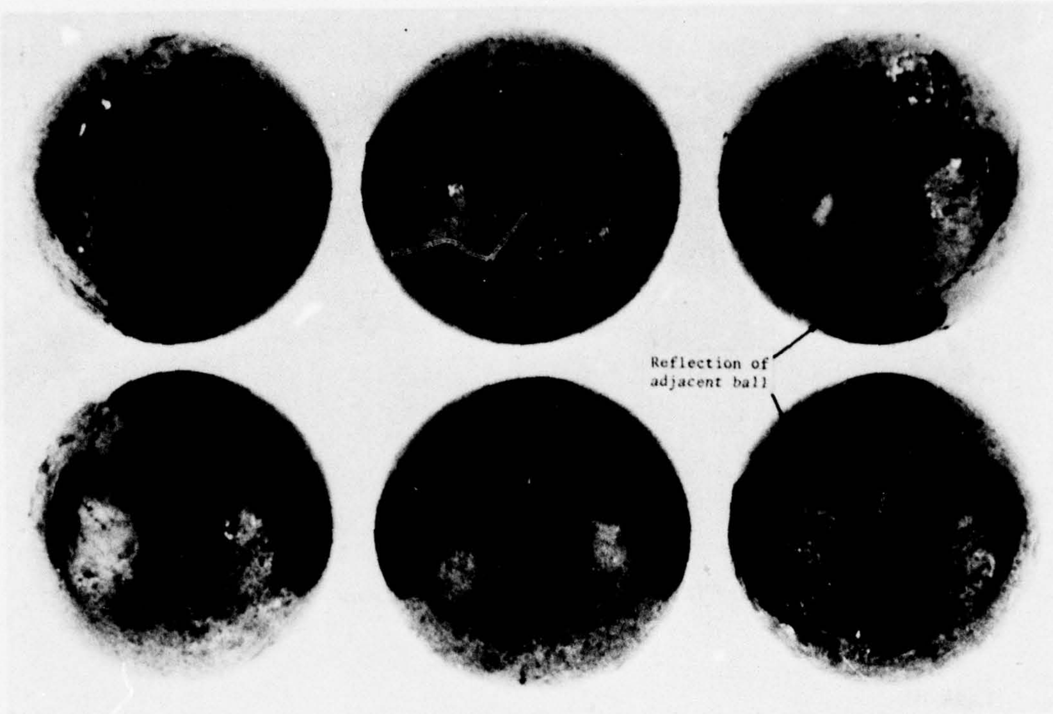

Figure 10. M-50 Balls After Oil Shutoff Test

Figure 11. Outer Race of M-50 Bearing After Oil Shutoff Test

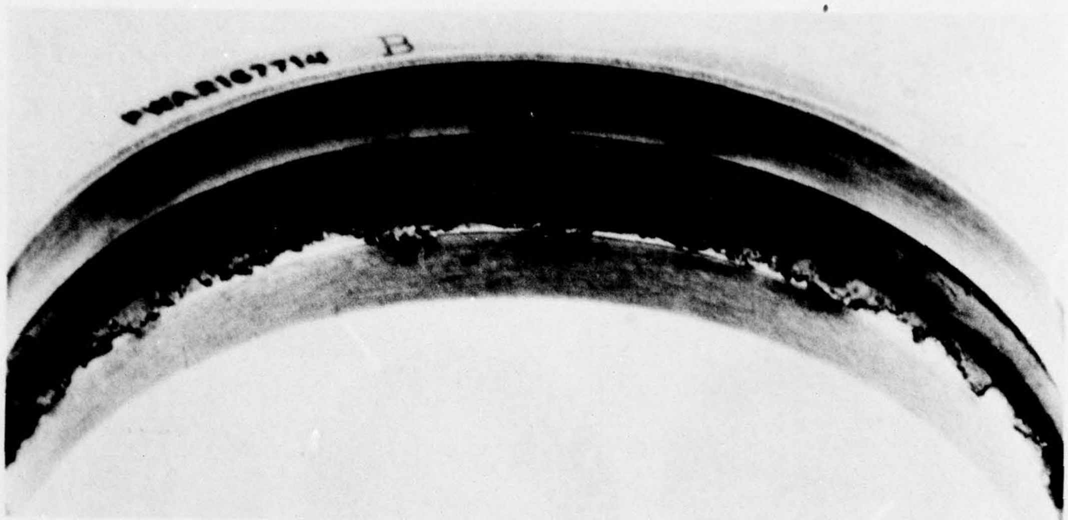

Figure 12. Outer Race of M-50 Bearing After Oil Shutoff Test

Task III

The high-speed bearing rig was reassembled with a silicon nitride ball bearing in the test position and returned to the test facility. A 5-min steady-state condition was established identical to the M-50 bearing prior to oil stoppage. After oil shutoff, the silicon nitride bearing produced similar speed and vibration indications as the M-50, but time to failure was increased to 90 sec. The data from the magnetic tape (Figure 13) show almost identical trends except that the outer race temperature increased at a rate of only 1.8 deg per sec to a maximum of 420°F.

Inspection of the bearing revealed that the silicon nitride bearing suffered much less distress than the M-50 bearing. Figures 14 through 18 show the conditions of the bearings.

The results of these tests show that the silicon nitride bearing survived twice as long as the M-50 bearing. Although the absolute time is different than the analytical model, this ratio compares favorably (1.74 vs 2.0).

A complete list of all data, and graphs of all transient data taken during Task II and Task III are in the Appendix.

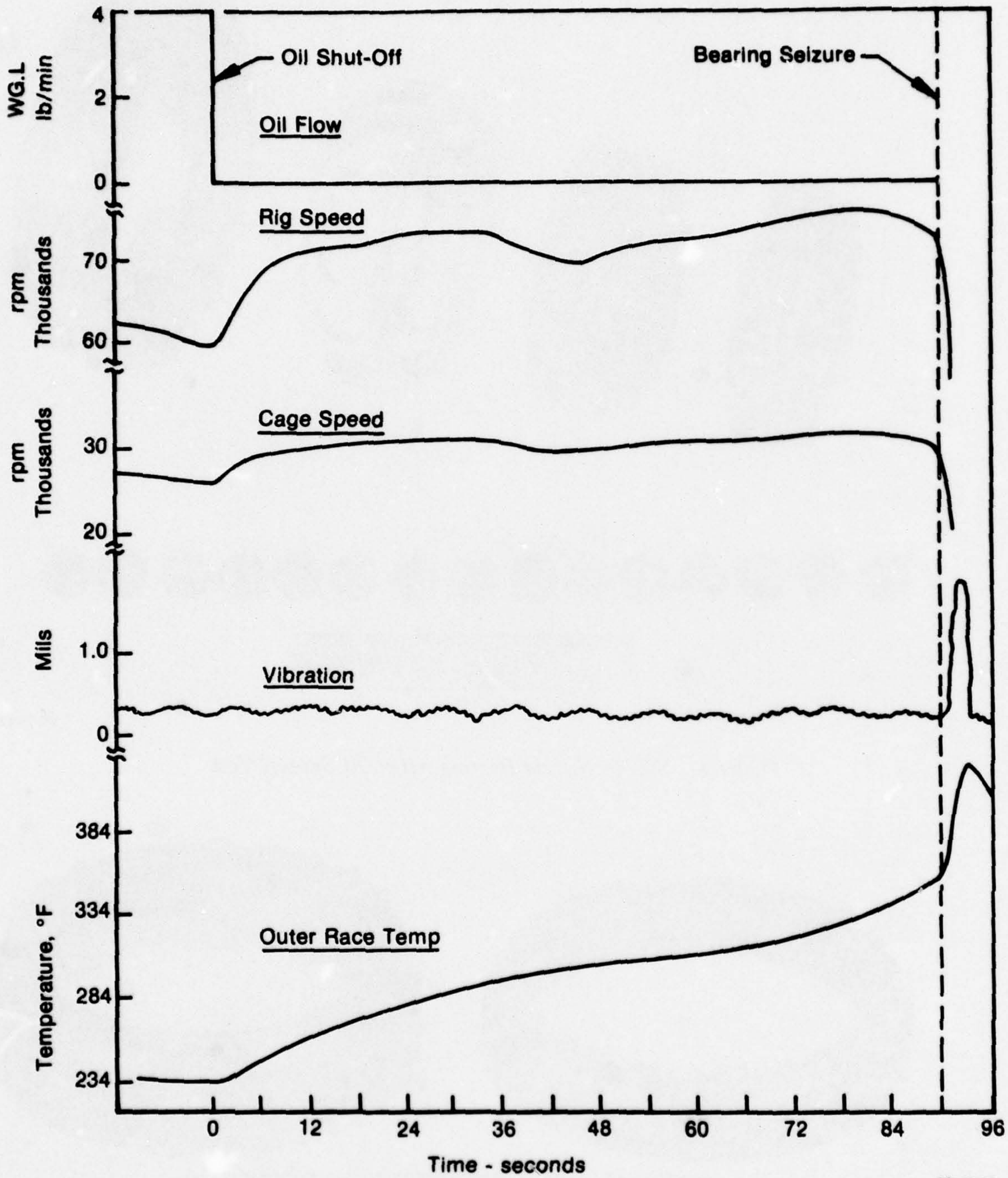

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Figure 13 Oil Shutoff Test Silicon Nitride Ball Bearing

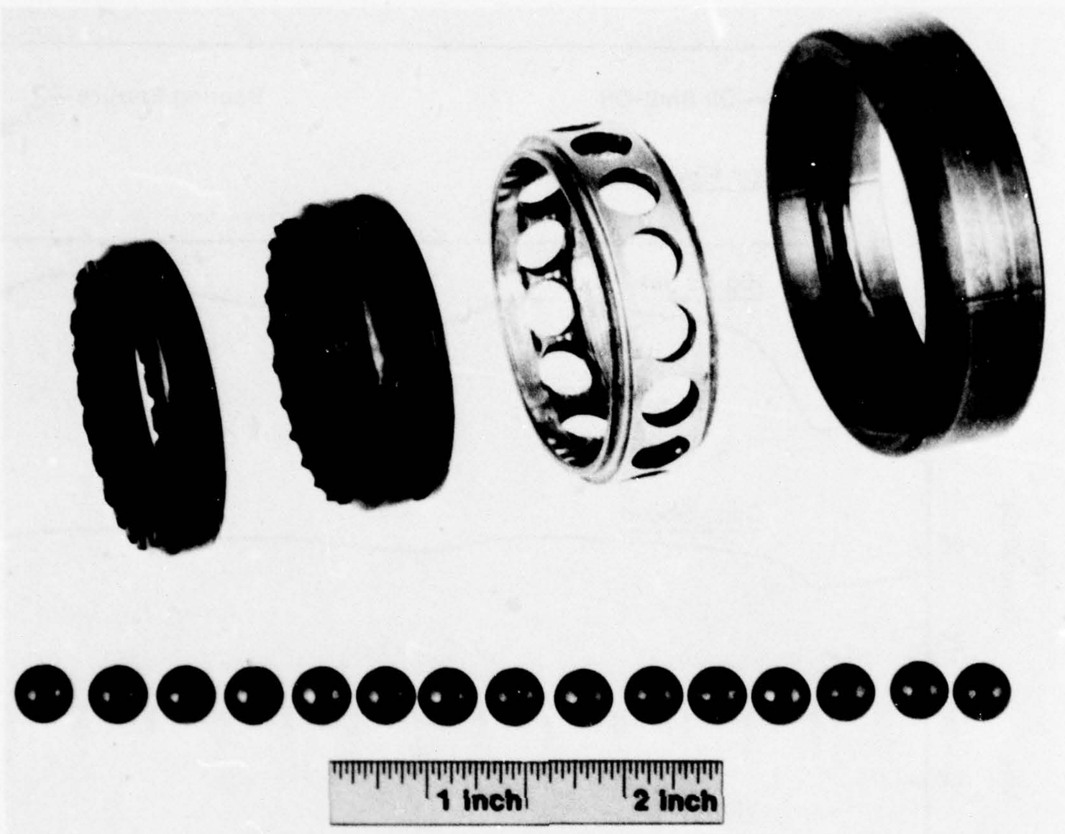

Figure 14. Silicon Nitride Bearing After Oil Shutoff Test

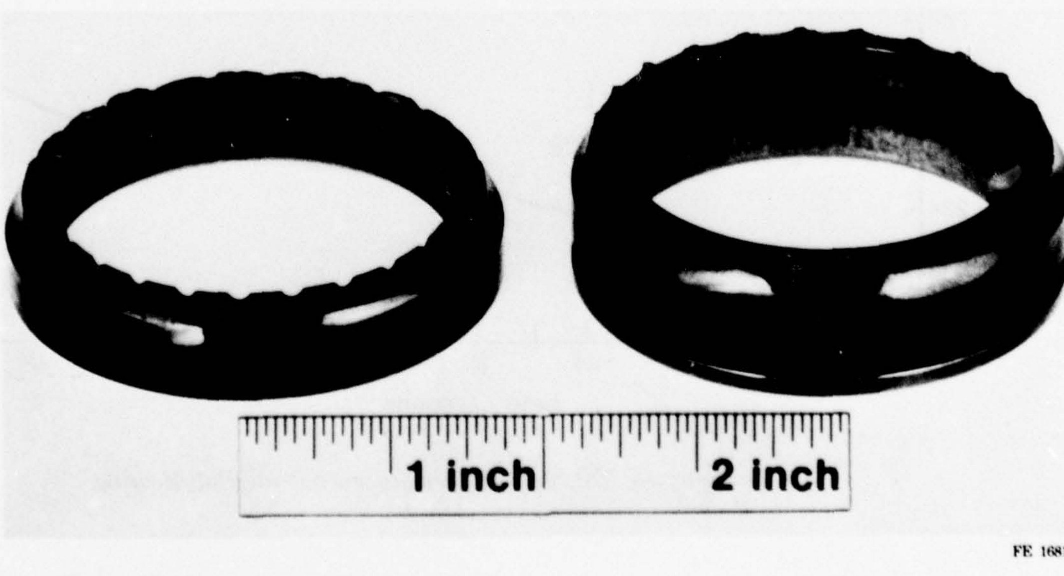

Figure 15. Inner Race of Silicon Nitride Bearing After Oil Shutoff Test

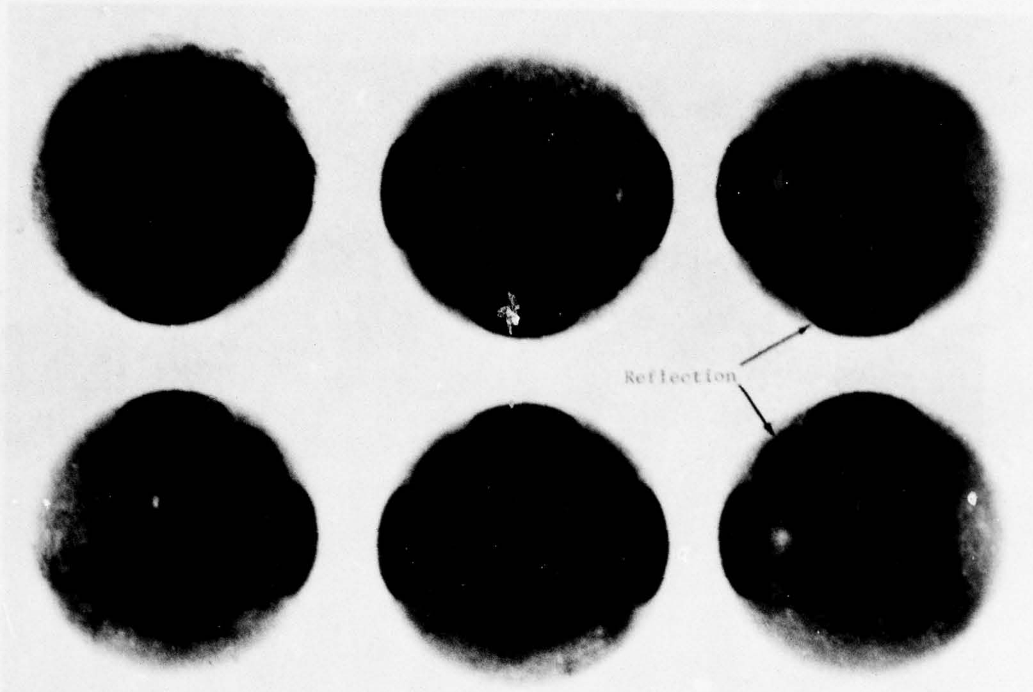

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Figure 16. Silicon Nitride Balls After Oil Shutoff Test

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Figure 17. Cage of Silicon Nitride Bearing After Oil Shutoff Test

Figure 18. Outer Race of Silicon Nitride Bearing After Oil Shutoff Test

SECTION VIII
REFERENCES

1. Report FR-6995 "Silicon Nitride Ball Bearing Demonstration Test," NAPTC Contract N00140-75-C-0382, J. M. Reddcliff, 10 May 1975.

2. AFAPL-TR-76-90 "Computer Program Operation Manual on SHABERTH: A Computer Program for the Analyses of the Steady State and Transient Thermal Performance on Shaft Bearing Systems."

APPENDIX

Original Date 13 Oct 1977
Revised Date 7 Mar 1978

INSTRUMENTATION SCHEDULE

Engine/Rig No. F-33836-7 Type High Speed Brg. Rig (RL10, JT11, etc.) Test of Oil Starvation-SiN BA11 Brg

Stand D-3 Build No. 6 Test Engineer J. Mohn

Work Order No. ______ Run Date 3 Apr 1978 Alt Test Engineer B. Grace

Item Description	Header	Range	Accuracy	Environment	TC Type	Recording and Readout Required: Gage	D DR	O-Graph	Meter	Strip Charts	Remarks
Rig Temperatures											
Test Brg. No.1 Outer Race Temp.	BRT1-1	Amb-1000°F	±5°F	Oil	C/A				Doric		
Test Brg. No.1 Outer Race Temp.	BRT1-2	Amb-1000°F	±5°F	Oil	C/A				Doric		
Test Brg. No.1 Outer Race Temp.	BRT1-3	Amb-1000°F	±5°F	Oil	C/A				Doric		
Test Brg. No.1 Outer Race Temp.	BRT1-4	Amb-1000°F	±5°F	Oil	C/A				Doric		
Test Brg. No.1 Oil Sump Temp.	BOST1-1	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Test Brg. No.1 Oil Sump Temp.	BOST1-2	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Test Brg. No.1 Scavenge Temp.	BOOT1	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Test Brg. No.1 Oil Supply Temp.	BOIT1	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Test Brg. No.2 Outer Race Temp.	BRT2-1	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		Monitored Continuously
Test Brg. No.2 Outer Race Temp.	BRT2-2	Amb-1000°F	±5°F	Oil	C/A				Doric		
Test Brg. No.2 Outer Race Temp.	BRT2-3	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Test Brg. No.2 Outer Race Temp.	BRT2-4	Amb-1000°F	±5°F	Oil	C/A				Doric		
Test Brg. No.2 Oil Sump Temp.	BOST2-1	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		Monitored Continuously
Test Brg. No.2 Oil Sump Temp.	BOST2-2	Amb-1000°F	±5°F	Oil	C/A				Doric		
Test Brg. No.2 Scavenge Temp.	BOOT2	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Test Brg. No.2 Oil Supply Temp.	BOIT2	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Test Brg. No.2 Air Temp. Puller Gr've	BATP-1	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Test Brg. No.2 Air Temp. Puller Gr've	BATP-2	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Test Brg. No.2 Air Temp. Oil Groove	BATO-1	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Test Brg. No.2 Air Temp. Oil Groove	BATO-2	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Interface Temp. 1A	IFT-1A	Amb-1000°F	±5°F	Oil	C/A				Doric		
Interface Temp. 1B	IFT-1B	Amb-1000°F	±5°F	Oil	C/A						
Interface Temp. 2A	IFT-2A	Amb-1000°F	±5°F	Oil	C/A				Doric		
Interface Temp. 2B	IFT-2B	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Interface Temp. 3A	IFT-3A	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Interface Temp. 3B	IFT-3B	Amb-1000°F	±5°F	Oil	C/A				Doric		
Interface Temp. 4A	IFT-4A	Amb-1000°F	±5°F	Oil	C/A				Doric		
Interface Temp. 4B	IFT-4B	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Interface Temp. 5A	IFT-5A	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Interface Temp. 5B	IFT-5B	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Interface Temp. 6A	IFT-6A	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Interface Temp. 6B	IFT-6B	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Flex Plate Temp.	FPT-1	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Flex Plate Temp.	FPT-2	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Oil Tank Temp.	OTT	Amb-1000°F	±5°F	Oil	C/A		Mag Tape		Doric		
Middle Brg. Compart. Scav. Temp.	MBOOT	Amb-1000°F	±5°F	Oil	C/A				Doric		

INSTRUMENTATION SCHEDULE (Continued)

Item Description	Header	Range	Accuracy	Environment	TC Type	Recording and Readout Required: Gage	D DR	O-Graph	Meter	Strip Charts	Remarks
Rig Oil Flows											
Test Brg. No.1 Oil Flow	BOF1	1-10 ppm					Mag Tape		Counter		S/N 14C15557
Test Brg. No.2 Oil Flow	BOF2	1-10 ppm							Counter		S/N 14C15697
Rig Pressures											
Axial Load Press.	ALP	0-100 psig				G3					
Brg. No.1 Oil Supply Press.	BOSP1	0-100 psig				G1					
Brg. No.1 Oil Sump Press.	BSP1	±15 psig				G7					
Brg. No.2 Oil Supply Press.	BOSP2	0-100 psig				G2					
Brg. No.2 Oil Sump Press.	BSP2	±15 psig				G8					
Rig Oil Supply Press.	ROSP	0-100 psig				G6					
Rig Vibrations											
Rig Horz. Vibs Brg. No.2	RHV1	0-10 mil				Mag Tape			X		
Rig Horz. Vibs Brg. No.1	RHV2	0-10 mil							X		
Rig Vert. Vibs Brg. No.2	RVV1	0-10 mil				Mag Tape			X		
Rig Vert. Vibs Brg. No.1	RVV2	0-10 mil							X		
Rig Speeds											
Shaft Speed	N2	0-100,000 rpm				Mag Tape			Counter		12 Lugs - 12 Pulses/Revolution
Brg. No. 2 Cage Speed	B2CS	0-45,000 rpm				Mag Tape			Counter		15 Pulses/Revolution
Turbine Temperatures											
Turb. Brg. No.1 Outer Race Temp.	TBRT1-1	Amb-1000°F	±5°F	Oil	C/A				Doric		
Turb. Brg. No.1 Outer Race Temp.	TBRT1-2	Amb-1000°F	±5°F	Oil	C/A				Doric		
Turb. Brg. No.2 Outer Race Temp.	TBRT2-1	Amb-1000°F	±5°F	Oil	C/A				Doric		
Turb. Brg. No.2 Outer Race Temp.	TBRT2-2	Amb-1000°F	±5°F	Oil	C/A				Doric		
Turb. Oil Inlet Temp. No.1	TOIT-1	Amb-1000°F	±5°F	Oil	C/A				Doric		
Turb. Oil Inlet Temp. No.2	TOIT-2	Amb-1000°F	±5°F	Oil	C/A				Doric		
Turb. Oil Scavenge Temp. No.1	TOOT1	Amb-1000°F	±5°F	Oil	C/A				Doric		
Turb. Oil Scavenge Temp. No.2	TOOT2	Amb-1000°F	±5°F	Oil	C/A				Doric		
Steam Inlet Temp.	SIT	Amb-1000°F	±5°F	Steam	C/A				Doric		
Steam Exhaust Temp.	SOT	Amb-1000°F	±5°F	Steam	C/A				Doric		
Turbine Pressures											
Steam Inlet Press.	SIP	0-100 psig				G-12					
Steam Exit Press.	SOP	0-30 psig				G-13					
Oil Inlet Press.	TOIP	0-30 psig				G-9					
Turb. Seal Dam Air No.1	TSDA1	0-30 psig				G-10					
Turb. Seal Dam Air No.2	TSDA2	0-30 psig				G-11					
Turbine Oil Flow	TOF	1-10 ppm							Counter		S/N 14C15373
Turbine Speed	TRPM	0-100,000 rpm							Counter		6 Lugs - 6 Pulses/Revolution
Turbine Horz. Vibs	THV	0-10 mil							X		
Turbine Vert. Vibs	TVV	0-10 mil							X		

LOG OF ENGINE TEST
EXPERIMENTAL TEST DEPARTMENT

Sheet No.: A-
Date: 2-23-78
Engineer: J. Mohn

Stand D-3 Engine/Rig F33836 Build 6 Project 110X-20-200-XX

Type of Test Oil Starvation — M-50 Steel Ball Bearing

Time a.m. p.m.	Total Hours	Rig Temperatures BRT1-3	BOST1-1	BOST1-2	BOIT1	BRT2-1	BRT2-2	BRT2-3	BRT2-4	BOST2-1	BOST2-2	BOIT2-1	BOOT2-1		BATP-1	BATP-2	BATO-1
Position No.		3	5	6	7	8	9	10	11	12	13	14	16	17	18	19	20
1230		244	251	251	148	249	249	248	250	244		147	238	238	243	243	238
1404		242	252	252	153	251	252	251	252	244		152	240	240	245	246	241
1410		239	249	250	150	247	247	247	249	242		149	237	237	241	242	237

LOG OF ENGINE TEST
EXPERIMENTAL TEST DEPARTMENT

Sheet No.: B-
Date: 2-23-78
Engineer: J. Mohn

Stand D-3 Engine/Rig F33836 Build 6 Project 110X-20-200-XX

Type of Test Oil Starvation — M-50 Steel Ball Bearing

Time a.m. p.m.	Total Hours	Rig Temperatures BATO-2	IFT-2A	IFT-2B			IFT-4A	IFT-4B	IFT-5A	IFT-5B	IFT-6A	IFT-6B	FPT-1	FPT-2	OTT	BOOT1-1	BOOT1-2
Position No.		21	24	25	26	27	29	30	31	32	33	34	35	36	37	38	39
1230		237	202	203	185	182	185	179	242	243	191	199			161	245	222
1404		241	200	200	187	184	184	178	246	244	188	197			167	246	221
1410		237	198	198	185	183	183	177	241	241	188	196			164	243	219

LOG OF ENGINE TEST
EXPERIMENTAL TEST DEPARTMENT

Sheet No.: C-
Date: 2-23-78
Engineer: J. Mohn

Stand D-3 Engine/Rig F33836 Build 6 Project 110X-20-200-XX

Type of Test Oil Starvation — M-50 Steel Ball Bearing

Time a.m. p.m.	Total Hours	Rig Temperatures TBRT1-1	TBRT1-2	TBRT2-1	TBRT2-2	TOIT-1	TOIT-2	TOOT-1	TOOT-2	SIT	SOT	Rig Oil Flow BOF2	BOF1	Turb Flow TOF	Speed T-RPM	N_1	B2CS1
Position No.		40	41	42	43	44	45	46	47	48	49	TOP4	TOP3	TOP2	TOP1	BOT2	BOT1
1230		214	214	202	203	148	147	184	185	226	211	4.0	3.8	3.9	62,900	62,800	27,600
1404		217	216	203	204	152	150	—	183	236	212	4.0	3.9	4.0	62,600	62,600	28,400
1410		215	215	203	203	151	150	—	185	228	211	4.0	4.0	4.0	62,100	62,100	27,300

LOG OF ENGINE TEST
EXPERIMENTAL TEST DEPARTMENT

Sheet No.: D
Date: 2-23-78
Engineer: J. Mohn

Stand D-3 Engine/Rig F33836 Build 6 Project 110X-20-200-XX

Type of Test Oil Starvation — M-50 Steel Ball Bearing

Time a.m. p.m.	Total Hours	Rig Pressures RALP	BOSP-1	BOSP-2	BSP-1	BSP-2	Turbine Pressure SIP	SEP	TOID-1	TSDA-1	TSDA-2	Rig Vibrations RHV-1	RHV-2	RVV-1	RVV-2	Turbine Vib THV	TVV
Position No.		G3	G1	G2	G7	G8	G12	G13	G9	G10	G11						
1230		37	11.5	29	0	0		16	6	8	4	0	0	0	0	.01	.01
1404		38	11.5	20.5	0	0		21.5	6	8	4	0	0	0	0	.02	0
1410		38	11.5	29.5	0	0		15	7	8	4	0	0	0	0	.03	0

LOG OF COMPONENT TEST
EXPERIMENTAL TEST DEPARTMENT

Sheet No. A-2
Date 05-07-78
Engineer J. Mohn
Operators Blake
Stand No. 403

Unit Name High Speed Bearing Baro Pressure ______ in. HG ______ °F
Serial No. 33836-7 Fluid Type Mobil Jet II (MIL-L-23699)
Part No. ______ Sp Gravity ______ at ______ °F
Type Test Oil Starvation SiN, Ball Brg. S/N 10 Std Gage Cal Date ______
Flowmeter S/N ______ Size ______ Range ______ Preset ______ Cal Date ______

Test Limits Time	Total Hours	Speeds - rpm: Turbine Speed Top	N_1 BOT4	B2CS 1 5	Flows — ppm: BOF 1 BOT 1	BOF 2 2	TOF 3	Pressures — Psig: BOSP 1 G1	BOSP 2 2	RALP 3	BSP 1 7	BSP 2 8	TOIP 9	TSDA 1 10	TSDA 2 11	SIP 13
0930	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1005		Start														
1015		4,900	4,900	2,400	4.0	4.0	3.9	8	32	37	0	0	8	6	3.5	2
1308		63,400	61,000	25,600	4.0	4.1	4.0	7.5	31.5	37	0	0	7	8	8	16
1318		No. 2 Bearing Oil Off														
1319.5		Abort		1.32 (RT)												
1320		Stop														

LOG OF COMPONENT TEST
EXPERIMENTAL TEST DEPARTMENT

Sheet No. B-2
Date 05-07-78
Engineer J. Mohn
Operators Blake
Stand No. 403

Unit Name High Speed Bearing Baro Pressure ______ in. HG ______ °F
Serial No. 33836-7 Fluid Type Mobil Jet II (MIL-L-23699)
Part No. ______ Sp Gravity ______ at ______ °F
Type Test Oil Starvation SiN, Ball Brg. S/N 10 Std Gage Cal Date ______
Flowmeter S/N ______ Size ______ Range ______ Preset ______ Cal Date ______

Test Limits Time	Total Hours	Tempera: BRT 1-1 A-1	BRT 1-2 2	BRT 1-3 3	BRT 1-4 4	BOST 1-1 5	BOST 1-2 6	BOIT 1 7	BRT 2-1 8	BRT 2-2 9	BRT 2-3 10	BRT 2-4 11	BOOT 2-1 12	BOOT 2-2 13	BOIT 2 14	BOOT 1 15	BOOT 2 16	MBOOT 17	BATP 1 18	BATP 2 19	BATO 1 20
0930	2	78	78	78	78	78	78	80	77	78	78	78	77	78	78	79	79	79	78	78	78
1005								Start													
1015		129	129	131	131	132	134	144	138	138	137	138	135	136	142	140	139	138	134	134	135
1308		247	248	247	247	252	245	151	244	243	244	246	232	233	152	247	243	221.	242	242	235
1318								No. 2 Bearing Oil Off													
1319.5								Abort													

LOG OF COMPONENT TEST
EXPERIMENTAL TEST DEPARTMENT

Sheet No. C-2
Date 05-07-78
Engineer J. Mohn
Operators Blake
Stand No. 403

Unit Name High Speed Bearing Baro Pressure ____ HG ____ °F
Serial No. 33836-7 Fluid Type Mobil Jet II (MIL-L-23699)
Part No. ____ Sp Gravity ____ at ____ °F
Type Test Oil Starvation SiN, Ball Brg. S/N 10 Std Gage Cal Date ____
Flowmeter S/N ____ Size ____ Range ____ Preset ____ Cal Date ____

Test Limits

Time	Total Hours	BATO 2 A-21	IFT 2A 24	IFT 2B 25	IFT 4A B-29	IFT 4B 30	IFT 5A 31	IFT 5B 32	HGT 02 33	IFT 6B 34	FPT 1 35	HCT 01 36	OTT 37
		Temperatures — °F											
[illegible]	2	78	78	78	78	76	78	78	78	78	77	78	79
1005								Start					
1015		139	114	114	115	117	138	140	141	114	125	135	141
1308		233	203	204	187	178	239	2[illegible]7	235	199	179	24[illegible]	102
1318							No. 2 Bearing Oil Off						
1319.5								Abort					

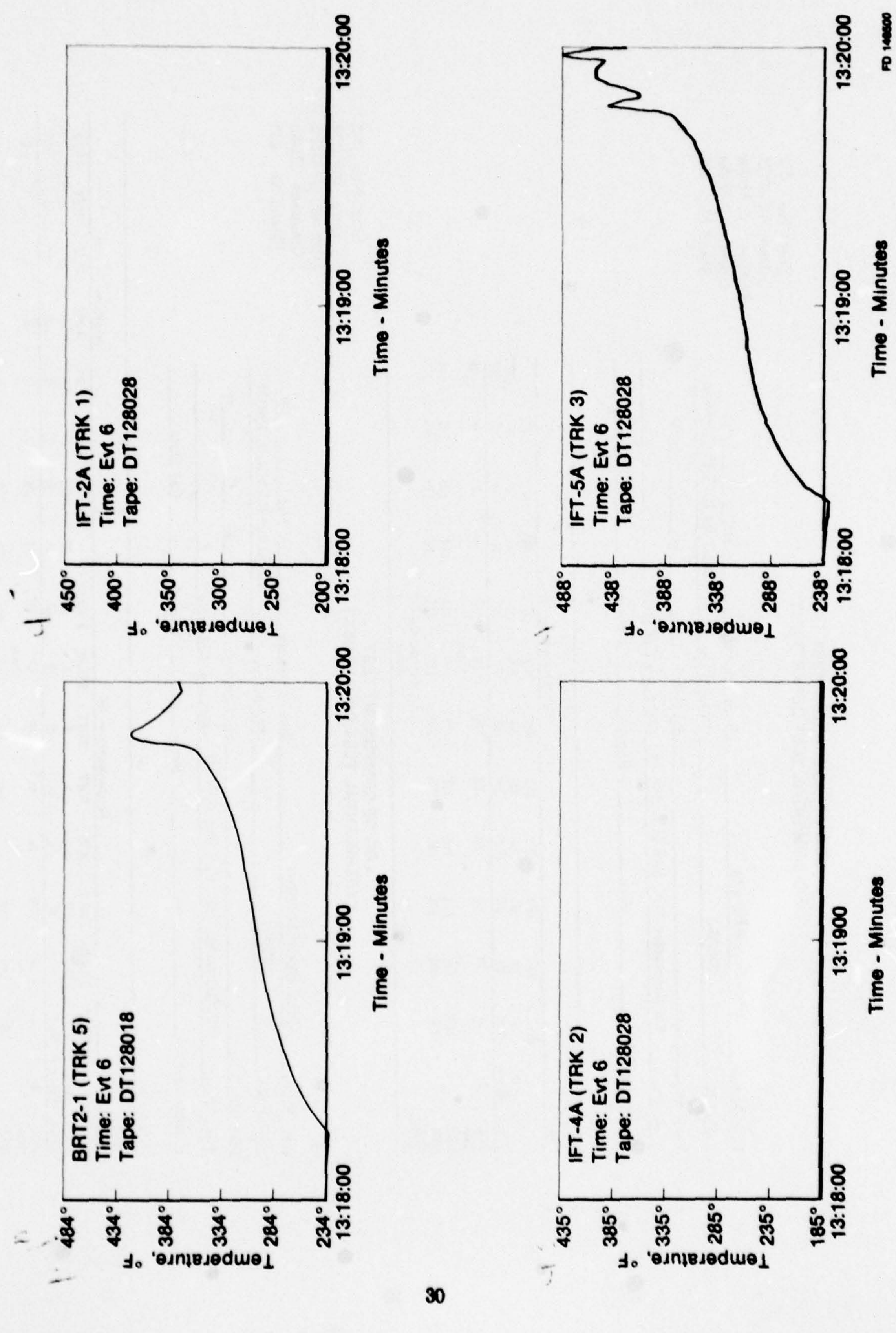
LOG OF COMPONENT TEST
EXPERIMENTAL TEST DEPARTMENT

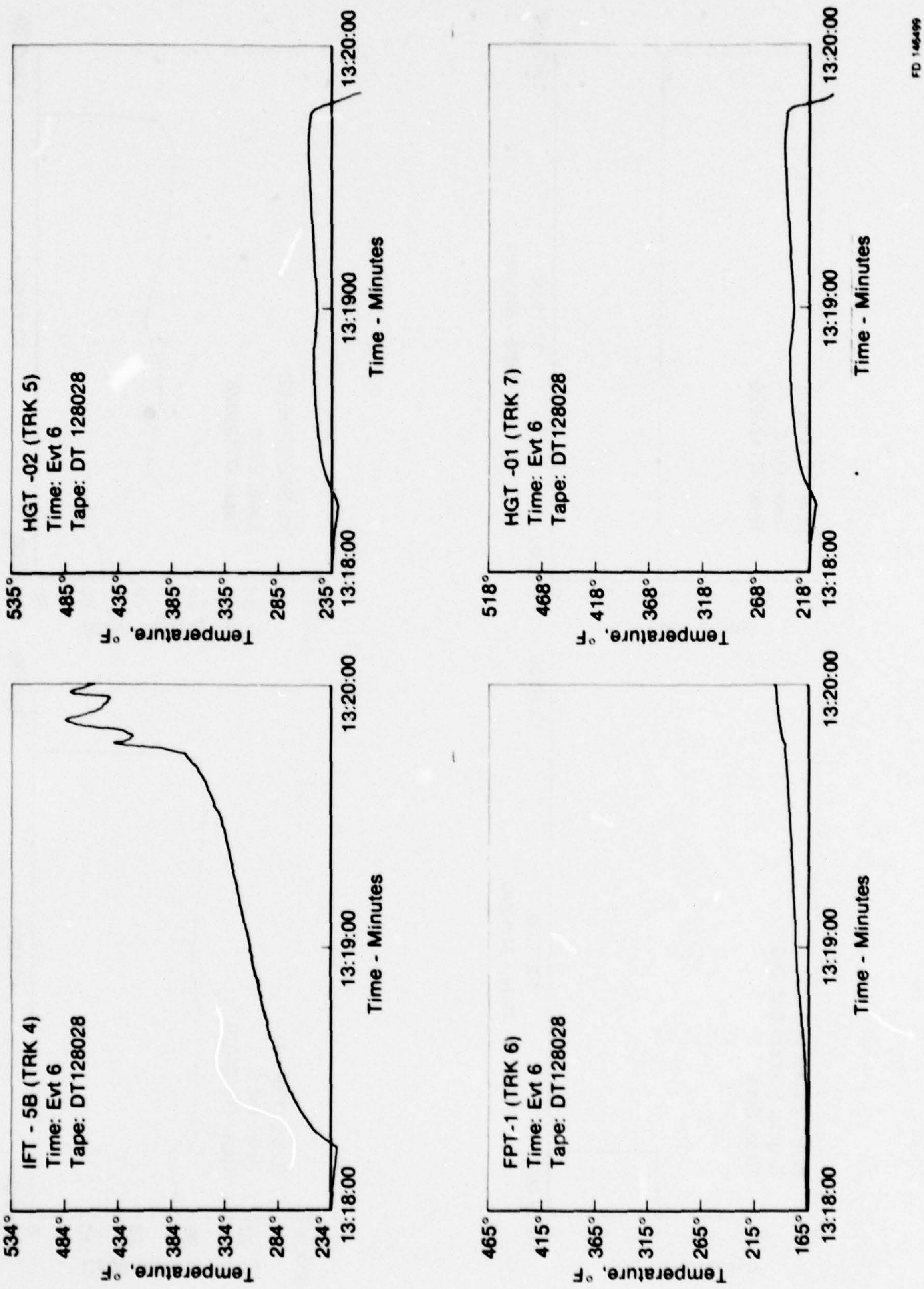
Sheet No. D-2
Date 05-07-78
Engineer J. Mohn
Operators Blake
Stand No. 403

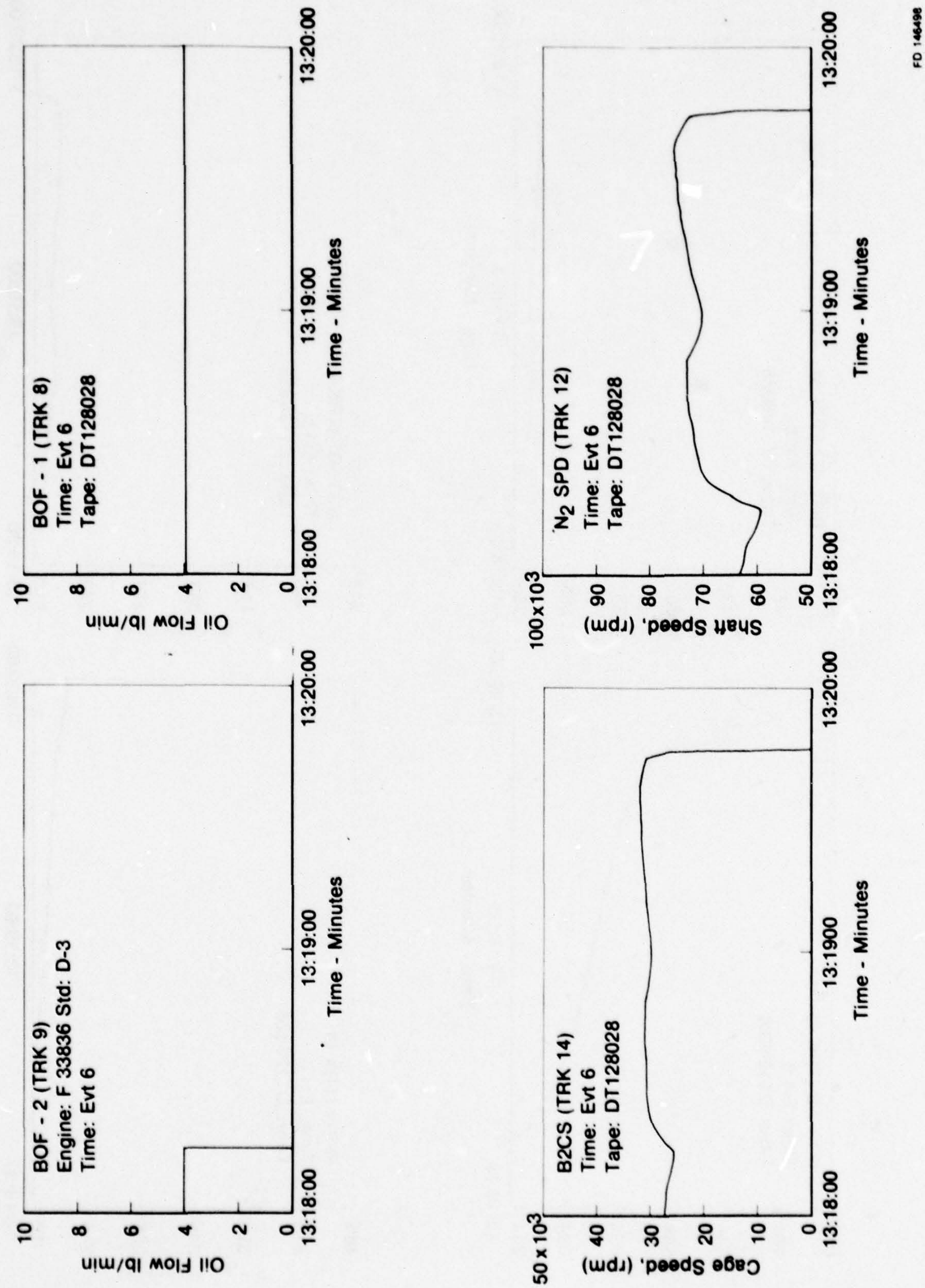
Unit Name High Speed Bearing Baro Pressure ____ in. HG ____ °F
Serial No. 33836-7 Fluid Type Mobil Jet II (MIL-L-23699)
Part No. ____ Sp Gravity ____ at ____ °F
Type Test Oil Starvation SiN, Ball Brg. S/N 10 Std Gage Cal Date ____
Flowmeter S/N ____ Size ____ Range ____ Preset ____ Cal Date ____

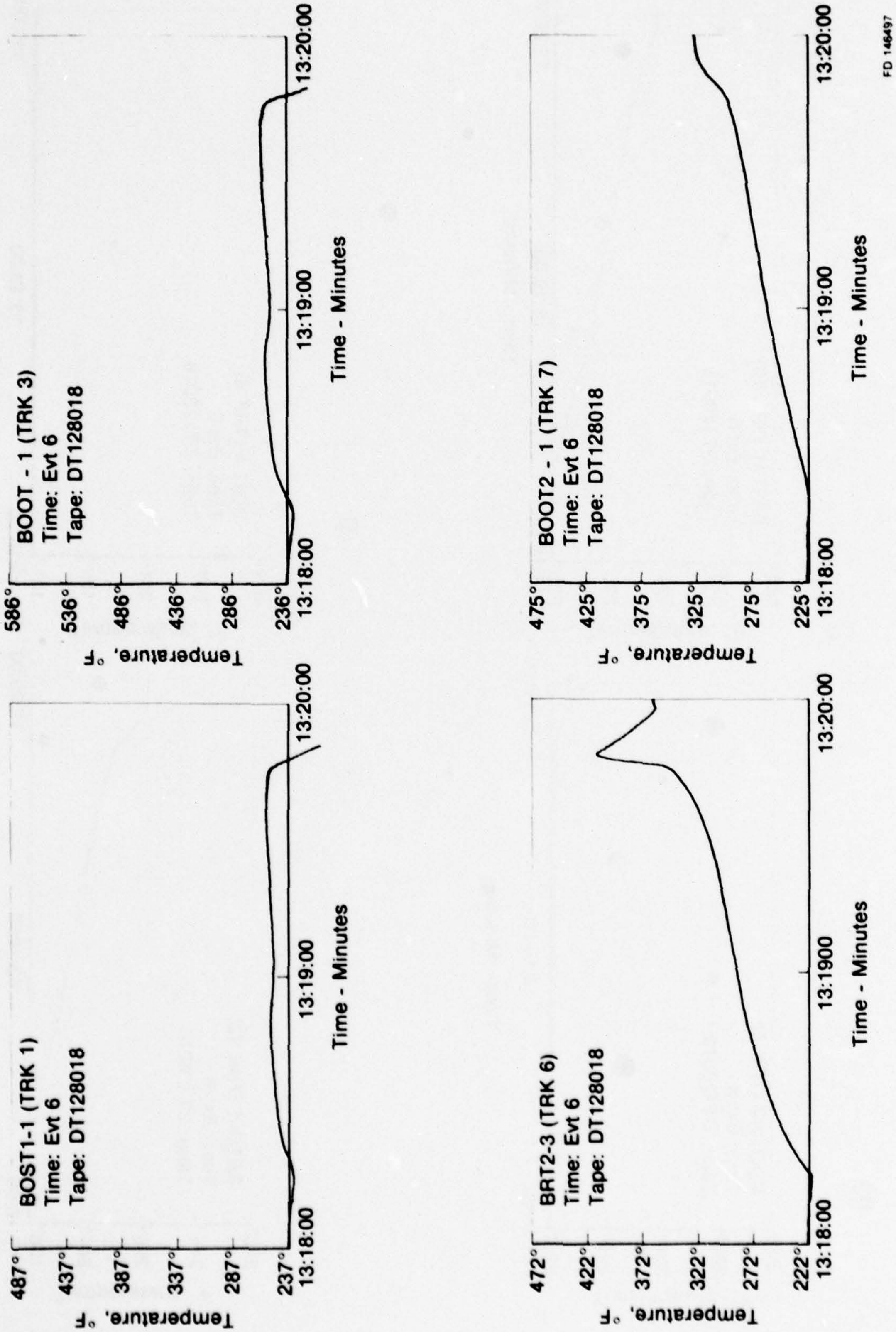
Test Limits

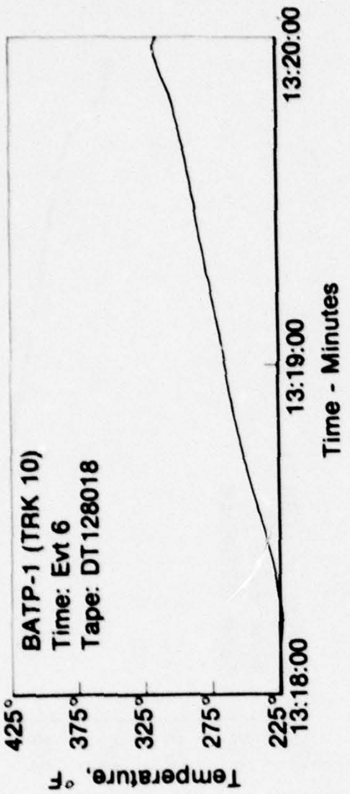
Time	Total Hours	TBRT 1-1 B-40	TBRT 1-2 41	TBRT 2-1 42	TBRT 2-2 43	TOIT 1 44	TOIT 2 45	TOOT 1 46	TOOT 2 47	SIT 48	SOT 49	VRV 1 1	VRV 2 2	VRH 1 3	VRH 2 4	VTV 1 5	VTH 1 6
		Temperatures — °F										Vibrations — mils					
[illegible]	2	78	78	78	78	81	81	80	79	79	79	0	0	0	0	0	0
1005								Start									
1015		166	165	156	157	142	141	156	147	202	212	0	0	0	0	0.05	0
1308		217	218	206	206	150	150	—	191	237	213	0	0	0	0	0	0/0.2
1318							No. 2 Bearing Oil Off										
1319.5								Abort									
1325								Stop									

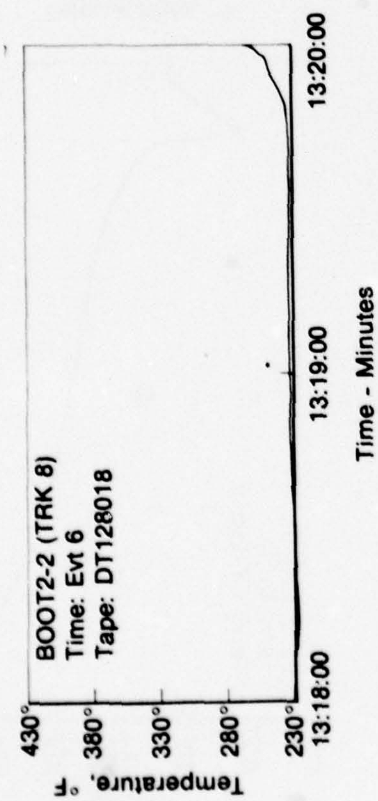

BRT2-1 (TRK 5)
Time: Evt 6
Tape: DT128018
Temperature, °F
484°
434°
384°
334°
284°
234°
13:18:00
13:19:00
13:20:00
Time - Minutes
IFT-2A (TRK 1)
Time: Evt 6
Tape: DT128028
450°
400°
350°
300°
250°
200°
IFT-4A (TRK 2)
Time: Evt 6
Tape: DT128028
435°
385°
335°
285°
235°
185°
13:1900
IFT-5A (TRK 3)
Time: Evt 6
Tape: DT128028
488°
438°
388°
338°
288°
238°

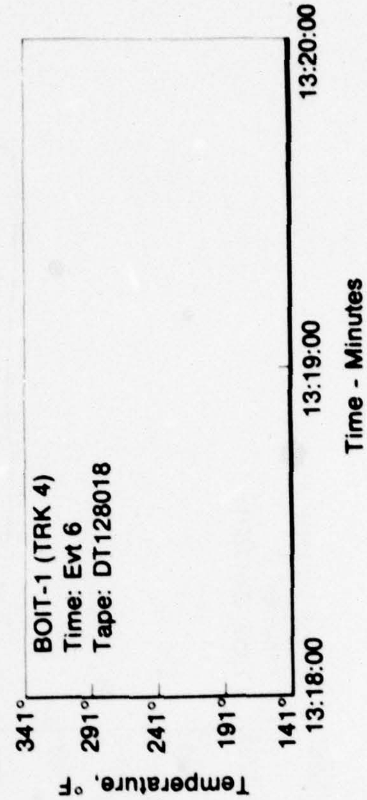

IFT - 5B (TRK 4)
Time: Evt 6
Tape: DT128028
Temperature, °F
534°
484°
434°
384°
334°
284°
234°
13:18:00
13:19:00
13:20:00
Time - Minutes
HGT -02 (TRK 5)
Time: Evt 6
Tape: DT 128028
Temperature, °F
535°
485°
435°
385°
335°
285°
235°
13:18:00
13:1900
13:20:00
Time - Minutes
FPT-1 (TRK 6)
Time: Evt 6
Tape: DT128028
Temperature, °F
465°
415°
365°
315°
265°
215°
165°
13:18:00
13:19:00
13:20:00
Time - Minutes
HGT -01 (TRK 7)
Time: Evt 6
Tape: DT128028
Temperature, °F
518°
468°
418°
368°
318°
268°
218°
13:18:00
13:19:00
13:20:00
Time - Minutes
FD 146499

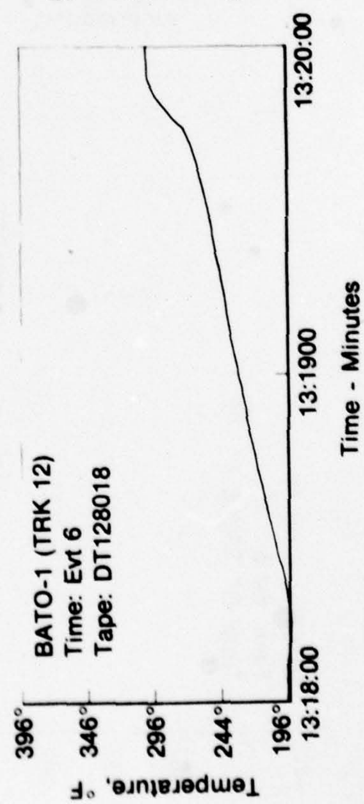

BOF - 1 (TRK 8)
Time: Evt 6
Tape: DT128028
Oil Flow lb/min
10
8
6
4
2
0
13:18:00
13:19:00
13:20:00
Time - Minutes
BOF - 2 (TRK 9)
Engine: F 33836 Std: D-3
Time: Evt 6
N2 SPD (TRK 12)
Time: Evt 6
Tape: DT128028
Shaft Speed, (rpm)
100x10³
90
80
70
60
50
B2CS (TRK 14)
Time: Evt 6
Tape: DT128028
Cage Speed, (rpm)
50 x 10³
40
30
20
10
0
13:1900
FD 146498


BOST1-1 (TRK 1)
Time: Evt 6
Tape: DT128018
Temperature, °F
487°
437°
387°
337°
287°
237°
13:18:00
13:19:00
13:20:00
Time - Minutes
BOOT - 1 (TRK 3)
Time: Evt 6
Tape: DT128018
Temperature, °F
586°
536°
486°
436°
286°
236°
13:18:00
13:19:00
13:20:00
Time - Minutes
BRT2-3 (TRK 6)
Time: Evt 6
Tape: DT128018
Temperature, °F
472°
422°
372°
322°
272°
222°
13:18:00
13:1900
13:20:00
Time - Minutes
BOOT2 - 1 (TRK 7)
Time: Evt 6
Tape: DT128018
Temperature, °F
475°
425°
375°
325°
275°
225°
13:18:00
13:19:00
13:20:00
Time - Minutes
FD 146497

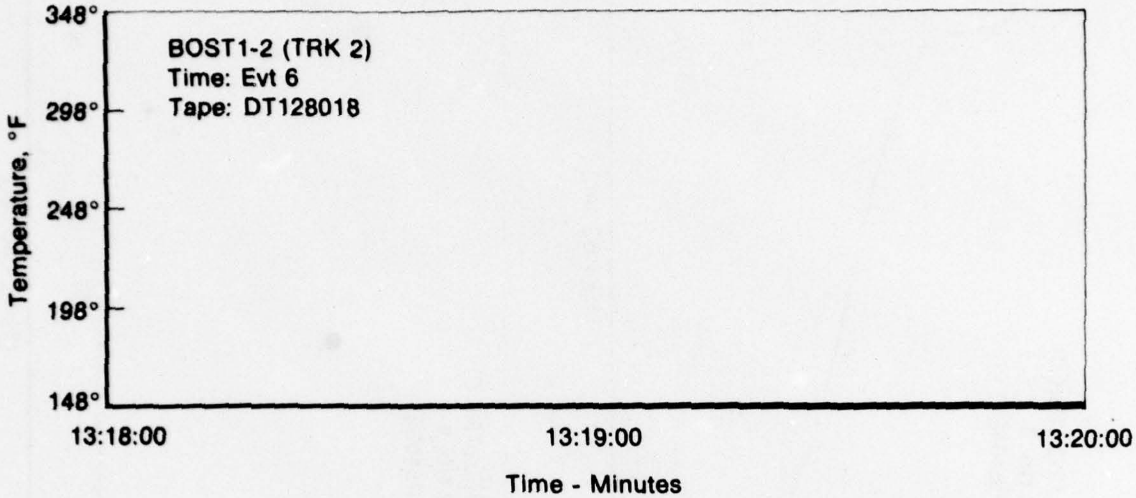

BATP-1 (TRK 10)
Time: Evt 6
Tape: DT128018
425°
375°
325°
275°
225°
Temperature, °F
13:18:00
13:19:00
13:20:00
Time - Minutes

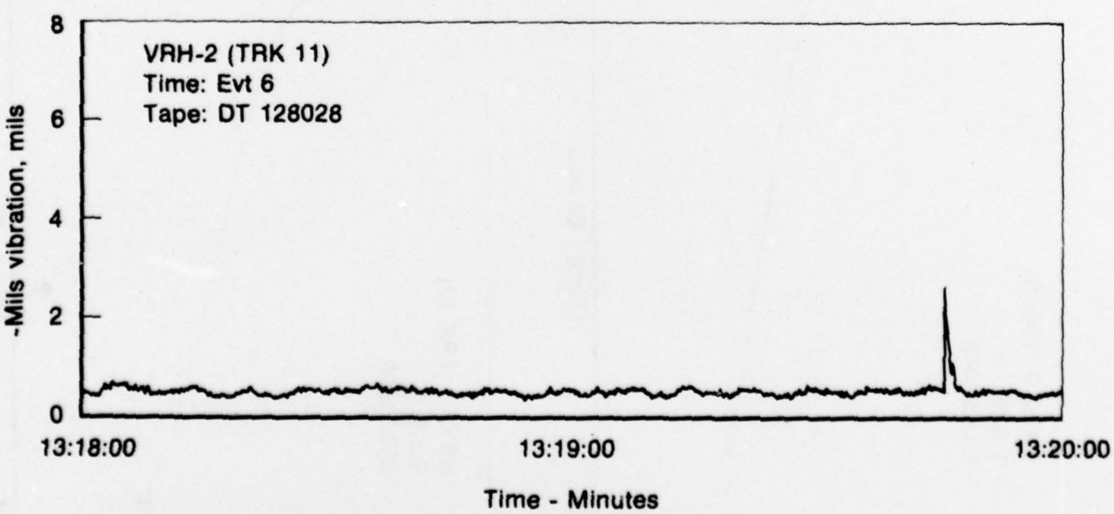

BOOT2-2 (TRK 8)
Time: Evt 6
Tape: DT128018
430°
380°
330°
280°
230°
Temperature, °F
13:18:00
13:19:00
13:20:00
Time - Minutes


BOIT-1 (TRK 4)
Time: Evt 6
Tape: DT128018
341°
291°
241°
191°
141°
Temperature, °F
13:18:00
13:19:00
13:20:00
Time - Minutes

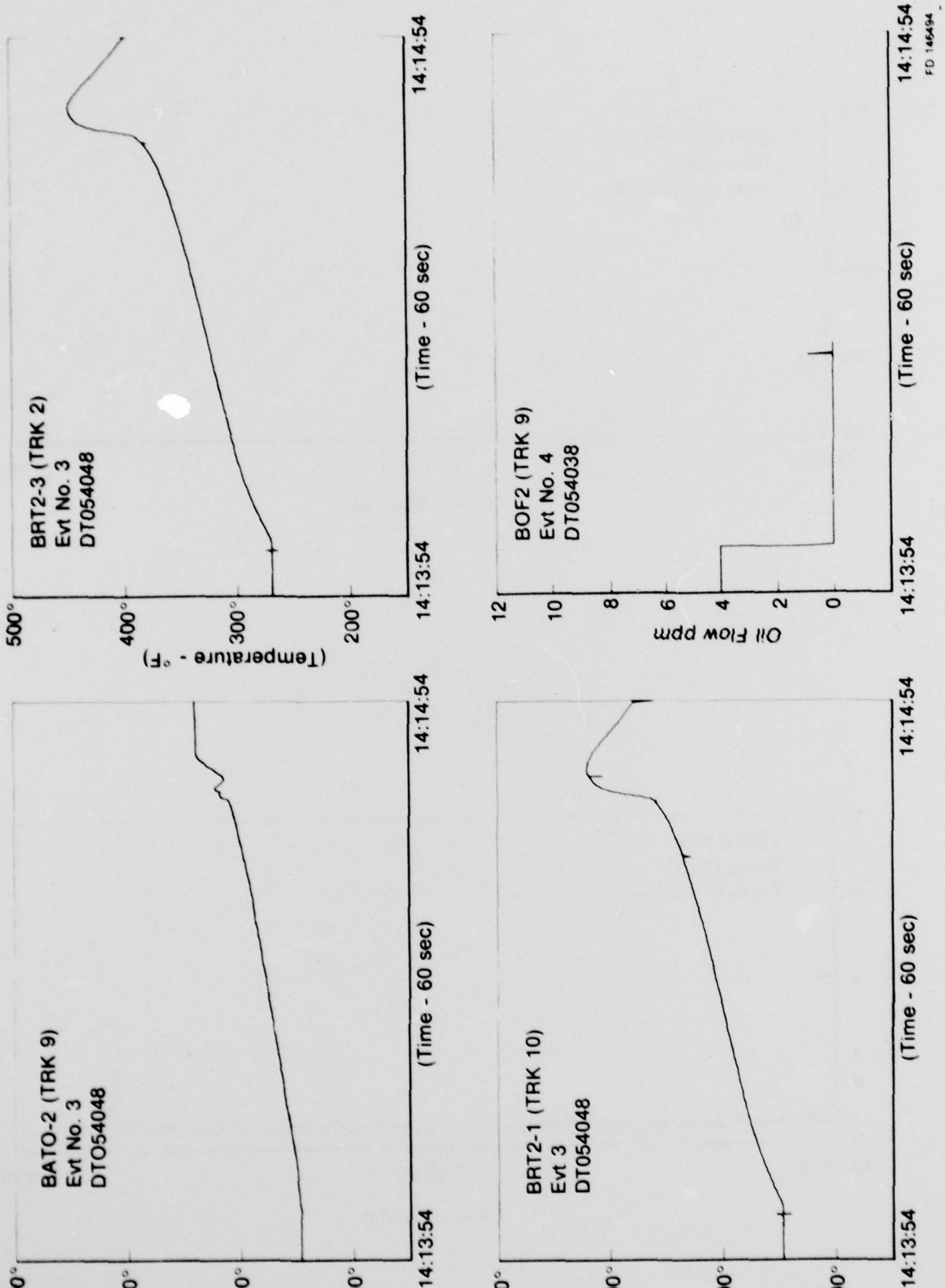

BATO-1 (TRK 12)
Time: Evt 6
Tape: DT128018
396°
346°
296°
244°
196°
Temperature, °F
13:18:00
13:1900
13:20:00
Time - Minutes

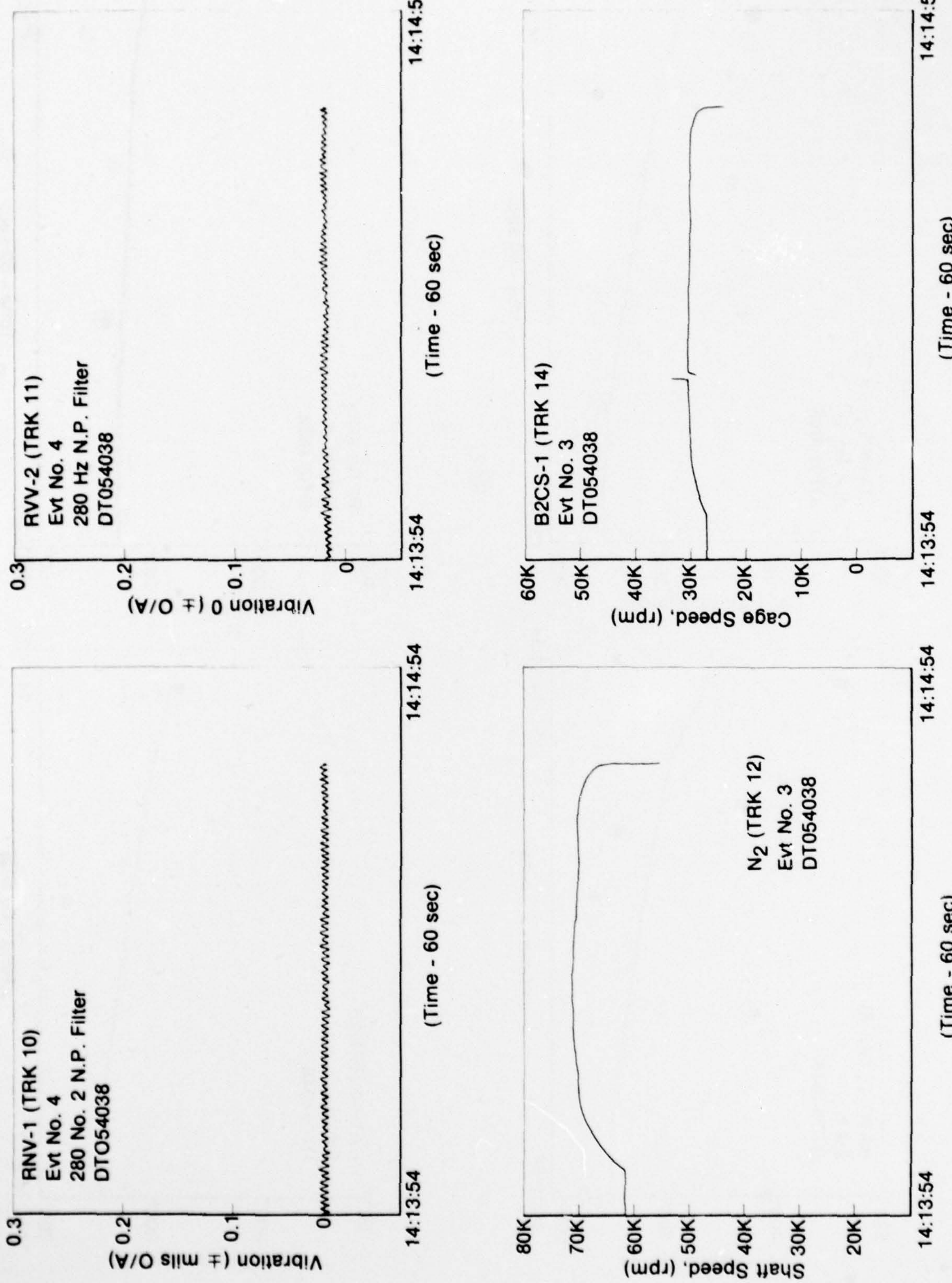
FD 148496


348°
298°
248°
198°
148°
Temperature, °F
BOST1-2 (TRK 2)
Time: Evt 6
Tape: DT128018
13:18:00
13:19:00
13:20:00
Time - Minutes

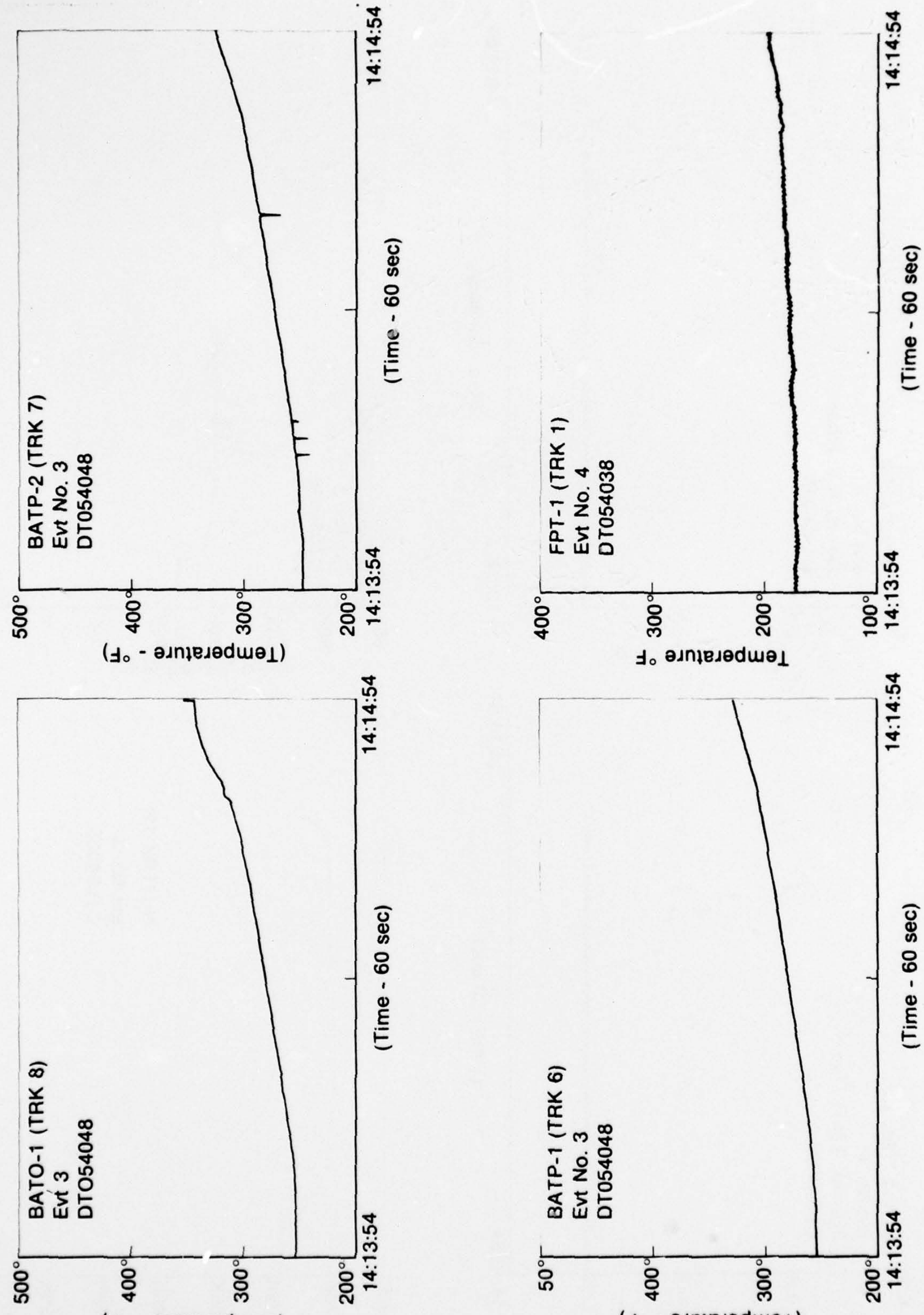

8
6
4
2
0
-Mils vibration, mils
VRH-2 (TRK 11)
Time: Evt 6
Tape: DT 128028
13:18:00
13:19:00
13:20:00
Time - Minutes

FD 146495

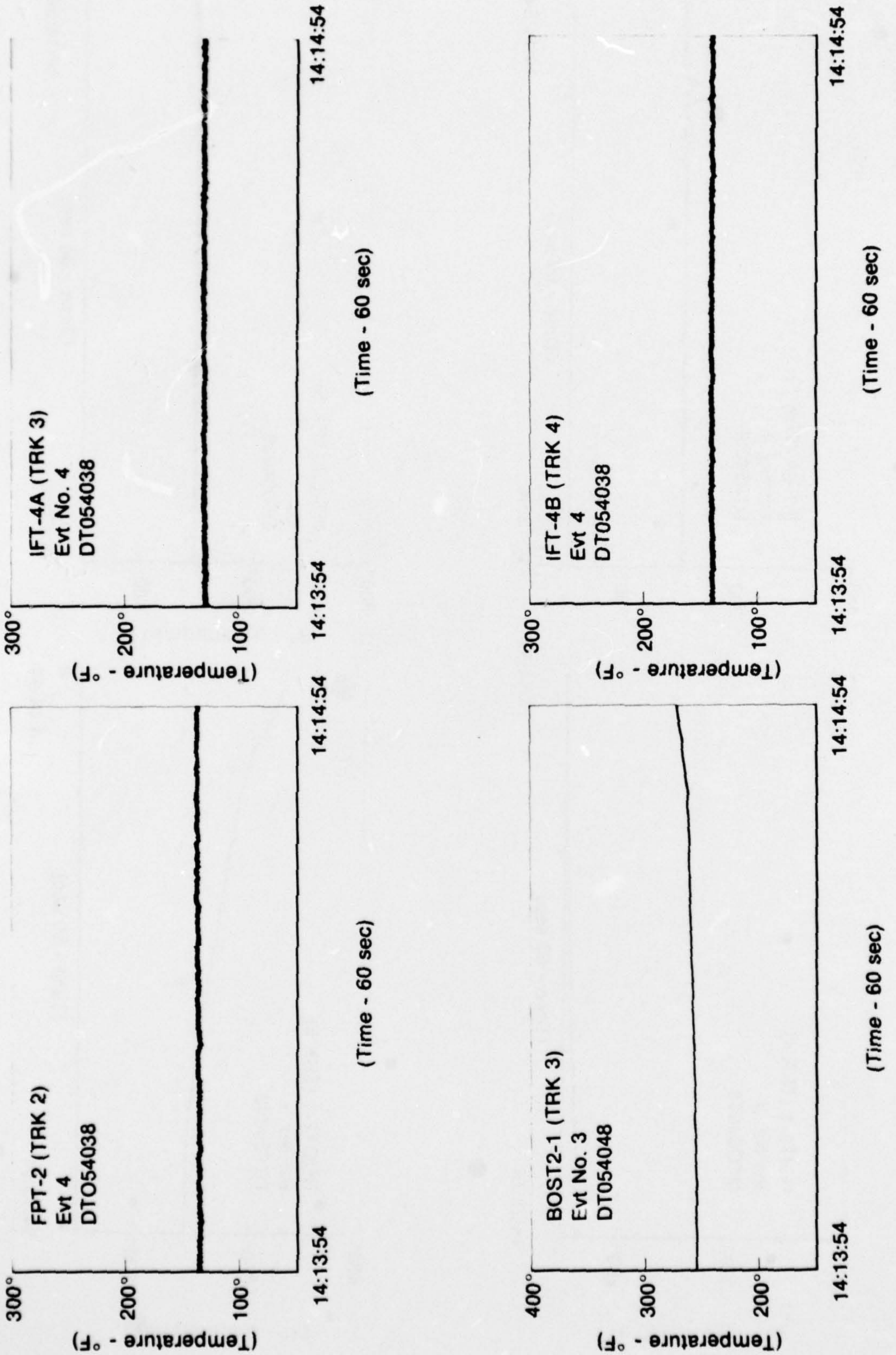

BRT2-3 (TRK 2)
Evt No. 3
DT054048
BATO-2 (TRK 9)
Evt No. 3
DTO54048
BOF2 (TRK 9)
Evt No. 4
DT054038
BRT2-1 (TRK 10)
Evt 3
DT054048
(Temperature - °F)
500°
400°
300°
200°
Oil Flow ppm
12
10
8
6
4
2
0
14:13:54
(Time - 60 sec)
14:14:54
FD 145494


RNV-1 (TRK 10)
Evt No. 4
280 No. 2 N.P. Filter
DTO54038
Vibration (± mils O/A)
0.3
0.2
0.1
0
14:13:54
14:14:54
(Time - 60 sec)
RVV-2 (TRK 11)
Evt No. 4
280 Hz N.P. Filter
DT054038
Vibration 0 (± O/A)
N2 (TRK 12)
Evt No. 3
DT054038
Shaft Speed, (rpm)
80K
70K
60K
50K
40K
30K
20K
B2CS-1 (TRK 14)
Evt No. 3
DT054038
Cage Speed, (rpm)
60K
50K
40K
30K
20K
10K
0

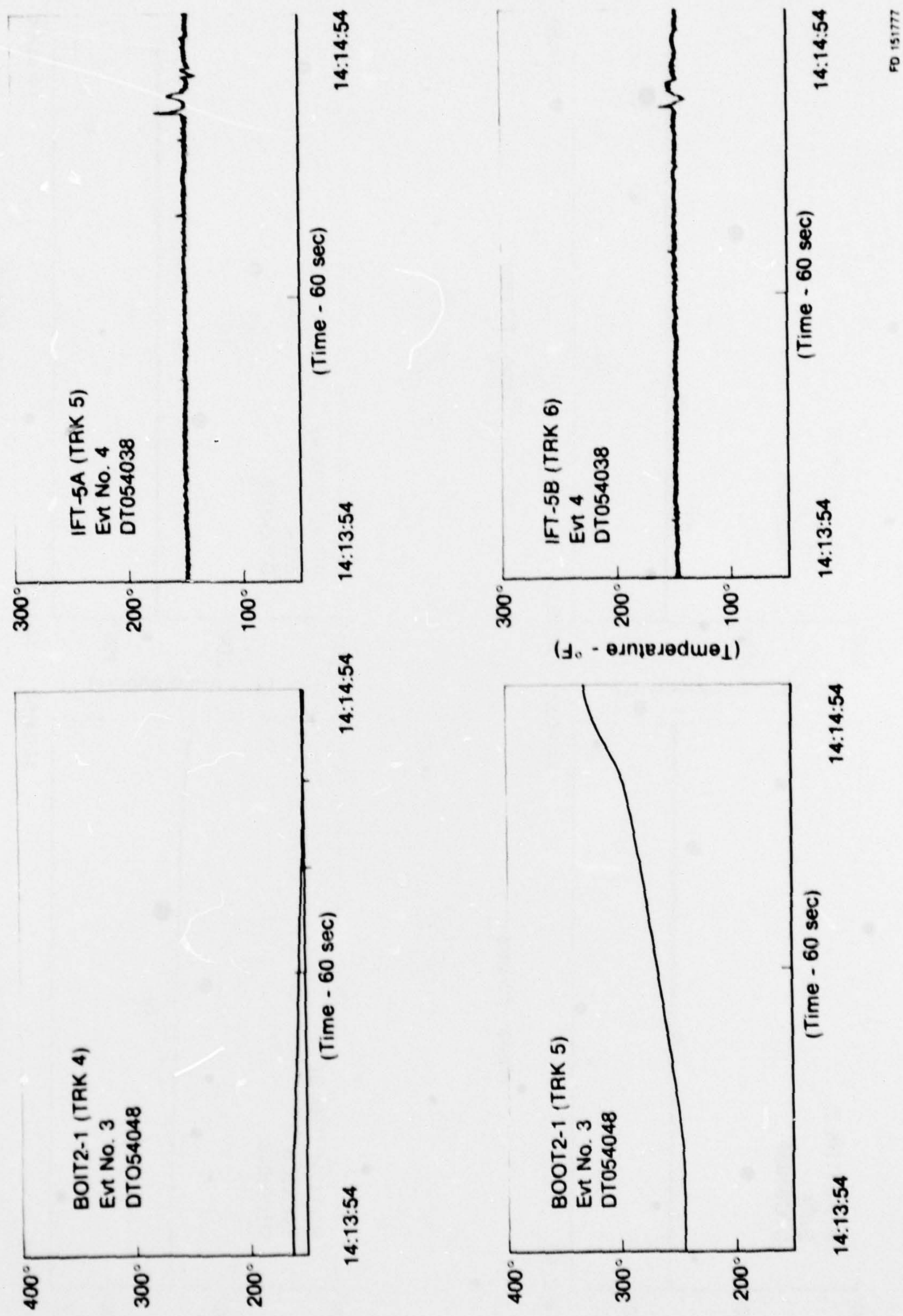
FD 151774

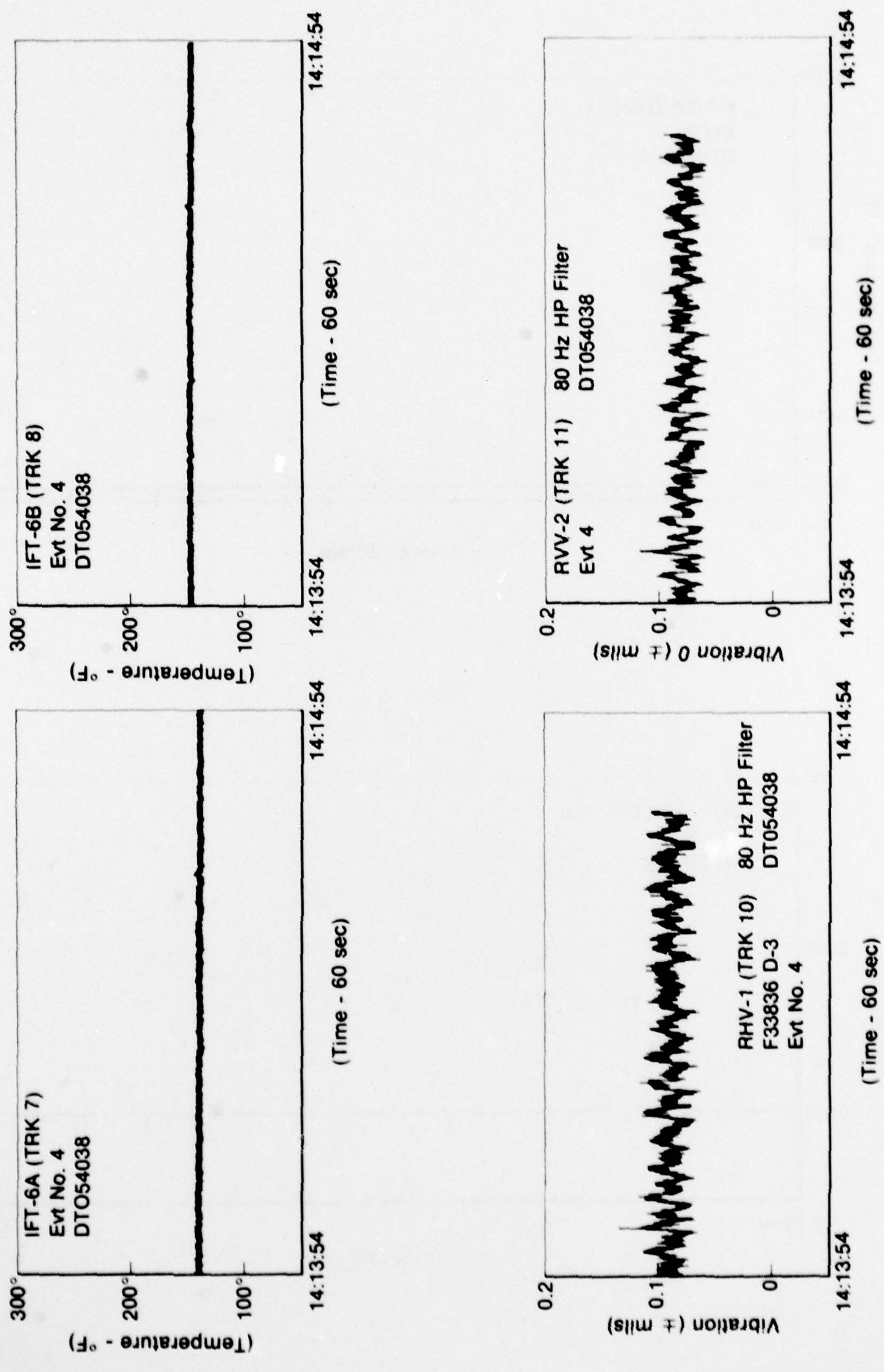

BATO-1 (TRK 8)
Evt 3
DTO54048
BATP-2 (TRK 7)
Evt No. 3
DT054048
BATP-1 (TRK 6)
Evt No. 3
DT054048
FPT-1 (TRK 1)
Evt No. 4
DT054038
(Temperature - °F)
Temperature °F
(Time - 60 sec)
14:13:54
14:14:54
500°
400°
300°
200°
100°
50°

FD 151775

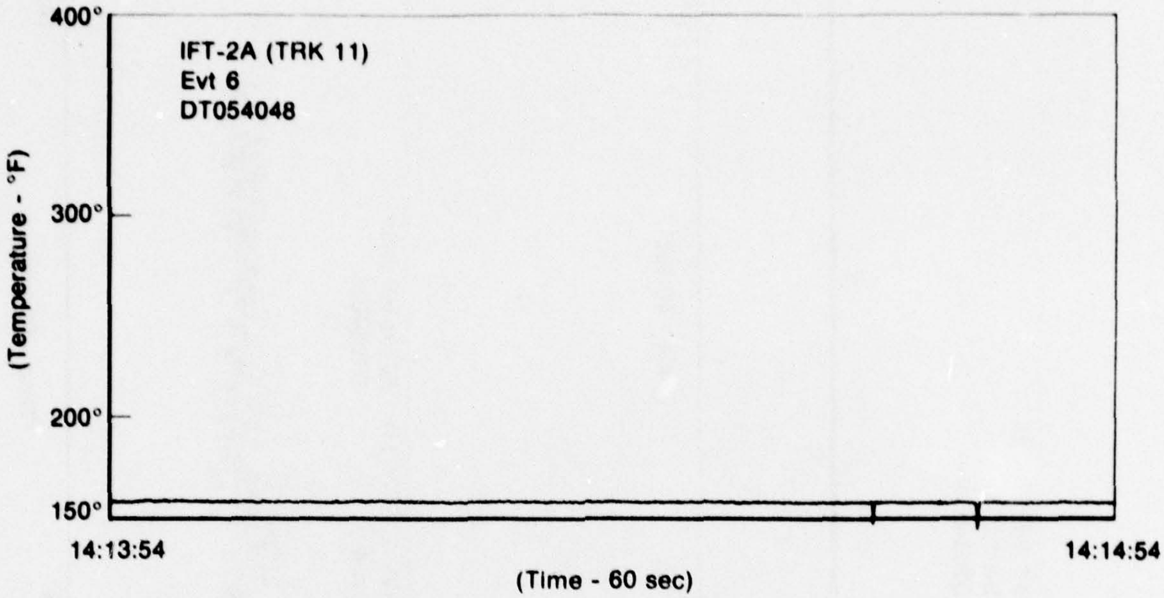

FPT-2 (TRK 2)
Evt 4
DTO54038
300°
200°
100°
(Temperature - °F)
14:13:54
14:14:54
(Time - 60 sec)
IFT-4A (TRK 3)
Evt No. 4
DT054038
300°
200°
100°
(Temperature - °F)
14:13:54
14:14:54
(Time - 60 sec)
BOST2-1 (TRK 3)
Evt No. 3
DT054048
400°
300°
200°
(Temperature - °F)
14:13:54
14:14:54
(Time - 60 sec)
IFT-4B (TRK 4)
Evt 4
DT054038
300°
200°
100°
(Temperature - °F)
14:13:54
14:14:54
(Time - 60 sec)

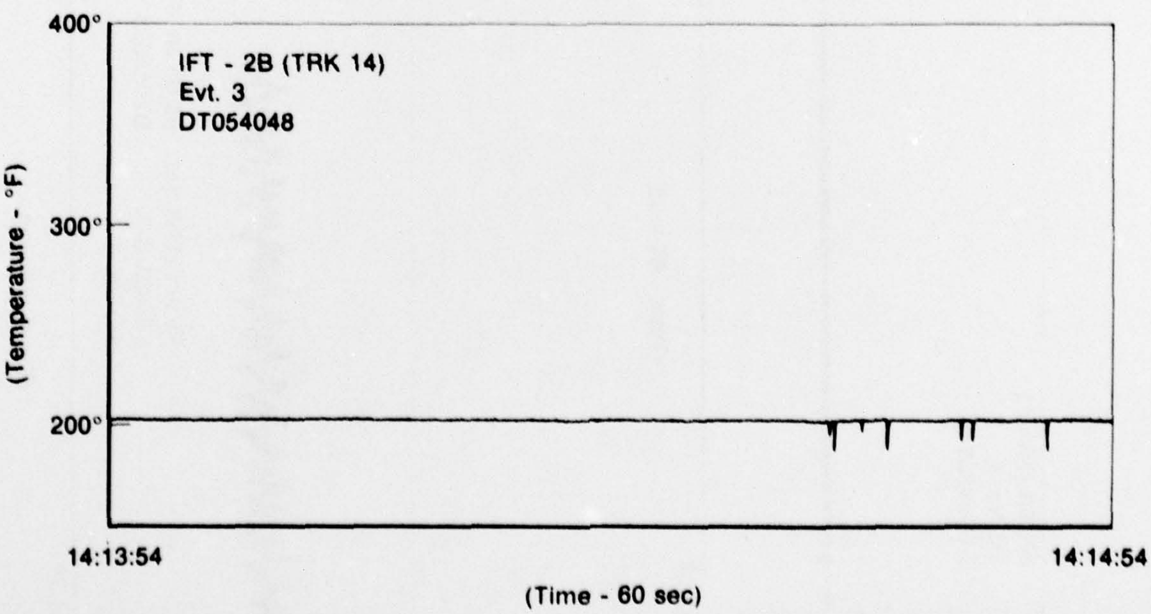
FD 151776


IFT-5A (TRK 5)
Evt No. 4
DT054038
IFT-5B (TRK 6)
Evt 4
DT054038
BOIT2-1 (TRK 4)
Evt No. 3
DTO54048
BOOT2-1 (TRK 5)
Evt No. 3
DT054048
(Temperature - °F)
(Time - 60 sec)
14:13:54
14:14:54
100°
200°
300°
400°
FD 151777


IFT-6A (TRK 7)
Evt No. 4
DTO54038
IFT-6B (TRK 8)
Evt No. 4
DT054038
(Temperature - °F)
300°
200°
100°
14:13:54
14:14:54
(Time - 60 sec)
RHV-1 (TRK 10)
F33836 D-3
Evt No. 4
80 Hz HP Filter
DT054038
RVV-2 (TRK 11)
Evt 4
80 Hz HP Filter
DT054038
Vibration (± mils)
Vibration 0 (± mils)
0.2
0.1
0

FD 151778


400°
300°
200°
150°
(Temperature - °F)
IFT-2A (TRK 11)
Evt 6
DT054048
14:13:54
14:14:54
(Time - 60 sec)


400°
300°
200°
(Temperature - °F)
IFT - 2B (TRK 14)
Evt. 3
DT054048
14:13:54
14:14:54
(Time - 60 sec)

FD 151779

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