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TRANSMISSION THERMAL MAPPING (CH-47C FORWARD ROTOR TRANSMISSION)

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13. ABSTRACT

This report presents the results of tests conducted to obtain the thermal maps of a CH-47C helicopter forward rotor transmission.

The tests were conducted at several torque levels and to several controlled oil-out target temperatures.

Thermal growth between selected points on the transmission case was measured and analyzed.

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Oil-Out Temperature						
Oil-In Temperature						
Gears						
Bearings						
Thermocouple						
Temperature Sensing Placards						
Pyrometric-Potentiometer						
Thermal Growth						

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ERRATA

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Pages 80 and 81. The artwork for Figures 75 and 76 was reversed in printing.

The illustration shown on page 80 belongs on page 81 with the title "Figure 76. Thermal Map of Dimensional Growth Run."

The illustration shown on page 81 belongs on page 80 with the title "Figure 75. Thermal Map of Hunting/Search Torque (40 Percent Run at Oil-Out = 400°F ± 10 Percent."

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This report was prepared by The Boeing Vertol Company under the terms of Contract DAAJ02-72-C-0075. It represents a step in a continuing program to obtain a self-contained helicopter transmission.

The single most vulnerable part of a helicopter drive system in combat is the lubrication and cooling system. Interruption of the oil supply to the transmission dictates an immediate power-off descent and landing. The overall objective is to reduce or eliminate oil cooling and lubrication components situated remotely from the transmission. The immediate objective of this program was to determine the complete thermal map of all main components of an instrumented CH-47 forward rotor transmission under various loads and inlet oil temperatures. Measurements of thermal growth of the casing have also been made.

This report has been reviewed by this Directorate and is considered to be technically sound. The technical monitor for this contract was Mr. E. R. Givens, Technology Applications Division.

Task 1G162207AA7201
Contract DAAJ02-72-C-0075
USAAMRDL Technical Report 73-24
May 1973

TRANSMISSION THERMAL MAPPING
(CH-47C Forward Rotor Transmission)

Final Report

D210-10545-1

By

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SUMMARY

This report presents the results of tests to obtain the thermal maps of a CH-47C forward rotor transmission. The tests were conducted at several torque levels and at several controlled oil-out target temperatures. Thermal growth between selected points on the transmission case was measured and recorded.

Generally, the results of the test are as follows:

1. The CH-47C forward rotor transmission specimen survived all tests.

2. "Classical" surface distress occurred on some gears at the mid and higher torque levels during the 400°F ± 10 percent oil-out tests. No other components showed visible signs of distress.

3. The tests, conducted with MIL-L-7808 bulk oil-out temperatures up to 286°F ± 10 percent, produced no deleterious effects either on the oil or on the metallurgical distress of gears, bearings, or other components.

4. The flowmeter (oil visible) indicated that, at approximately 350°F, mechanical or chemical "breakdown" of the oil was accelerating.

5. Full bypass of the cooler is possible at oil-out temperatures of 400°F ± 10 percent at approximately 40 percent torque.

6. Thermal growth between points on the specimen transmission case was generally of a "classical" nature following the linear thermal coefficients of expansion.

7. Heat paths followed the dominant heat transfer mechanism available in any test or test segment.

8. A replication of a previously conducted test of a CH-47 aft transmission at full oil-cooler bypass has been successfully matched during these tests.

FOREWORD

This report presents the results of an experimental test program conducted to determine the temperatures of the main components and a complete thermal map of a CH-47C forward rotor transmission under various loads and inlet oil temperatures.

The program was conducted during the period May 1972 through December 1972 for the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, under the authority of DA Task 1G162207AA7201.

Technical direction was provided by Mr. Rouzee Givens, Project Engineer, Eustis Directorate, Technology Applications Division.

The Program Manager for this project at the Boeing Vertol Company was A. J. Lemanski, Chief Advanced Drive System Technology. This program was conducted under the technical direction of R. C. Tocci, P. E. (Reg.), Project Engineer. The principal test engineers were N. J. Ayoub and H. J. Nonemaker. Acknowledgement is made to instrumentation engineers F. E. Maroone and J. P. Senese, and to T. T. Link, operations technician, for their contributions to the success of this project. The infrared technology support was conducted by N. James and S. Lantieri of Quality Assurance Technology

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INTRODUCTION

Helicopter operations have shown that the transmission system is highly vulnerable to combat damage due to the remote location of oil coolers. The single most vulnerable subsystem of a helicopter drive system is the lubrication and cooling system. Any type of a ballistic hit in any one of the lubrication system's many components, as well as a hit in adjacent transmission case areas, will result in a lubricant/coolant loss. If the supply of oil to the transmission is interrupted, failure may occur within minutes and the helicopter may have to make a forced landing. Methods to reduce the vulnerability and complexity of such lube oil cooling systems must be developed to overcome this deficiency.

One approach to reduce vulnerability is to design an integral gearbox-lube oil system (i.e., delete the external oil cooler and accomplish the heat rejection by radiation and natural convection through the housing walls). This approach may develop oil-out temperatures greater than 400°F, which would result in the main components' being subjected to higher temperatures than are currently permissible. To accomplish this objective of a self-contained transmission, the first step is to develop an accurate thermal map of existing transmissions.

The objective of the work performed under this contract was to determine the temperatures of all main components and to make a complete thermal map of a CH-47C forward rotor transmission under 10 percent, 50 percent, 75 percent, and 100 percent torque loads (rotor shaft speed at 243 rpm) and oil-out controlled temperatures of 180°F ± 10 percent, 286°F ± 10 percent, and 400°F ± 10 percent.

Figure 1 is an illustration of the CH-47C helicopter drive system. The specimen used in this test was a forward rotor transmission. Its relationship to the other gearboxes and drive system elements is shown in Figure 1. Figures 2 and 3 are a photograph and sectional illustration respectively of a CH-47 forward rotor transmission. Figure 4 illustrates a typical sequence of development required to arrive at a lubricant-integral sealed transmission.

A typical helicopter transmission lubricating system comprises a pump, oil cooler, and blower assembly together with the

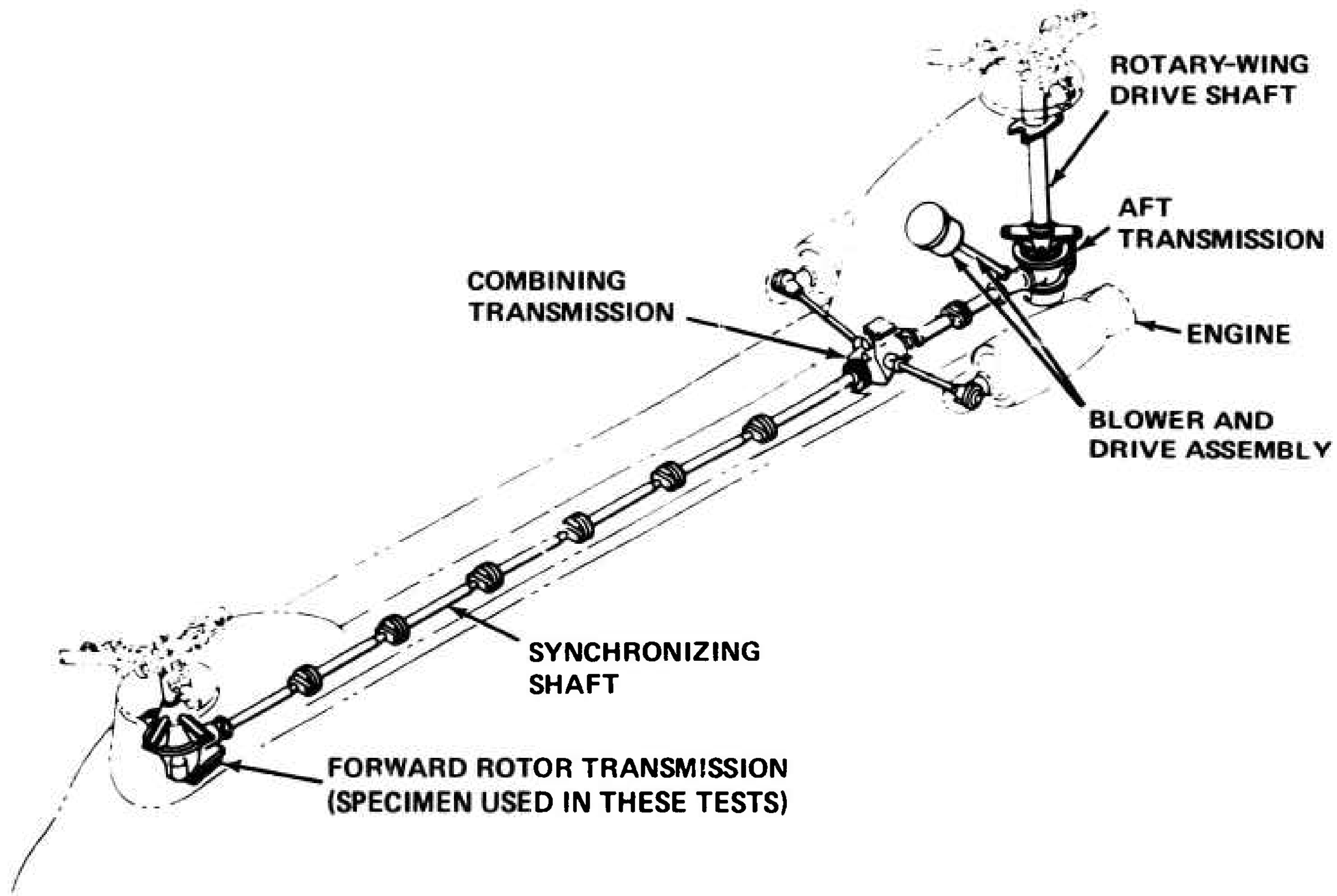


Figure 1. CH-47C Helicopter Drive System.

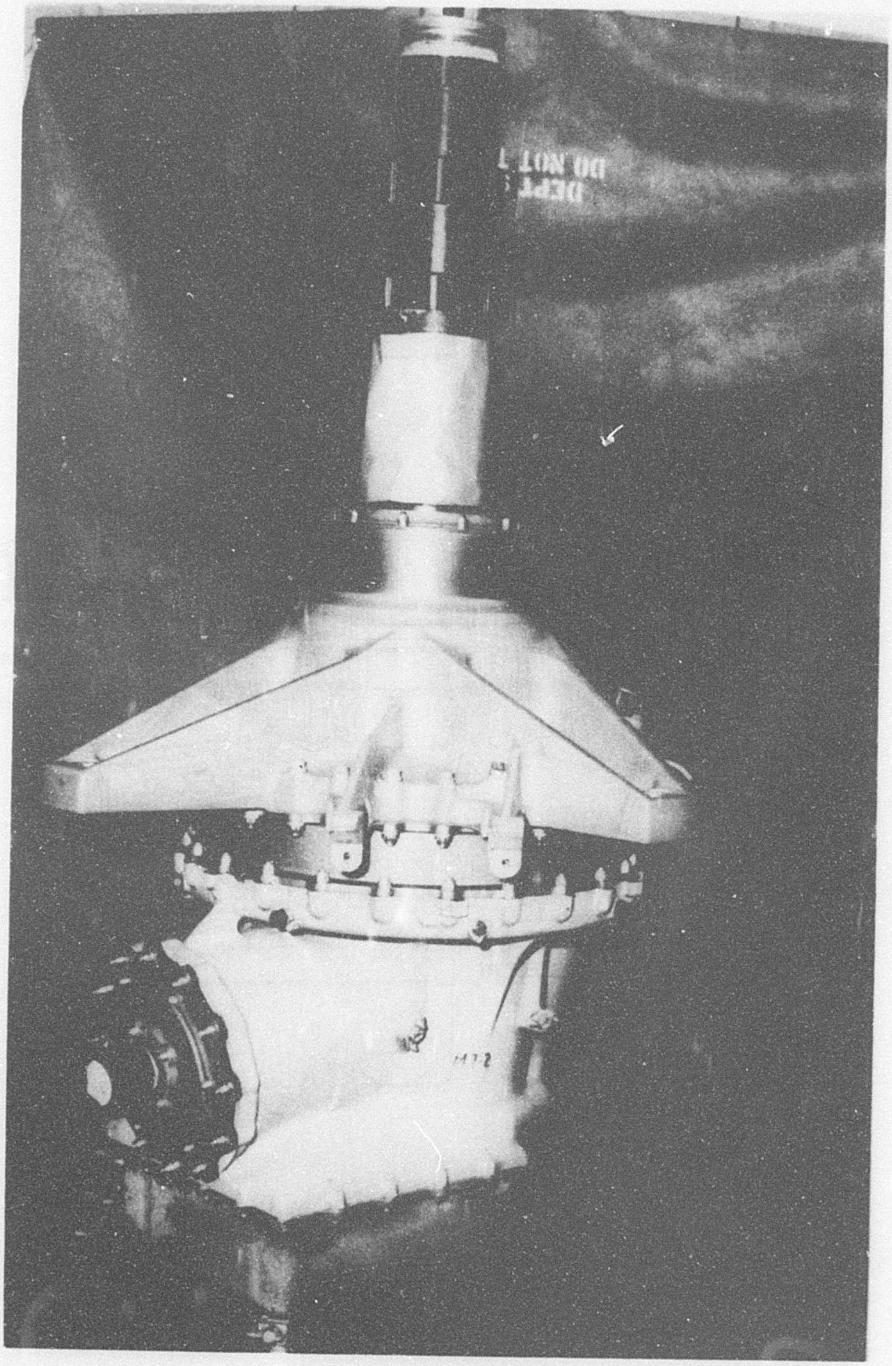


Figure 2. CH-47 Forward Rotor Transmission.

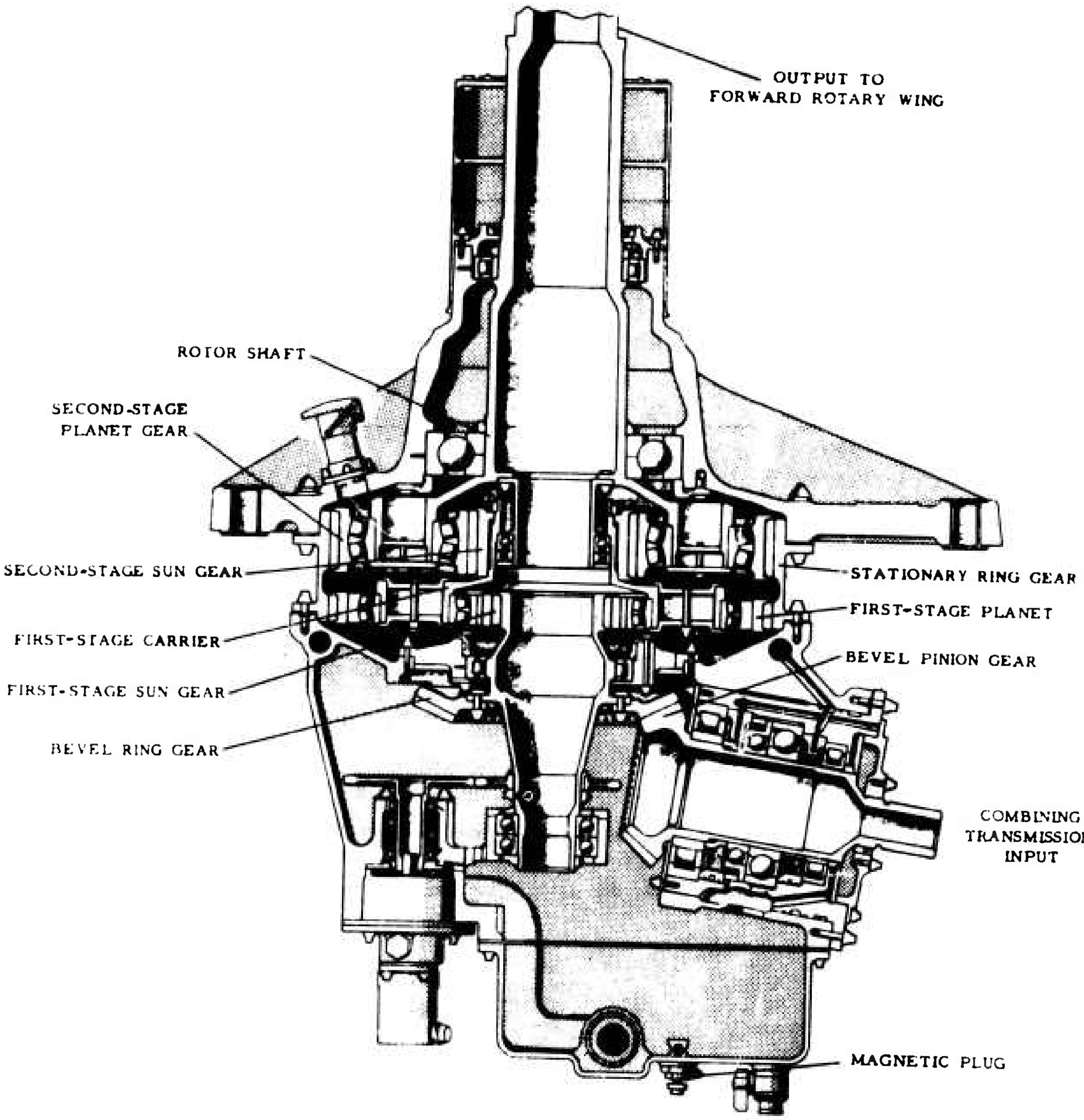


Figure 3. Sectional View of CH-47 Forward Transmission.

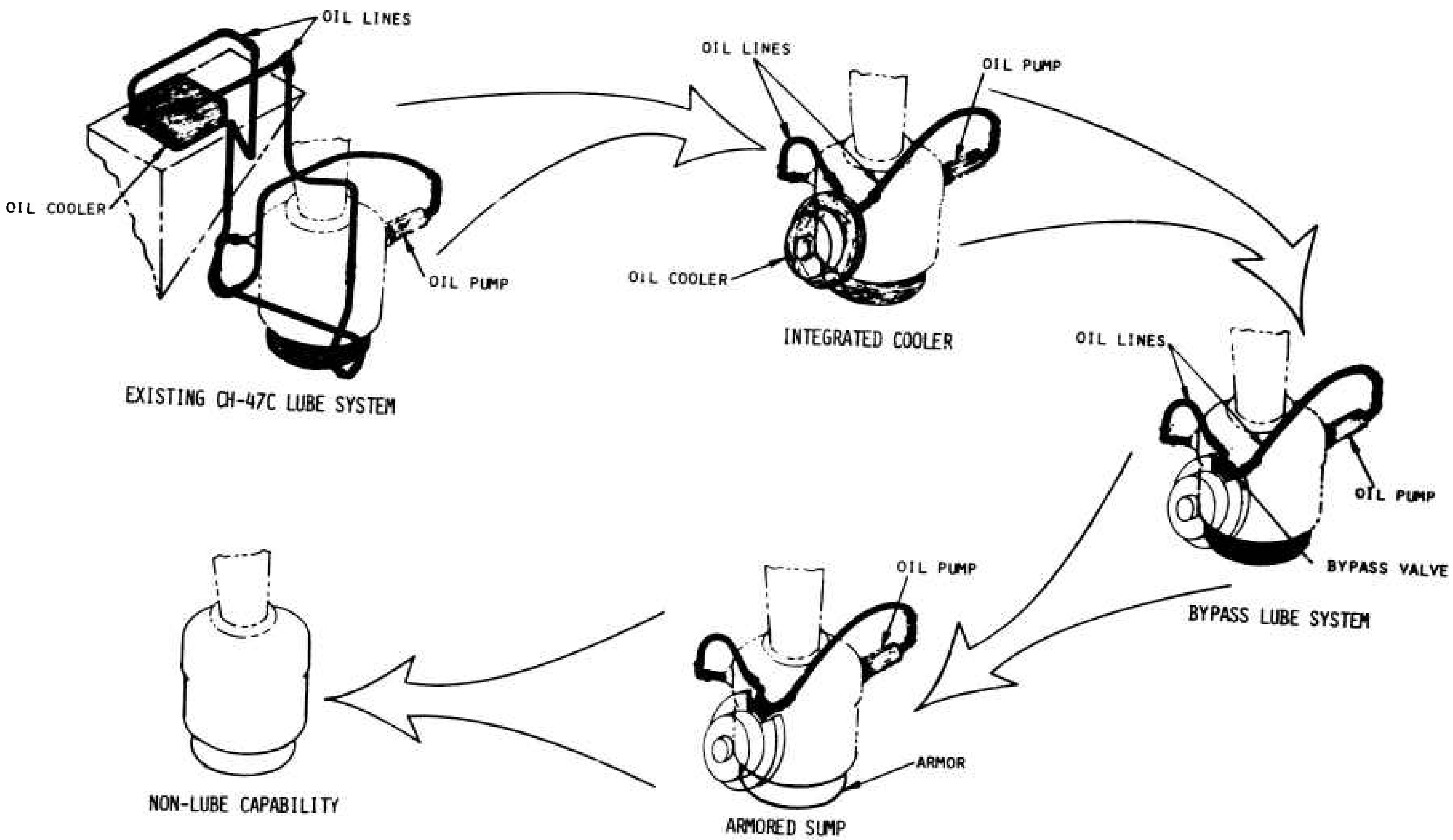
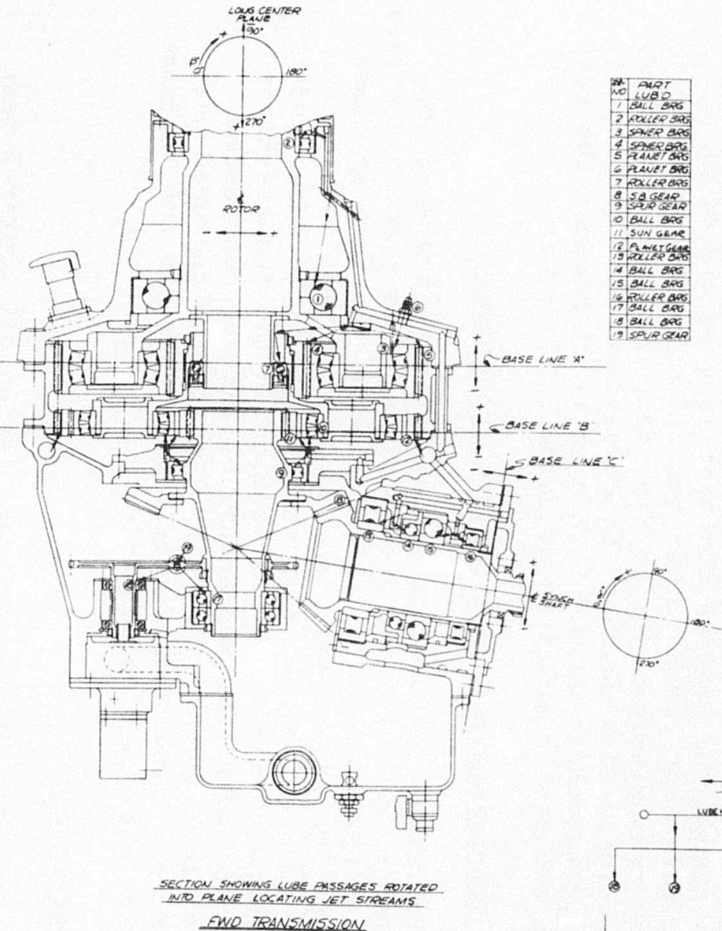


Figure 4. Sequence of Development Required to Arrive at a Lubricant Integral Sealed Transmission.

necessary interconnecting lines, filters and valves. The pump draws oil from its respective sump, pressurizes it, and sends it through external lines to the cooler, from which it flows to the transmission jets. These jets meter the oil and direct it into the gears and bearings. The oil then drains by gravity to the sump and is recirculated by the pump. Figure 4 illustrates a typical sequence of development required tc arrive at a lubricant-integral sealed transmission. Figure 5 is a schematic drawing of the CH-47 forward transmission lubrication system.



NO.	PART LUBED
1	BALL BRG
2	ROLLER BRG
3	SPHER BRG
4	SPHER BRG
5	PLANET BRG
6	PLANET BRG
7	ROLLER BRG
8	SB GEAR
9	SPUR GEAR
10	BALL BRG
11	SUN GEAR
12	PLANET GEAR
13	ROLLER BRG
14	BALL BRG
15	BALL BRG
16	ROLLER BRG
17	BALL BRG
18	BALL BRG
19	SPUR GEAR

LUBE TARGET POINT DIMENSIONS

TARGET	COORDINATES: BASE LINE	COORDINATES: ROTOR SHAFT	COORDINATES: LOUS CTR PLANE	RADIUS @ SYNC	SPACING	ANGULAR SPACING AROUND	NO. OF JETS
1	A+5.081	+4.63				+232° 30'	1
2	A+3.762	+4.19				+232° 30'	1
3	A+.810	+9.09				+232° 30'	1
4	A+1.445	+4.065				[illegible]	6
5	A+1.72	+10.35				[illegible]	6
6	A+.810	+9.12				+90°	3
7	A+1.985	+2.05				+195°	1
8		+5.16	-1.531	+2.91			1
9	B-.202	+3.53				TO SUIT ASSY	2
10	B-.585	+4.25				TO SUIT ASSY	4
11	B-.585	+3.65				TO SUIT ASSY	4
12	B-.563	+10.57				[illegible]	6
13	C-6.670			2.845	TO SUIT ASSY		1
14	C-5.545			2.636	TO SUIT ASSY		1
15	C-2.945			2.655	TO SUIT ASSY		1
16	C-1.840			2.535	TO SUIT ASSY		1
17	B-9.595	-1.047	-1.50				1
18	B-8.986	-6.180	-.745				1
19	B-8.063	-3.500	-.890				1

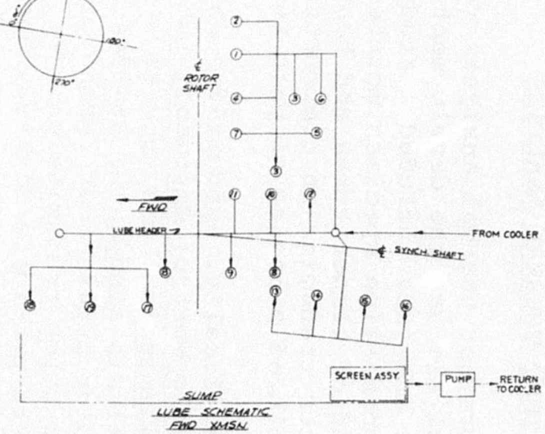


Figure 5. Schematic Lube Diagram of CH-47 Transmission.

TEST METHOD AND DESIGN OF EXPERIMENTS

PRETEST THERMAL ANALYSIS

A pretest thermal analysis was conducted. The object of this analysis was the development of the thermal mapping test plan. The analysis included a study of the test configuration (the transmission specimen mounted in its test stand) in order to predict temperatures and heat paths in the CH-47C forward rotor transmission components. The detail nature of the study included a review of past test data.

Specifically, appropriate data from Boeing Document D8-0544, Development of Emergency Lubrication Capability for CH-47A Transmission, was used as a basis of the pretest thermal analysis study. The D8-0544 document is a record of an oil cooler bypass test (among other tests) conducted on a CH-47A aft rotor transmission. The thermal data obtained from these tests provide a limited base for comparison with the thermal mapping tests conducted under this contract because the test specimen and test conditions differed as follows:

1. Aft Transmission Versus Forward Transmission

   Most of the previous oil cooler bypass tests were conducted on a CH-47A aft transmission. This present contract uses a CH-47C forward transmission as the test specimen. Except for an accessory section, which lies outside the main torque-loop, a small shaft angle difference, and the presence of a main thrust bearing in the forward transmission, both specimen transmissions are considered essentially equal. The thermal analysis concluded that component temperatures should be comparable for the same equivalent power and efficiency.

2. Power Levels

   The previous CH-47A aft transmission oil cooler bypass tests were run at 16,600 inch-pounds and 6,800 rpm at the synchronizing shaft (spiral bevel pinion). The equivalent shaft horsepower was:

$$\text{shp} = \frac{\text{Torque x RPM}}{63025} = \frac{TN}{k} = \frac{16600 \times 6800}{63025} = 1790 \text{ shp}$$

The present CH-47C specimen (this contract) design shp is 60 percent of aircraft transmission power = 0.6 x 6000 = 3600 shp. This contract 100 percent torque condition translates to 933,702 inch-pounds and 243 rpm at the rotor shaft (output shaft of the transmission). Therefore, the 100 percent present test equivalent shaft horsepower is

$$shp = \frac{933702 \times 243}{63025} = 3600 \text{ shp}$$

By comparison, the previous aft transmission tests were run at a fraction of this present contract equivalent shaft horsepower; i.e., $\frac{1790 \text{ shp}}{3600 \text{ shp}}$ = 49.7 percent, which is within 0.3 percent of the 50 percent level torque tests included in this present effort.

In the design of experiments, repeatability is a desirable requirement if a high degree of credibility is to be achieved. Test 1 (oil-out controlled to 180°F ± 10 percent) had been identified as the baseline case for subsequent comparison and analysis of data derived from test 2 (oil-out controlled to 286°F ± 10 percent) and test 3 (oil-out controlled to 400°F ± 10 percent, or oil-cooler fully bypassed, if tolerable). The 50 percent torque test in test 3 satisfies the desired replication dictated in any properly planned test. Table I gives a comparison of the conditions of the numbered test runs and their segments.

Heat Rejection Modes

A Boeing-Vertol internal report indicates an efficiency for the CH-47 forward rotor transmission of 98.6 percent. At 100 percent CH-47C forward transmission power (3600 shp), the heat rejection rate is 128,000 Btu/hr (2134 Btu/min). For 75 percent and 50 percent power, the heat rejection rates are 96,000 Btu/hr (1600 Btu/min) and 64,000 Btu/hr (1067 Btu/min), respectively.

For the pretest thermal analysis, the following heat rejection means were identified:

- o Conduction (to a heat sink)
- o Radiation

TABLE I. COMPARISON OF TEST RUN CONDITIONS

Load Condition 243 Rotor Shaft RPM	Test 1 Baseline Test Oil-Out = 180°F±10%	Test 2 Aircraft Red Line Oil-Out = 286°F±10%	Test 3 Oil-Out = 400°F±10% or, Cooler 100% Bypass
50% Torque Segment	Normal and run-in. Routine data baseline points (after 10% torque segment run).	No problems in collecting data anticipated. Bracketed by Tests 1 and 3.	Approximately equivalent to previous aft transmission tests (oil-out temperature 300°F to 310°F). *Oil cooling required.
75% Torque Segment	Approximately equivalent to previous normal tests of CH-47 fwd transmission published data. (oil-out temperature 180°F; oil-in temperature 160°F.)	No problems in collecting data anticipated. Bracketed by 50% and 100% torque loads.	Unknown, but the estimated torque level achievable without requirement of cell oil-cooler partly in operation is 80% (for 400°F oil-out temperature limit). *Full oil-cooler bypass subsequently estimated at approximately 40% torque.

TABLE I - Continued

Load Condition 243 Rotor Shaft RPM	Test 1 Baseline Test Oil-Out = 180°F±10%	Test 2 Aircraft Red Line Oil-Out = 286°F±10%	Test 3 Oil-Out = 400°F±10% or, Cooler 100% Bypass
100% Torque Segment (933,702 inch pounds at rotor shaft)	No problems in collecting data anticipated. Unpublished 122% overload tests have been run with oil-out temperature 195°F. (Oil-in temperature 165°F.)	No problems in collecting data anticipated. Cell oil-cooler capacity adequate. Bracketed by oil-out of test 1 at 100% and test 3 at 50%.	Contractual oil-out temperature of 400°F may be reached without stabilization, thereby requiring cell oil-cooler only partially bypassed.

*Due to the presence of residual oil cooling in previous oil-cooler bypass tests, using a specimen without a thermal blanket, the initial test plan projected the possibility of achieving a 100 percent bypass of oil cooler for these test segments.

- o Convection

  - Natural (free) convection

  - Forced (heat generator - to conveying fluid (oil) - to cooler core - to fluid sink (air in aircraft, water in test cell)).

- o Changes of State

The amount of heat rejected by conduction was assumed to be negligible (aircraft and cell). Radiation and natural convection is also small or trivial when the transmission oil-cooler is used. Therefore, when the oil-cooler is bypassed in our tests, the only means to obtain a heat rate balance are conduction, radiation, natural convection, forced convection (other than oil cooler), and changes of state.

There are six possible paths for heat to be conducted into the massive steel beams in the test cell. The remote interface pads and shafts do not appear to be large enough as conductors especially since the other slave transmission shafts are acting as conductors for their own host transmissions. At present, no transmission test cell systems analysis documentation exists which presents studies of heat rejection by forced convection (other than by oil-cooler) and changes of state. All that is known is that smoke-off (change of state) has been recorded at 240°F with aggravated smoke-off (vaporization) at 300°F. In one case (non-lube test), the flash point was reached with ignition of oil and magnesium taking place.

Figure 6 is a theoretical (graphical) projection of specimen power levels (and heat rejection rate) versus average case temperature (assumed equal to oil-out temperature). The equations used in the pretest thermal analysis were:

1. Conduction: None used - assumed negligible

2. Radiation: The Stefan-Boltzmann Law:

$$q_r = Q = A\epsilon\sigma\,(T_1^4 - T_2^4) = A\epsilon\sigma\,\left((t_1 + 460)^4 - (t_2 + 460)^4\right)$$

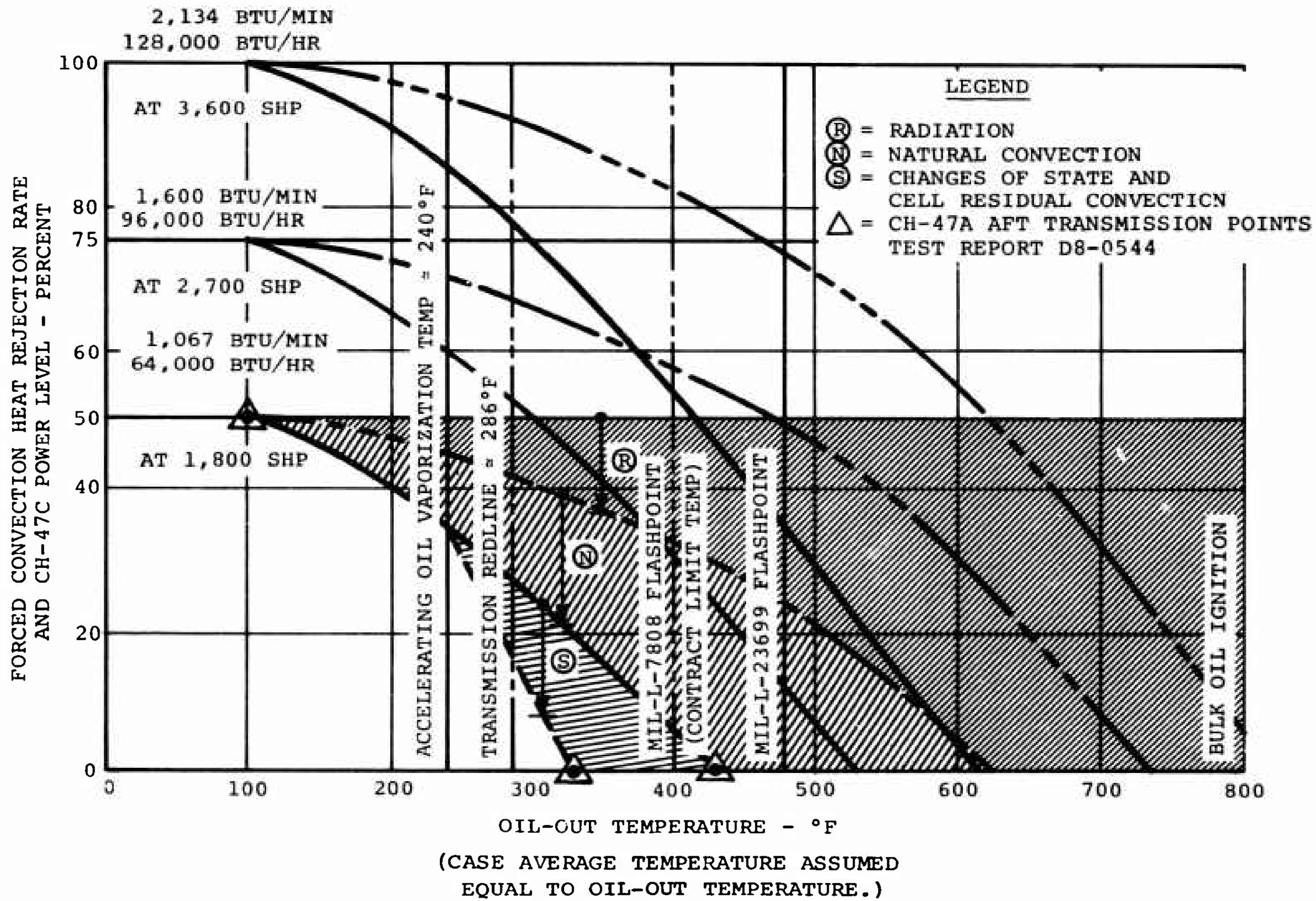


Figure 6. Theoretical Temperature Projection for Given Heat Rejection Rates and Power Levels (Based on CH-47 Forward Transmission Efficiency of 98.6 Percent).

where, q_r = heat rejection rate, Btu/hr

A = black/gray body (specimen transmission) surface area, ft^2 = 29 ft^2

T_1 = black/gray body surface temperature, (equal to oil-out temperature) ^oR

T_2 = temperature of surroundings (test cell wall temperature - ambient air temperature), 560^oR

ϵ = emissivity/absorptivity constant; optimistically assumed at 0.9/ non-dimensional

σ = Stefan-Boltzmann constant assumed at 0.173×10^{-8}; Btu/hr/ft^2/R^4

which becomes

$$q_r = 4.5153 \times 10^{-8}((t_1 + 460)^4 - (t_2 + 460)^4)$$

3. Convection:

Natural Convection

$$q_{cn} = h\,A\,(t_1 - t_2)$$

where q_{cn} = heat rejection, Btu/hr

A = specimen transmission surface area = 29 ft^2

h = $0.22\,(t_1 - t_2)^{1/3}$ for D specified below

D = specimen transmission average diameter = 2 ft

t_1 = specimen transmission surface temperature, ^oF

t_2 = ambient air temperature, ^oF

which becomes

$$q_{cn} = 6.38\ (t_1 - t_2)^{4/3}$$

Forced Convection (Oil)

$$q_{cf} = WC\ (t_1 - t_2)$$

where W = oil flow, 8775 lb/hr

C = 0.485 Btu/lb/^{o}F

t_1 = specimen transmission oil-out temperature, ^{o}F

t_3 = specimen transmission oil-in temperature, ^{o}F

Based on Boeing test data

$(t_1 - t_3) = \Delta t = 30^{o}F$,

and

$$q_{cf} = 8775 \times 0.485 \times 30 = 127{,}676 \text{ Btu/hr}$$

heat rejected by oil for 100 percent CH-47C transmission power.

Forced Convection (other than Oil)

None used (cell residual convection and heat of oil vaporization assumed from previous tests).

4. Changes of State: None used - unknown

The family of curves in Figure 6 indicate the three specimen power levels of the CH-47C transmission (which are one-to-one with the heat rejection rate) versus (the average case temperature) oil-out temperature when heat rejection is accomplished by a combination of natural convection, radiation, and partial amounts of forced convection (oil-cooler). When the oil cooler is fully bypassed and heat rejection is to be accomplished by natural convection and radiation alone, the case temperatures theoretically would reach those points indicated by the intersection of the curves with the 0 percent ordinate (horizontal) line. An analysis of the aft transmission (prior) test, however, does not bear this out. With the evidence of smoke-off beginning at 240°F and terminal temperature at 320°F, it appears that other means of heat rejection are operating (otherwise the case temperature would reach approximately 430°F). The straight line intersecting the lowest curve at 240°F and 0 percent (horizontal) line at 330°F represents a cutoff of case temperature rise to match test experience. A word of caution is appropriate here. The word stabilization has been used in several prior reports (including the proposal for this contract) which implied that no significant further rise in temperature could be expected with the continuation of the test run. Keeping in mind that aircraft redline (286°F) has been exceeded, that vaporization is in process, and that the flash point of the lubricant (MIL-L-7808 = 400°F) is being at least approached, the continuation of the test, at some point in time, will have depleted the system of its coolant and lubricant such that the bypass test becomes a nonlube self-destruct system. It is suggested that stabilization be used as a term only when the rate of vaporization is well known (or nonexistent) and under test controls.

Table I gave a comparison of the test conditions with their segments. Of the nine elements in the matrix, only one test segment (test 3, at 100 percent torque) may require heat rejection assist by partially employing the oil cooler so as not to exceed the contractual 400°F oil-out limit. It was planned that proper precautions be taken to reduce the risk of fire when approaching the 400°F (MIL-L-7808 flash point) limit.

At the original writing of this test plan, the substitution of MIL-L-23699 oil to replace MIL-L-7808 lubricant had been decided upon for these tests. The published minimum flash point of 400°F for MIL-L-7808 oil was compared to flash points of sample batches of MIL-L-23699 oil between 475°F and 500°F. (Specification, MIL-L-23699 minimum flash point = 475°F.) Subsequently, contractual requirements dictated the use of MIL-L-7808G since it formed a baseline.

THERMAL MAPPING TEST PLAN

Temperature

The thermal mapping test plan involved the placement of thermocouples and thermoplacards to record local temperatures experienced by the CH-47 forward transmission components. Figure 7 is a pictorial display of these components. The azimuthal and other identified positions of the thermocouples are shown in Table II. The positions of the bearing thermocouples include the maximum load points. The maximum load points of bearings A, C, D and E are shown in Figures 7 and 8.

The thermoplacard positions and their temperature (small dot type placards) ranges are identified in Table III. The temperature dot ranges are based on the prior aft transmission oil cooler bypass tests for the low-temperature end and the pretest thermal analysis (this contract) for the high-temperature end of the range. Where practical, a multiple number of temperature dots were positioned to preclude the necessity of a large number of disassemblies of components between tests to replace damaged or ineffective placards. As other backup means, thermopaint (or thermocrayon) smears were studied to obtain temperature data on these rotating parts that cannot be monitored in real time.

For selected test(s) determined during test segment runs, specifically between the 50 percent and 75 percent torque load test segment and the 75 percent and 100 percent torque load test segment of test 3, a visual check may be made of the actuated dot thermoplacards and thermopaint smears on rotating parts made visible by dropping the sump without disassembly of the transmission major components.

As an additional backup means of obtaining a record and corroboration of rotating component temperatures in the specimen transmission, a study for the practical placement of a machined access hole on the case near the intersection of the spiral bevel pinion face midplane and the sync shaft horizontal plane was made. The hole can be mechanically sealed to allow quick access between numbered test runs by a thermocouple probe to measure the gear blank temperature. Subsequently alternate means were devised.

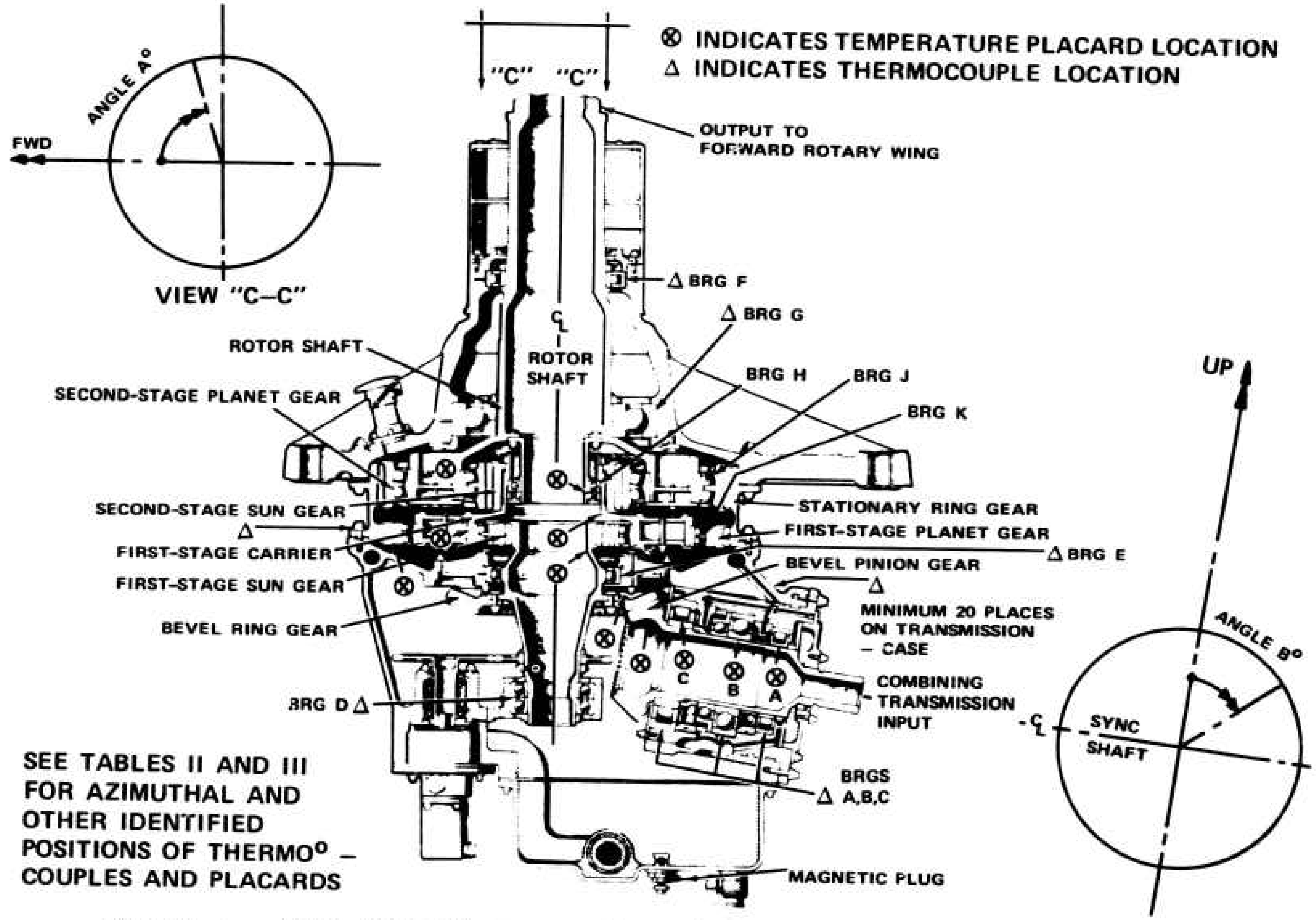


Figure 7. Test Plan Thermocouple and Temperature Placard Positions.

TABLE II. POSITIONS OF THERMOCOUPLES

THERMOCOUPLE NUMBER	TRANSMISSION/COMPONENT	ANGLE A	ANGLE B
1	Bearing D	100°	
2	Bearing E	75°	
3	Bearing F	12°	
4	Case/1st Stage Ring Gear	50°	
5	Bearing C		264.5°
6	Bearing C		150°
7	Bearing B		126°
8	Bearing A		126°
9	Bearing A		250°
10	Bearing G	0°	
11	Bearing D	280°	
12	Bearing E	255°	
13	Bearing F	192°	
14	Case/1st Stage Ring Gear	315°	
15	Bearing C		60°
16	Bearing B (Reverse Thrust)		126°
17	Bearing B (Reverse Thrust)		306°
18	Bearing A		12°
19	Subsequently Deleted		
20	Bearing G	180°	
21	Case/2nd Stage Ring Gear	45°	
22	Case/2nd Stage Ring Gear	190°	
23	Case/2nd Stage Ring Gear	315°	
24	Case Upper 114D1088	0°	On Arms 2" from
25	Case Upper 114D1088	90°	Fwd Bolt Equal
26	Case Upper 114D1088	180°	Radii from ℄
27	Case Upper 114D1088	270°	
28	Case Upper 114D1088	0°	Between Thrust
29	Case Upper 114D1088	180°	and Radial Bearings
30	Case Upper 114D1088	Approx 240°	(Surface)
31	Case Lower 114D1089	190°	(Oil-In)
32	Case Lower 114D1089	170°	(Oil-In)
33	Case Lower 114D1089	100°	(Surface at S/B Mesh Jet)
34	Case Lower 114D1089	180°	(S/B Cartridge Oil Drain)

TABLE II - Continued

THERMOCOUPLE NUMBER	TRANSMISSION/COMPONENT	ANGLE A	ANGLE B
35	Case Lower 114D1089	0°	At Plane of S/B Cone ℄
36	Case Lower 114D1089	90°	At Plane of S/B Cone ℄
37	Case Lower 114D1089	270°	At Plane of S/B Cone ℄
38	Case Lower 114D1089	In Plane of Brg B	90°
39	Case Lower 114D1089	In Plane of Brg B	270°
40	Sump 114D1042	210°	
41	Oil-Out Temp Probe (114D1042)	340°	Base of Filter (Oil Temp.)
42	Oil-In Temp Probe	35°	(Oil Temp.)
43	Test Stand (Heat Sink)	0°	Near Mtg Bolt
44	Test Stand (Heat Sink)	Fwd Cradle Box (Left on Box)	
45	Test Stand (Heat Sink)	Fwd Cradle Stand (Left on Stand)	
46	Air: Ambient Test Cell	90°	At ℄ Cone S/B
47	Air: Ambient Test Cell	On Console (on Hallwall)	
48	Air: Ambient Test Cell	0°	Near Box Mtg

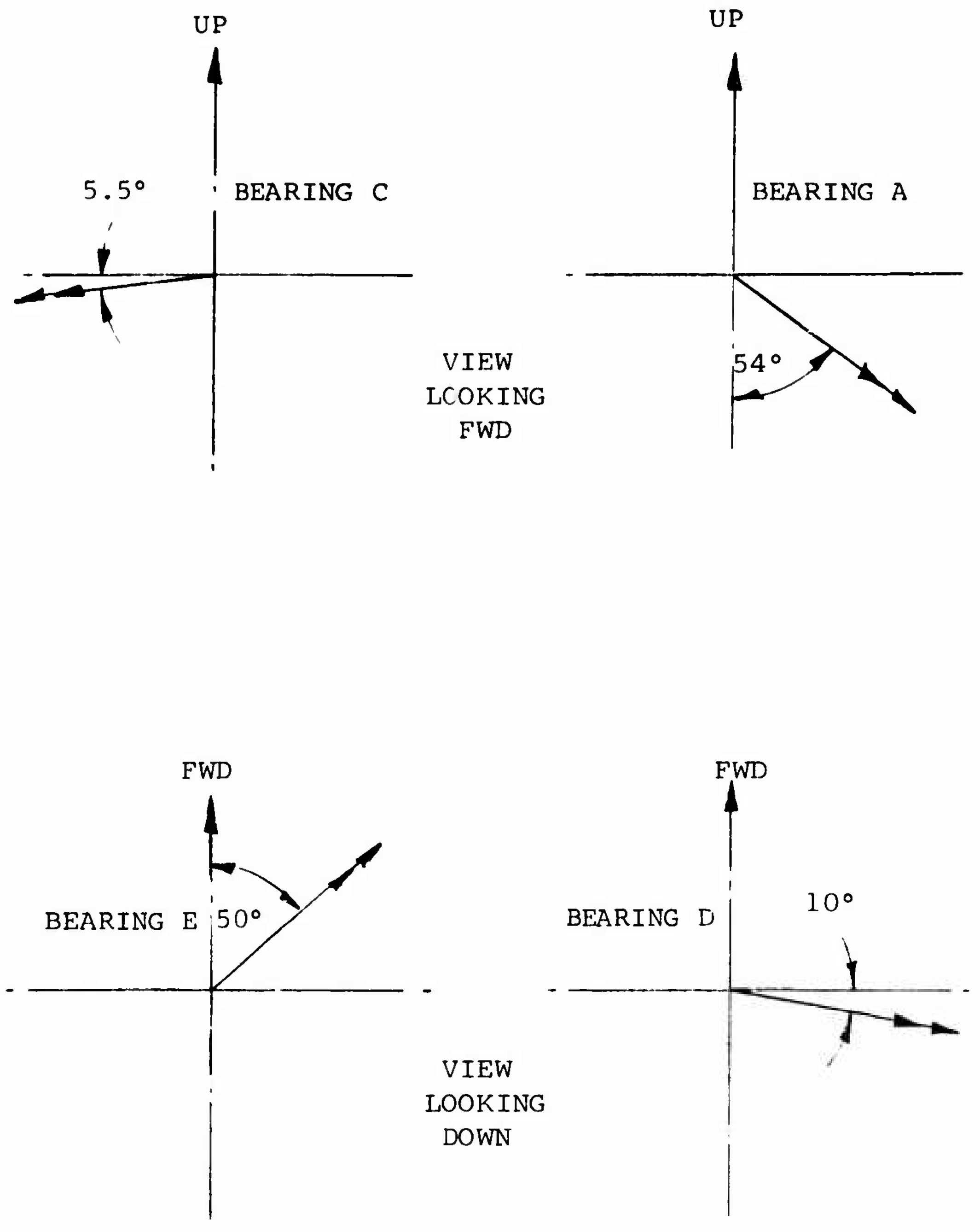


Figure 8. Maximum Load Vectors of Bearings A, C, D, and E.

TABLE III. POSITIONS OF THERMOPLACARDS

THERMOPLACARD NUMBER	TRANSMISSION COMPONENT	TEMPERATURE RANGE (°F)	TEMP-PLATE PART NO.*
		290,300,310	430
1	S/B Pinion	380,390,400	430
	Under Teeth	480,490,500	430
		550,600,650,700	101-4
2	S/B Pinion	290,300,310	430
	Under Brg. A	380,390,400	430
3	S/B Pinion	290,300,310	430
	Under Brg. B	380,390,400	430
4	S/B Pinion	290,300,310	430
	Under Brg. C	380,390,400	430
		290,300,310	430
5	S/B Gear	380,390,400	430
	Under Teeth	480,490,500	430
		550,600,650,700	101-4
		290,300,310	430
6	1st Sun Gear	380,390,400	430
	Under Teeth	480,490,500	430
		550,600,650,700	101-4
7	1st Planet	290,300,310	430
	Lower Face	380,390,400	430
8	1st Planet	290,300,310	430
	Carrier Arm I.D.	380,390,400	430
		290,300,310	430
9	2nd Sun Gear	380,390,400	430
	Shaft I.D.	480,490,500	430
		550,600,650,700	101-4
10	2nd Planet	290,300,310	430
	Lower Face	380,390,400	430

TABLE III - Continued

THERMOPLACARD NUMBER	TRANSMISSION COMPONENT	TEMPERATURE RANGE (°F)	TEMP-PLATE PART NO.*
11	2nd Planet Carrier Arm I.D.	290,300,310 380,390,400	430 430
12	2nd Sun Shaft Under Bearing H	290,300,310 380,390,400	430 430
13	(Same as 1 and 5)		
14	Rotor Shaft O.D. Above Seal	290,300,310 380,390,400	430 430
15	Deleted		
16	Deleted		

*Temp-plate No. 430 or No. 101-4 as fabricated by William Wahl Corporation or equivalent.

Growth

The thermal mapping test plan also involves the measurement of thermal growth. A work statement line item specifies that the thermal growth of the transmission housing shall be deduced from a suitable combination of measurements and analytical methods.

Table IV identifies diametrical and axial dimensions from which growth to be measured before and after each numbered test run may be selected. When the dimensional records were taken, the temperatures indicated by the thermocouples were also recorded. Figure 9 is a display of these dimensional checks for subsequent thermal growth analysis which is included in this final report.

The subsequent measurements were taken by direct micrometer/ trammel readings. The reading real-times were noted on the thermocouple oscillograph records in real-time.

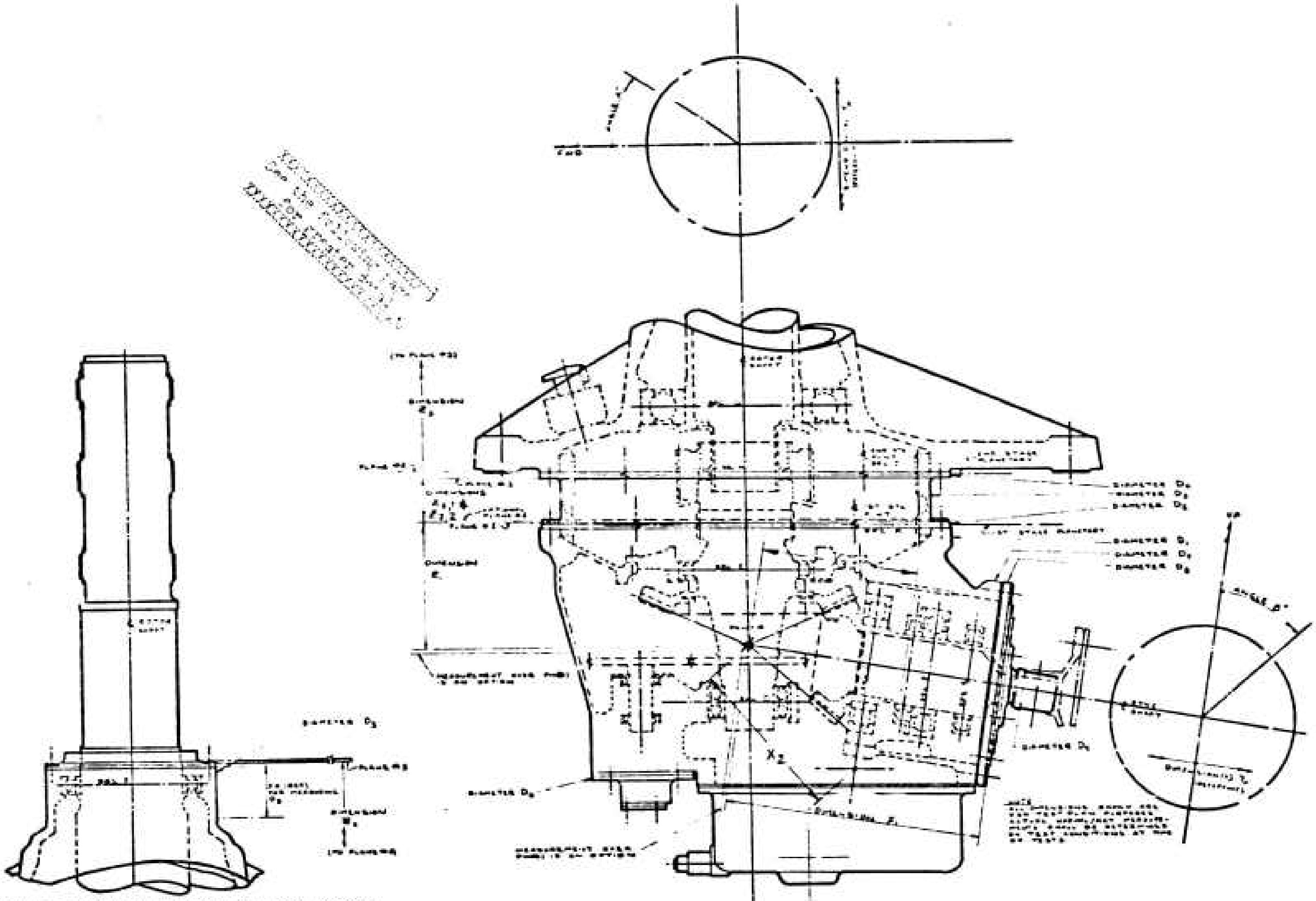


Figure 9. CH-47C Forward Transmission Thermal Growth Dimensions Drawing.

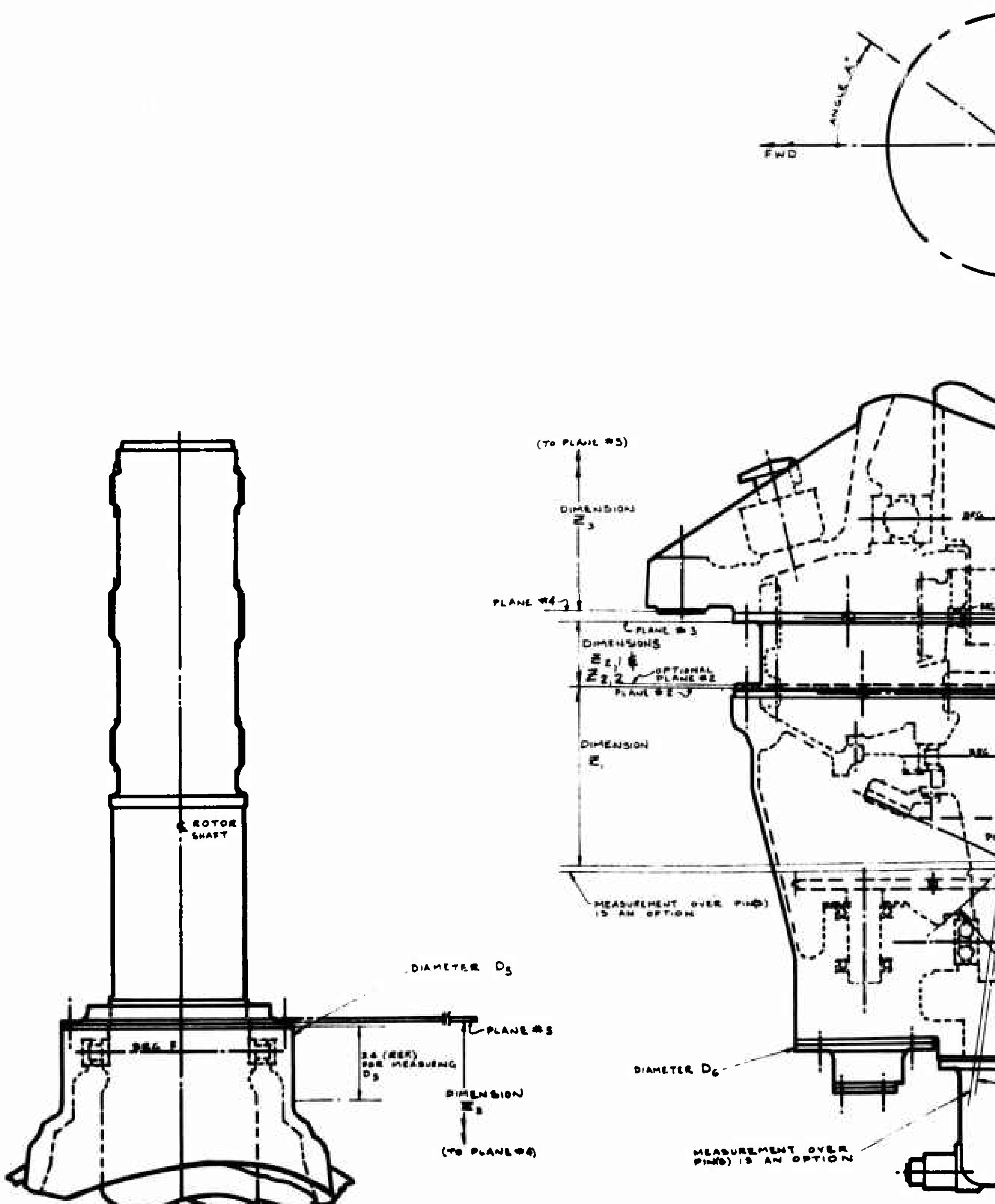
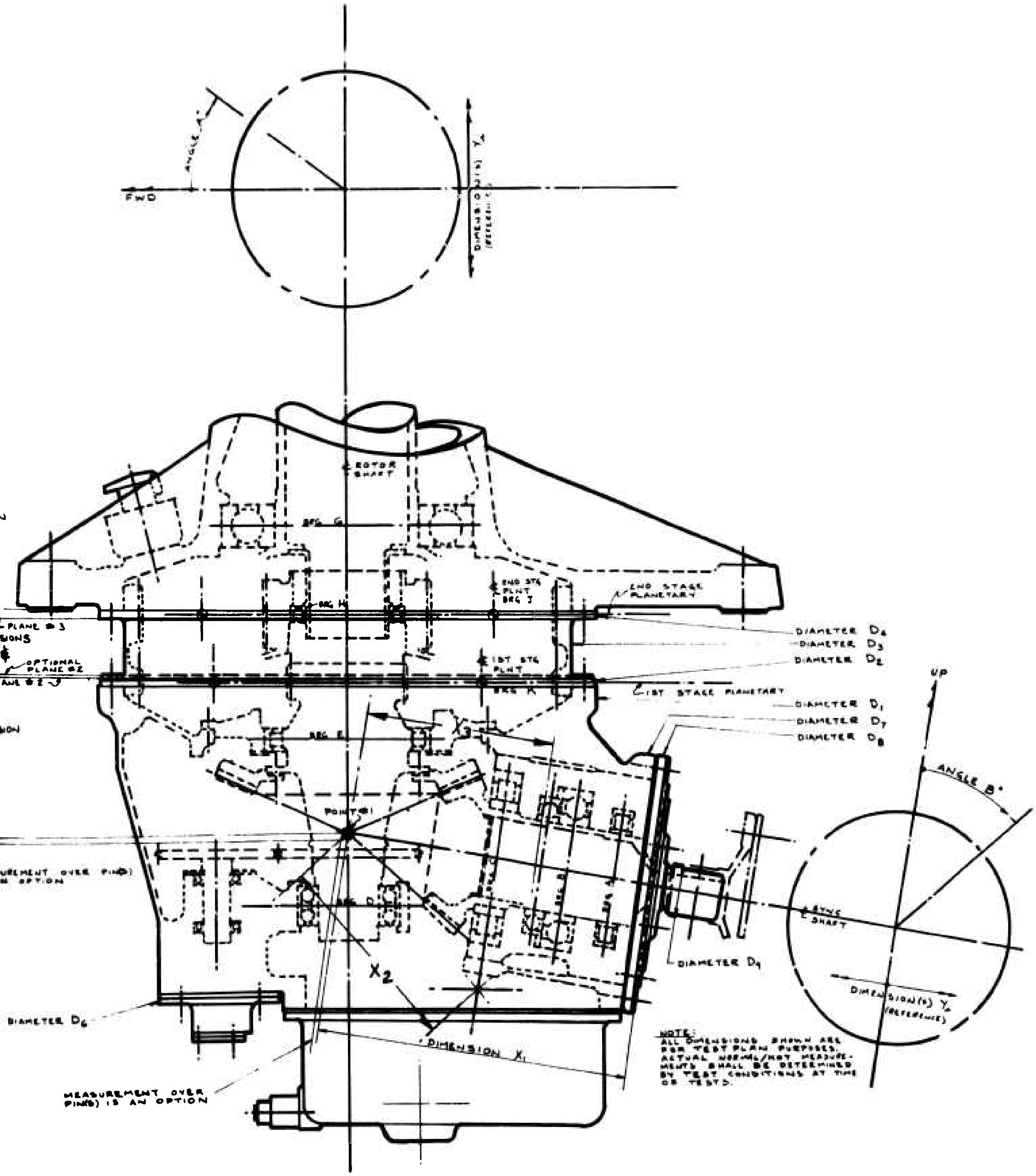


Figure 9. CH-47C Forward Transmission Thermal Growth Dimensions Drawing.



FWD
ANGLE A°
DIMENSION (Z) Y₁ (REFERENCE)
ROTOR SHAFT
BRG G
BRG H
2ND STG PLNT BRG J
2ND STAGE PLANETARY
DIAMETER D₄
DIAMETER D₃
DIAMETER D₂
1ST STG PLNT BRG K
1ST STAGE PLANETARY
DIAMETER D₁
DIAMETER D₇
DIAMETER D₈
OPTIONAL PLANE #2
BRG E
POINT #1
X₃
X₂
UP
ANGLE B°
SYNC SHAFT
DIAMETER D₉
DIMENSION (Z) Y₂ (REFERENCE)
DIAMETER D₆
DIMENSION X₁
MEASUREMENT OVER PIN(S) IS AN OPTION
NOTE: ALL DIMENSIONS SHOWN ARE FOR TEST PLAN PURPOSES. ACTUAL NORMAL/HOT MEASUREMENTS SHALL BE DETERMINED BY TEST CONDITIONS AT TIME OF TESTS.

TABLE IV. MEASUREMENTS OF THERMAL GROWTHS (Case Elements)	
DIMENSIONS OR DIAMETERS*	LOCATIONS*
D1 (Dia.)	Around Planetary Stages
D2 (Dia.)	
D3 (Dia.)	
D4 (Dia.)	
D5 (Dia.)	Rotor Shaft Radial Bearing Housing
D6 (Dia.)	Pump Housing
D7 (Dia.)	Sync Shaft
D8 (Dia.)	
D9 (Dia.)	Sync Shaft Coupling
X1 (Dim.)	Point thru Rib at Cone ℄ S/B and ℄ Shaft at D7 Diameter
X2 (Dim.)	Diagonal: ℄ S/B Cone and Sump Flange at Bearing C
X3 (Dim.)	Between B and C Bearings on ℄ Shaft and Cone ℄ S/B
Z1 (Dim.)	S/B Cone Center and Plane 2
Z2, 1 (Dim.)	Outer Points
Z2, 2 (Dim.)	Inner Points
Z3 (Dim.)	Between Planes 4 and 5

*See Figure 9

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SPECIMEN TRANSMISSION MODIFICATION AND INSTRUMENTATION

After receipt of approval of the thermal mapping test plan, the test specimen (one GFE CH-47C forward rotor transmission) was inspected and its condition for use in this test was deemed acceptable. Upon further review it was found necessary to lock the outer races of the spiral bevel pinion bearings from rotation in their case liners in anticipation of thermal expansion/growth. The bearings were then keyed against bearing drag torque. The interchange of the equivalent bearing elements, however, required reshimming from 0.046 inch thickness to 0.070 inch thickness in order to maintain the proper spiral bevel mesh gear pattern. The acceptable condition of all components after preparation for instrumentation thermocouples, thermoplacards, and thermal growth measurement locations was recorded by Polaroid photographs. The selected photographs which follow display the modifications made, consistent with the plan of performance and the thermal mapping test plan, including backup thermal instrumentation.

BACKUP THERMAL INSTRUMENTATION

As a backup against washing-out of temperature placards on the spiral bevel pinion and gear, a balanced, paired set of thermocouples was placed under the spiral bevel teeth at the I.D. and the leads threaded through the oil seal dam and attached to the drive shaft Thomas coupling adapter.

Additional and subsequent backup against placard washout was provided by removing the baffle and screen from the breather and reassembling the breather, with a quick-disconnect standpipe venting to atmosphere, to the transmission. This standpipe quick-disconnect feature allowed visual inspection and recording of temperature of the first- and second-stage planet gear blanks. At shutdown of any test segment, the spiral bevel pinion temperature was recorded on a separate oscillograph and afforded the opportunity to investigate the presence or absence of time-lag soakback phenomena. The temperatures of the first- and second-stage planets were recorded using a pyrometric-millivolt potentiometer hookup. The readings were locked-in on real-time notations using the real-time thermocouple oscillographs which were kept operational after test segment run shutdowns.

SPECIMEN MODIFICATIONS

Figures 10, 11 and 12 are inspection records of the acceptable condition of the spiral bevel pinion and gear, first-stage sun and planet, and second-stage sun and planet, respectively. Figure 13 shows the machining preparation for Thermocouple 2 (Bearing E). Figure 14 is a record which shows several seal-type spring-loaded thermocouples in position in the lower case (with spiral bevel gear subassembly omitted). Figures 15, 16, and 17 are right side, left side, and bottom side records of thermocouple and/or receptacle positions on the lower case, respectively. Figure 18 is a typical record of a trammel detent marking (the position shown is the spiral bevel gear cone center projected to the outside web on the lower case used to measure thermal growth). Figures 19 through 26 give a photographic record of the temperature placards and/or thermocouple backup for the spiral bevel pinion and gear; first-stage sun, planet, and planet carrier arm; and second-stage sun, planet, and planet carrier arm; respectively. Figure 27 is a record of the spiral bevel pinion cartridge in a modified state to accept thermocouples and bearings A, B, and C outer-race drag-torque locking key machining/assembly. Figure 28 shows the spiral bevel pinion and gear (with first-stage sun) in a subassembly state (the locking keyways on bearings A, B, and C can be seen in Figure 27). Figures 29 through 32 are records of the assembled modified specimen transmission (with thermocouple leads attached) prior to installation in the test stand. The order presented represents the forward, right, aft, and left sides, respectively.

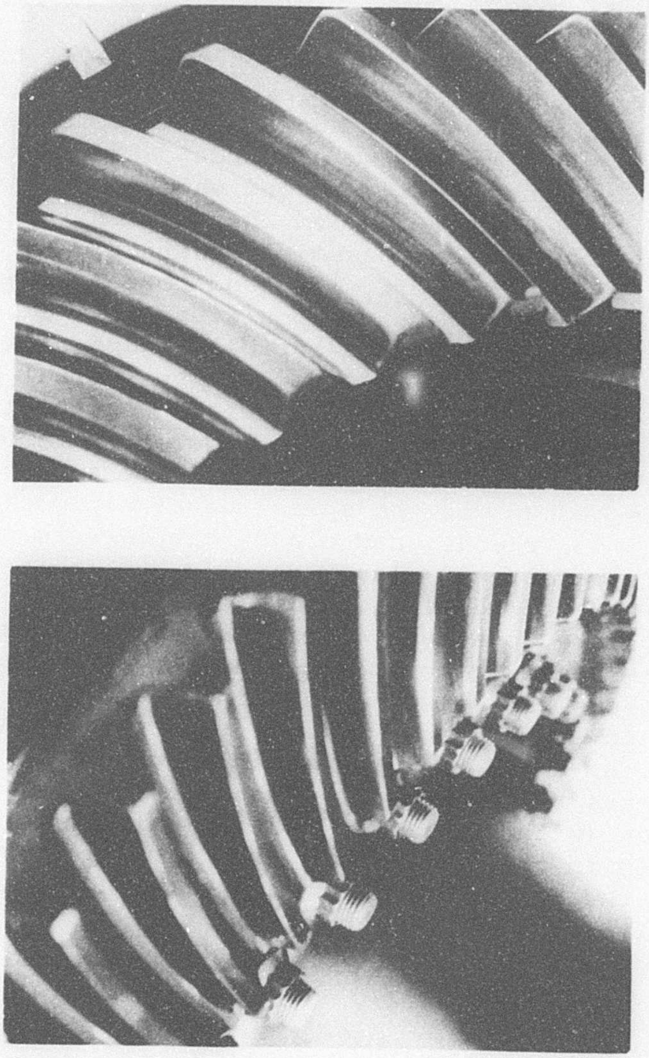


Figure 10. Postinspection Photograph of Spiral Bevel Pinion and Gear.

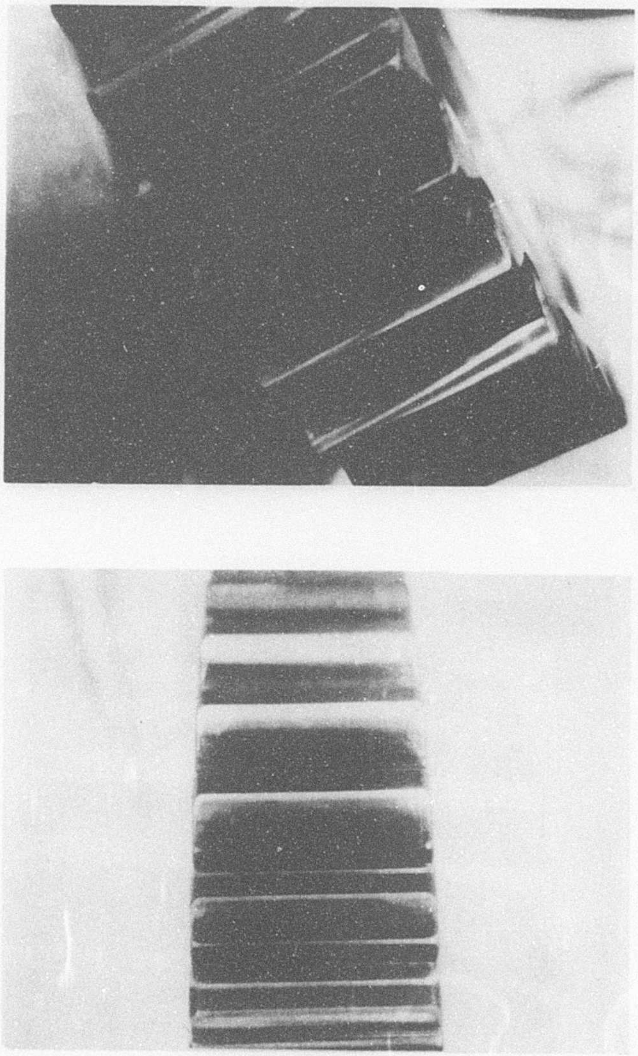


Figure 11. Postinspection Photograph of First-Stage Sun and Planet Gears.

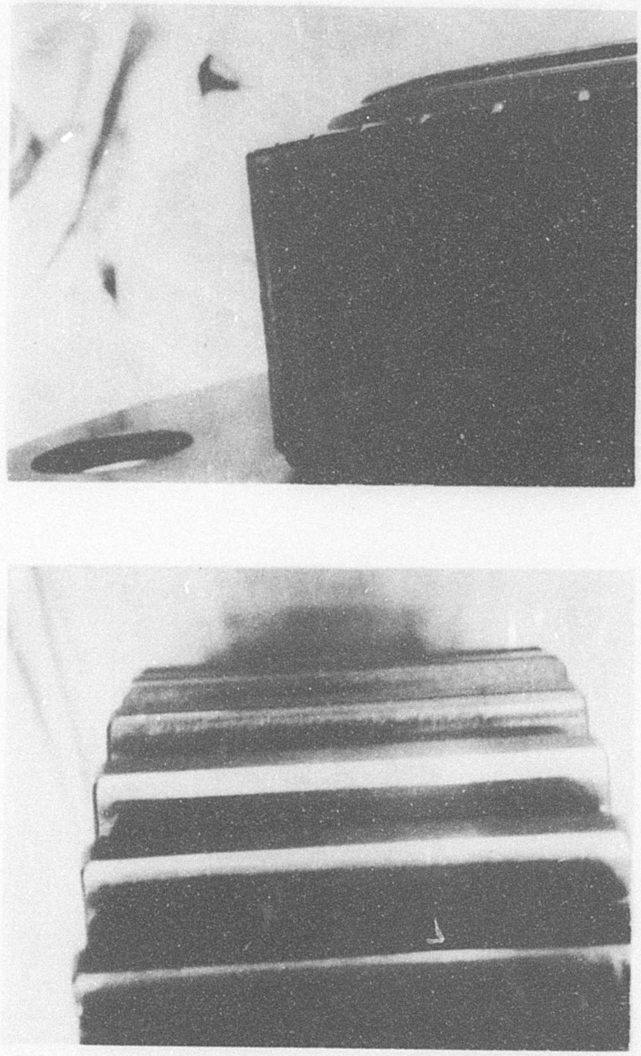


Figure 12. Postinspection Photograph of Second-Stage Sun and Planet Gears.

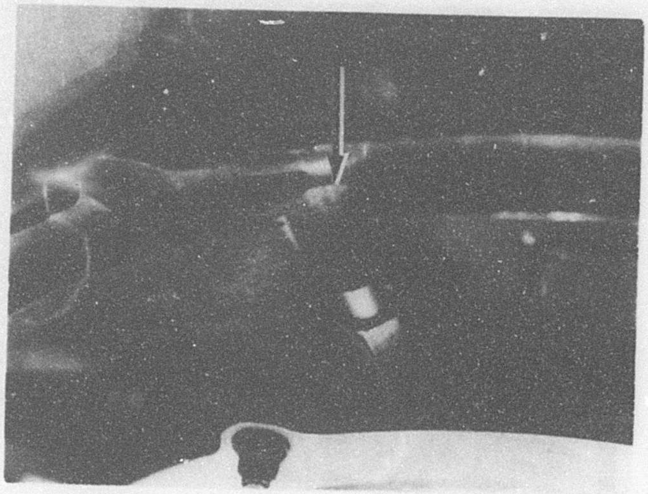


Figure 13. Machining Preparation for Thermocouple 2 (Bearing E).

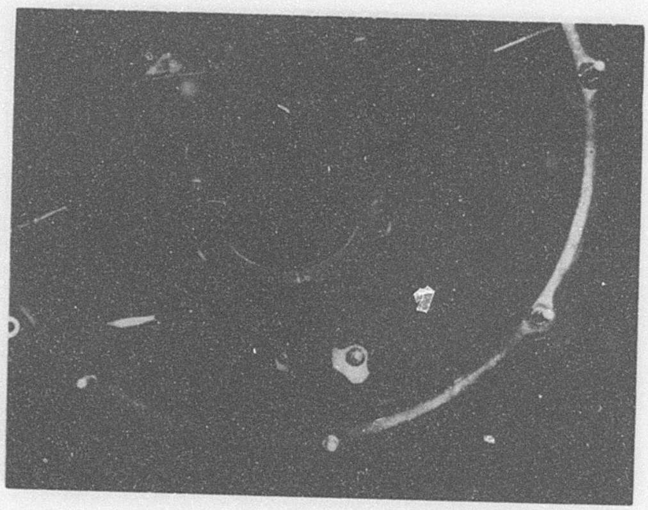


Figure 14. Several Seal-Type Spring-Loaded Thermocouples in Position in Lower Case.

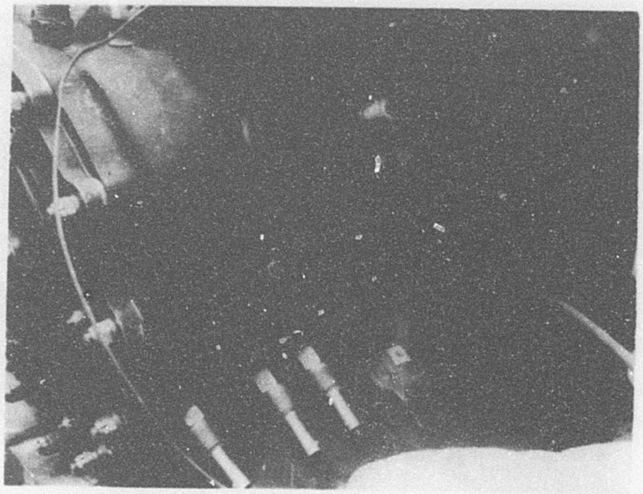


Figure 15. Right Side of Thermocouple and Receptacle Positions on Lower Case.

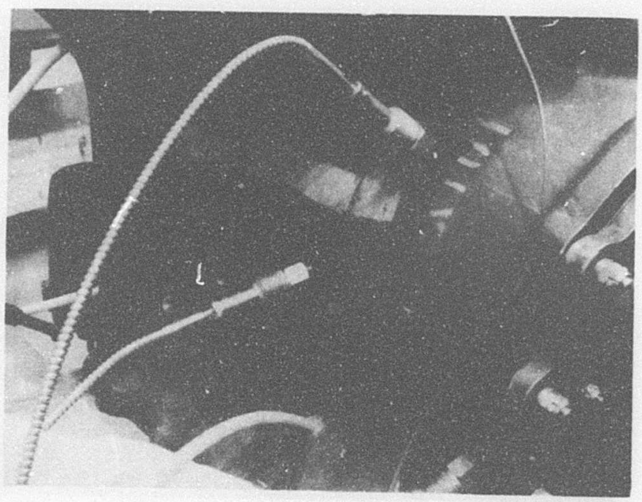


Figure 16. Left Side of Thermocouple and Receptable Positions on Lower Case.

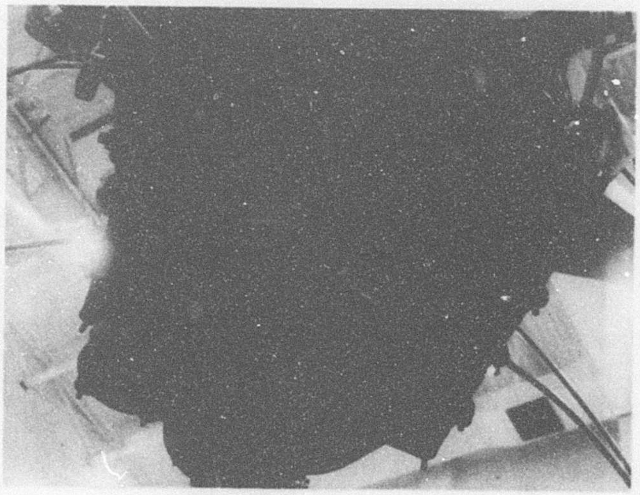


Figure 17. Bottom Side of Thermocouple and Receptacle Positions on Lower Case.

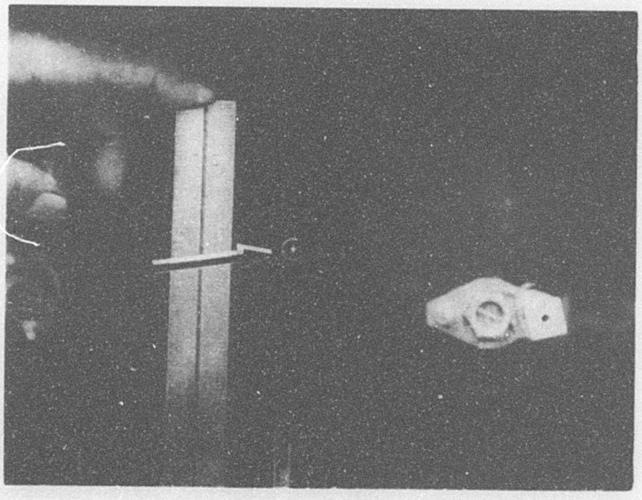


Figure 18. Typical Trammel Detent Marking (Used to Measure Thermal Growth).

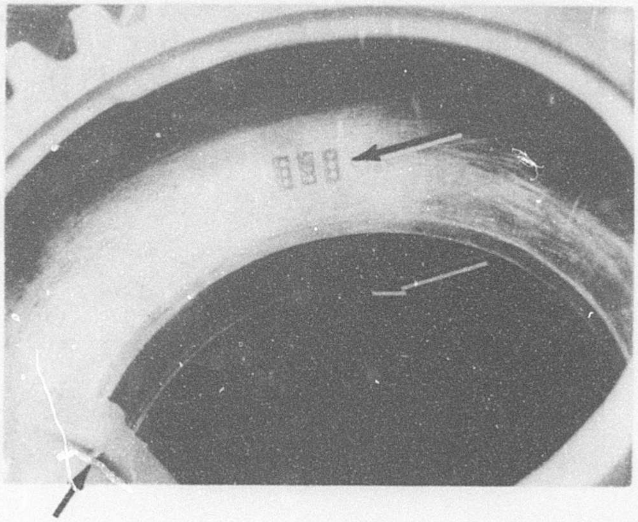


Figure 19. Temperature Placards and Thermocouple Backup of Transmission Gear Elements.

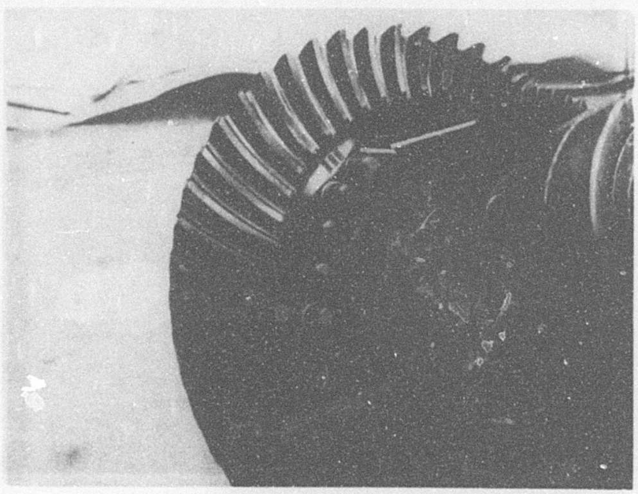


Figure 20. Temperature Placards and Thermocouple Backup of Transmission Gear Elements.

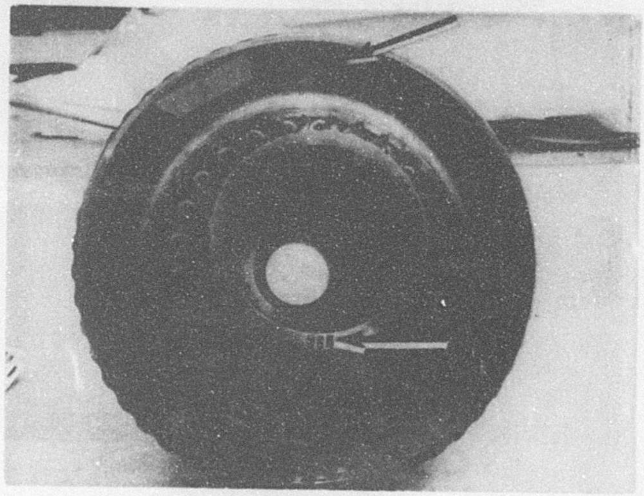


Figure 21. Temperature Placards and Thermocouple Backup of Transmission Gear Elements.

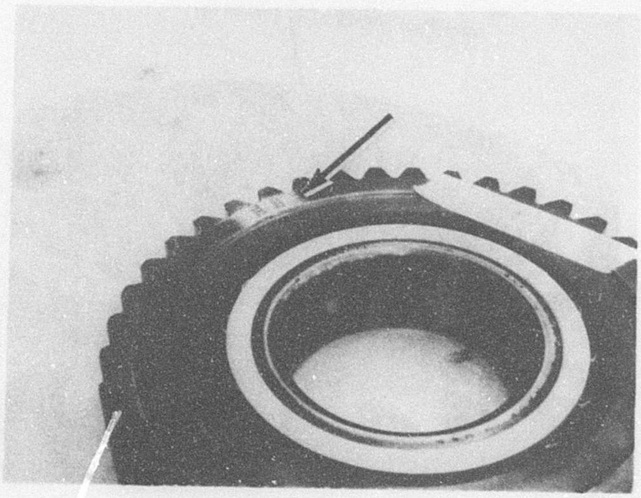


Figure 22. Temperature Placards and Thermocouple Backup of Transmission Gear Elements.

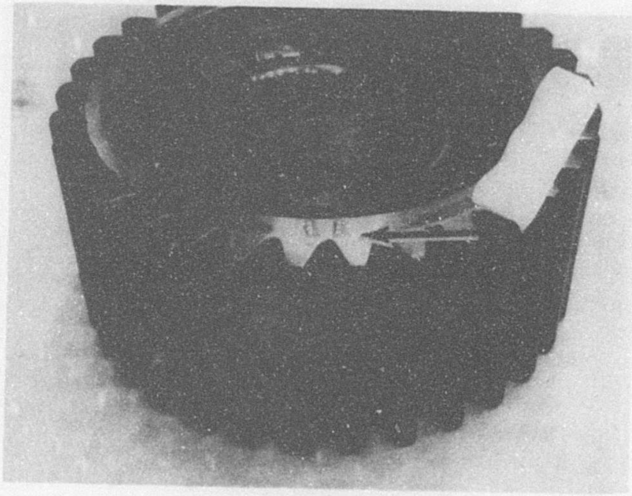


Figure 25. Temperature Placards and Thermocouple Backup of Transmission Gear Elements.

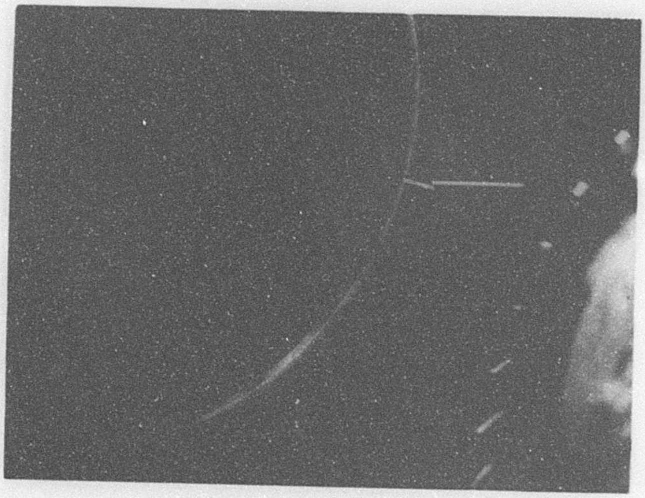


Figure 26. Temperature Placards and Thermocouple Backup of Transmission Gear Elements.

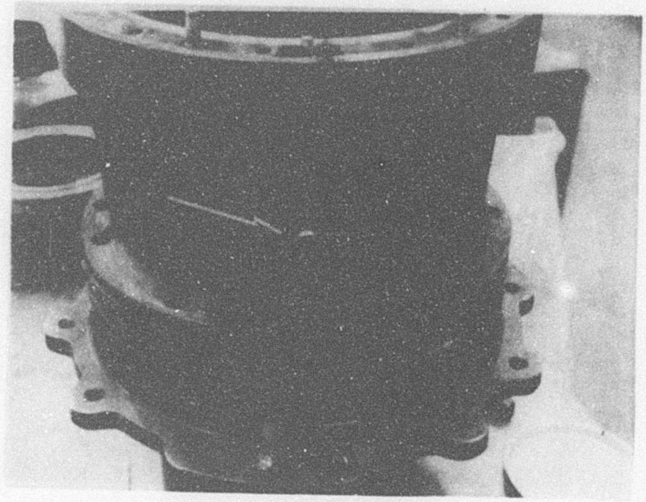


Figure 27. Modified Spiral Bevel Pinion Cartridge.

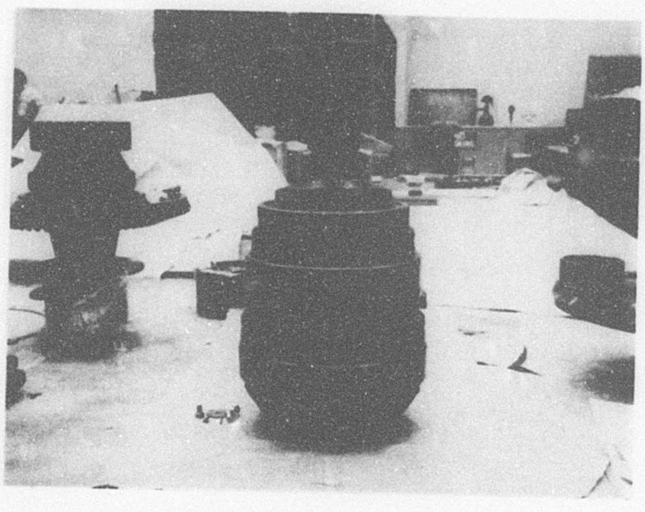


Figure 28. Spiral Bevel Pinion and Gear Subassembly.

Figure 29. Forward Side of Instrumented Transmission.

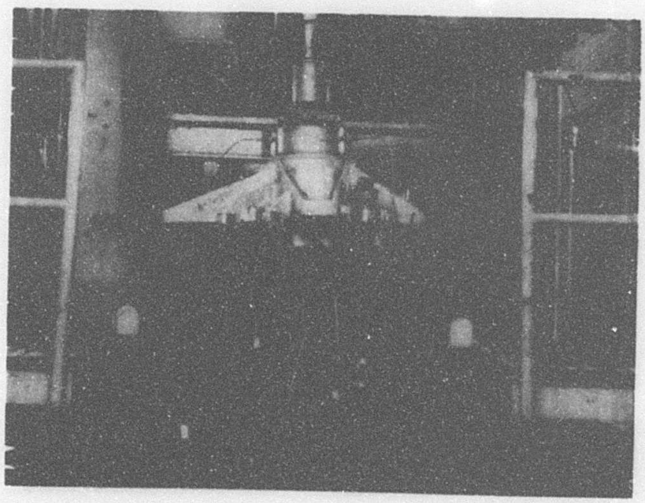


Figure 30. Right Side of Instrumented Transmission.

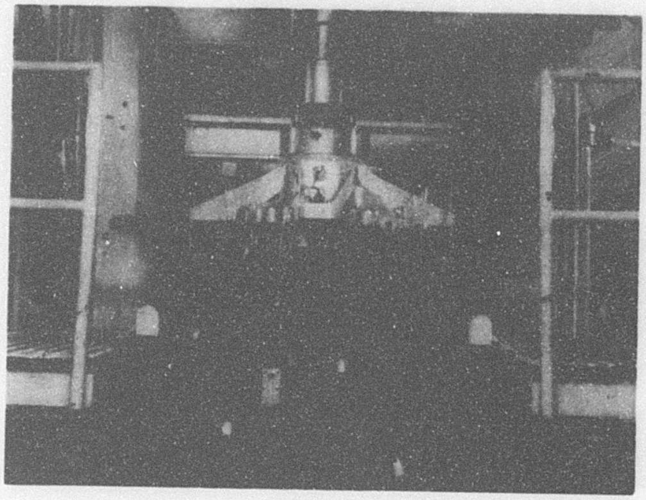


Figure 31. Aft Side of Instrumented Transmission.

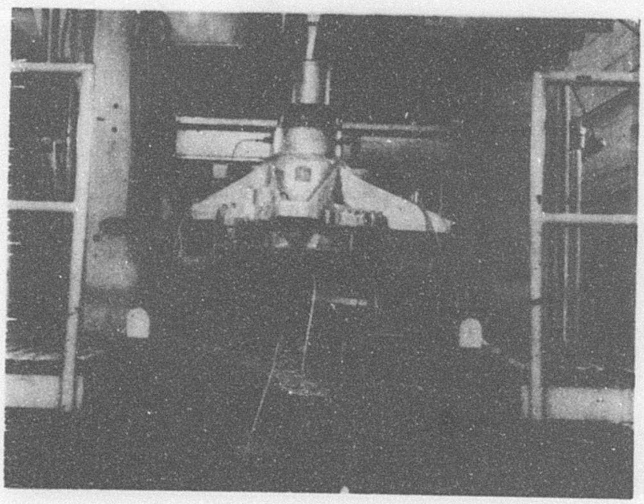


Figure 32. Left Side of Instrumented Transmission.

TEST CELL MODIFICATIONS AND INSTRUMENTATION

The forward rotor transmission test stand was purged of lubricant MIL-L-23699 in preparation for charging the system with MIL-L-7808 lubricant. The Cell 5 on-off oil-cooling switch was bypassed and replaced by a variable control valve for remote control on the back of the cell instrument console. In addition, the specimen instrumentation console was placed adjacent to the cell permanent console. Infrared (sensing/transmitting) equipment was placed inside the cell to augment recording and monitoring of the surface temperatures of the specimen in real-time. Scanning of the specimen is by remote control outside the cell. Special oil-in and oil-out temperature gages to bracket the ranges expected during the tests were provided (since present console gage maximums are 300°F).

The transmission specimen was positioned in the four-square test stand torque-loop. All calibrations (mechanical, electrical, thermal, and infrared) for the stand and additional equipment were made. Several oil leaks where thermocouple leads protrude from the specimen were sealed. The system was charged with approximately 35 quarts of MIL-L-7808 lubricant.

Figure 33 is a schematic diagram of the subsystems making up the closed-loop test stand. Figures 34 through 37 show the specimen instrumented transmission mounted in the test stand. The respective figures in order are: fwd (oblique), right-aft (oblique), left-aft (oblique), and top-aft views. These photographs show the specimen with the thermal instrumentation hookups as well as the lubrication lines leading to the console located outside the test cell. Figure 38 is a photograph of the test monitoring units. The heat exchanger water-flow control valve modification (for control of oil inlet and oil outlet temperatures) is out of the field of view in Figure 38, but lies on the floor between the cell permanent instrumentation console and the special oscillographic (including backup channel) console for this test on the far right. Behind the oscillographic console, the infrared recording console can be seen. A better view of the infrared temperature recording console is shown in Figure 39 with CRT visor and Polaroid camera mounted to the display unit. Figure 40 shows the infrared sensing and transmitting unit in position in the test cell. It is targeted on the

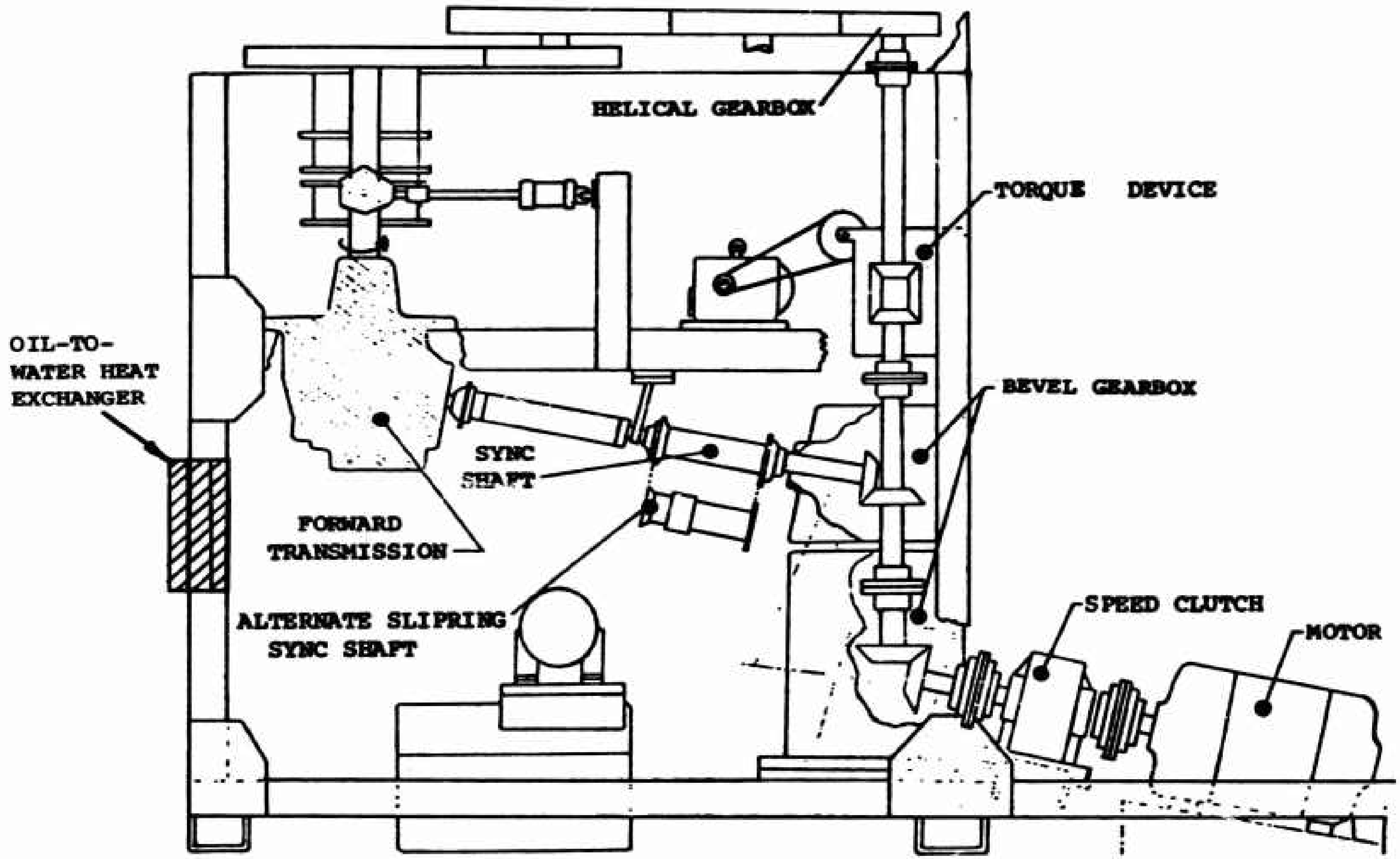


Figure 33. Schematic Diagram of Closed-Loop Test Stand.

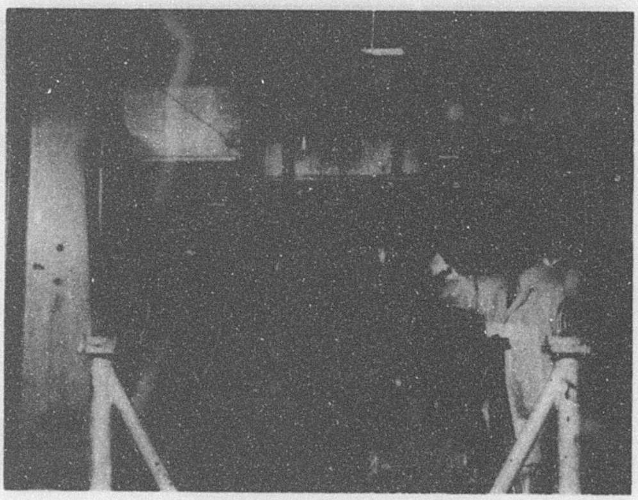


Figure 34. Forward View of Specimen in Test Stand.

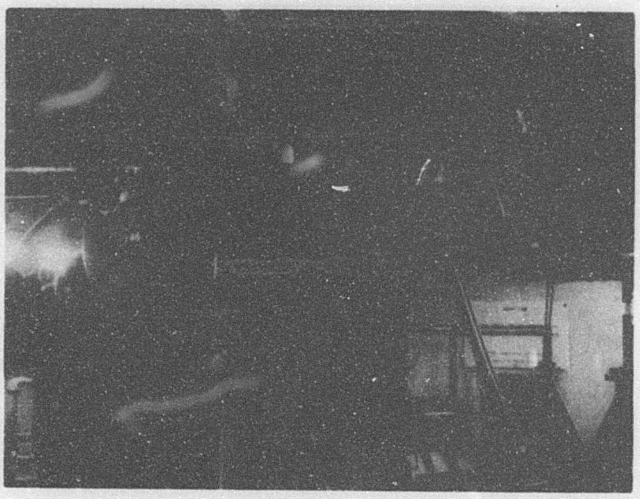


Figure 35. Oblique Right-Aft View of Specimen in Test Stand.

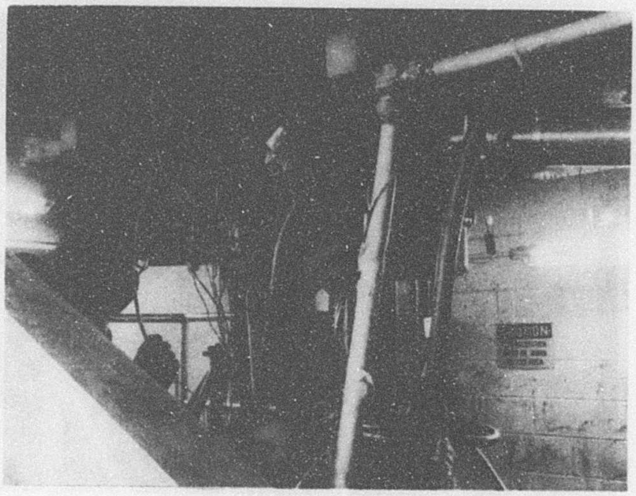


Figure 36. Oblique Left-Aft View of Specimen in Test Stand.

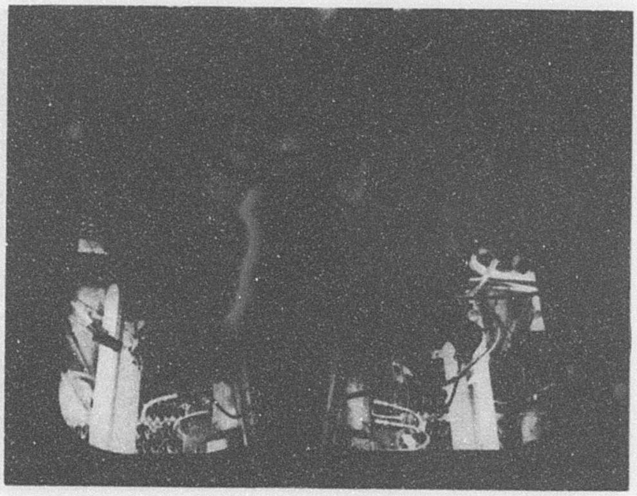


Figure 37. Oblique Top-Aft View of Specimen in Test Stand.

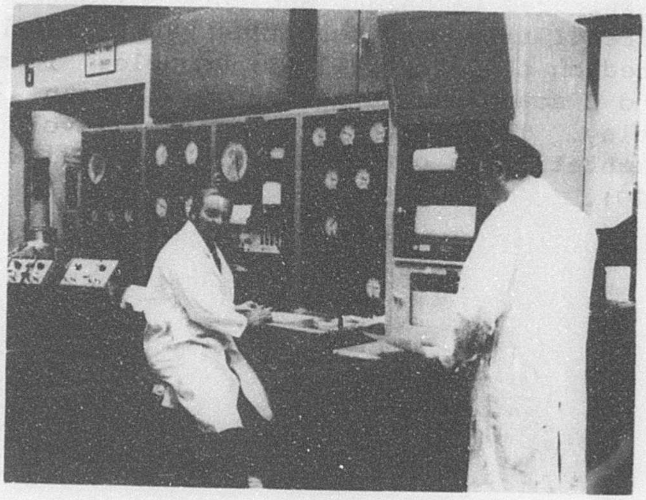


Figure 38. Test Monitoring Units.

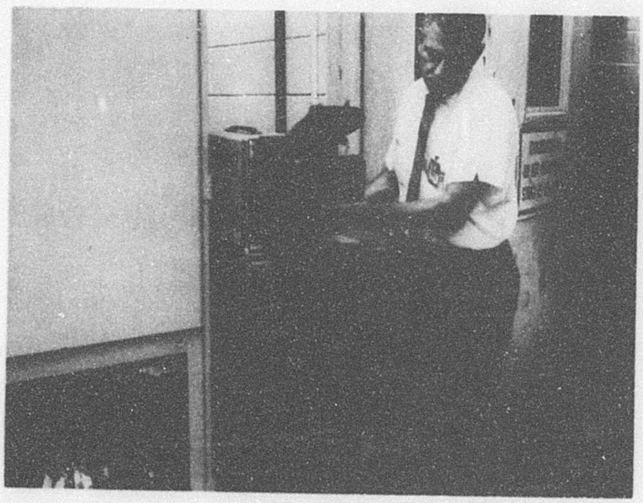


Figure 39. Infrared Temperature Recording Console.

specimen's right side. Appendix I gives a complete description of the infrared technique and data collected during these tests. Figure 41 is a representative record of the infrared data presented on the display (CRT) console. It shows superimposed A and C scans including changes in scan signatures with time delay. The backup pyrometric-millivolt potentiometer instrumentation is out of the fields of view (Figures 38 through 40).

Figure 40. Infrared Sensing and Transmitting Unit in the Test Cell.

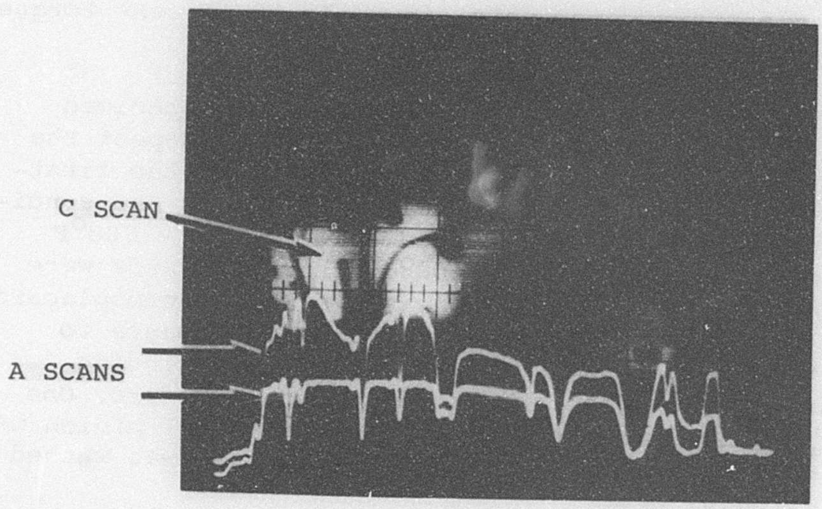


Figure 41. Typical Infrared Data Display.

TEST RESULTS

In accordance with the test plan and the performance plan, all tests were conducted with lift, drag, and pitch loads of 23,000 lb, 4,000 lb, and 157,000 in.-lb, respectively, in addition to the torque/rpm schedules shown in Table I.

TEST 1 THERMAL DATA AND INSPECTION
(Oil-out = 180°F ± 10 Percent)

Figures 42 through 46 are thermal maps indicating the component and/or case surface temperatures recorded in real-time and/or at shutdown. In order, these are records of test segments at 10 percent, 50 percent, 75 percent, and 100 percent torque, respectively. The reader is referred to the section below entitled Data Reduction and Evaluation for a critique of this presented data. No disassembly inspections between test 1 torque load segments were planned; no need to inspect from symptomatic monitoring test segments was indicated; and therefore no disassembly inspection was made. A visual inspection was made, however, of the first- and second-stage planetary components after the 50 percent torque load segment.

At the conclusion of all segments of test 1, the specimen transmission was disassembled, in the stand, to inspect the spiral bevel gear mesh teeth condition as well as the first- and second-stage planet gear blank(s) temperatures and condition. Oil from the sump was strained. Two 550°F - 700°F thermoplacards and two 380°F - 400°F thermoplacards were recovered from the oil. In addition, all of the thermoplacards on the spiral bevel pinion and gear indicated exposure to high temperature even though real-time records including infrared monitoring did not substantiate such exposure. One 380°F - 400°F thermoplacard from the spiral bevel pinion was washed off, and one 550°F - 700°F thermoplacard was washed off the spiral bevel gear.

It became obvious that backup means of recording gear blank temperatures (other than thermoplacards) must be used. Consequently, the transmission breather was disassembled, its baffle and screen were removed, a standpipe (venting to atmosphere and rigged for quick removal) was fixed to the breather, and the breather was reassembled to the transmission. This

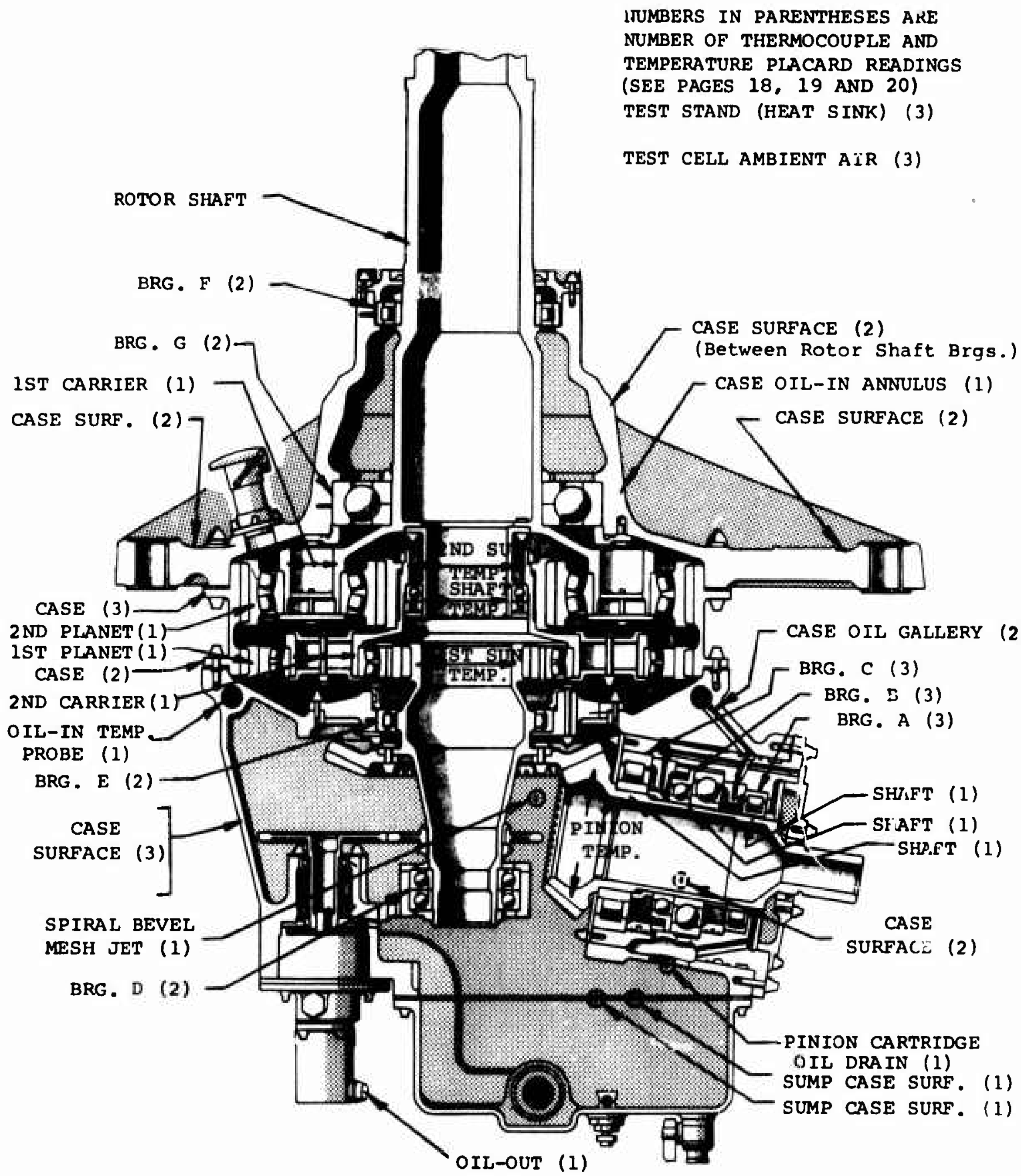


Figure 42. Thermal Mapping Component Temperature Legend.

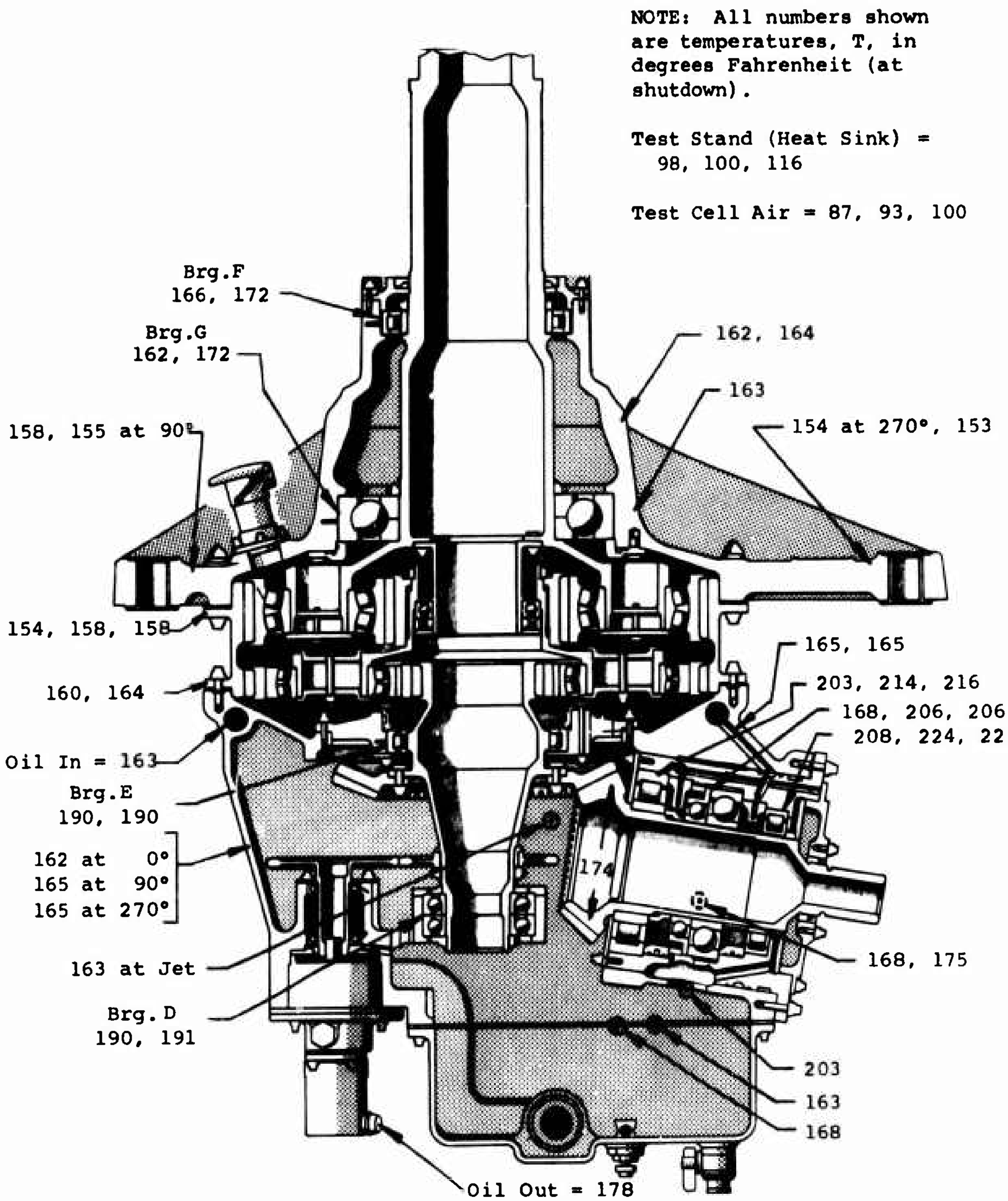


Figure . Thermal Map of Test 1 at 10 Percent Torque.

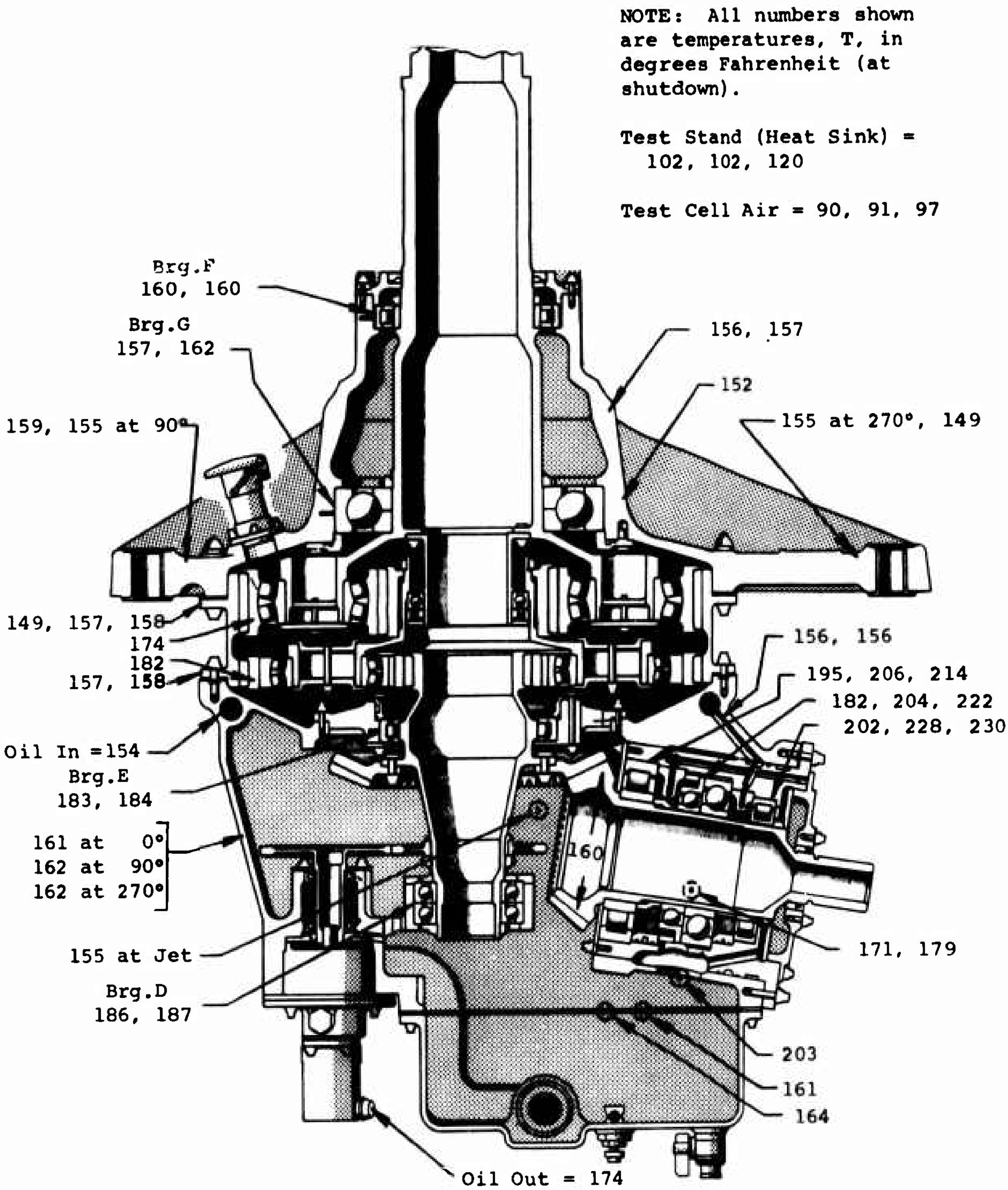


Figure 44. Thermal Map of Test 1 at 50 Percent Torque.

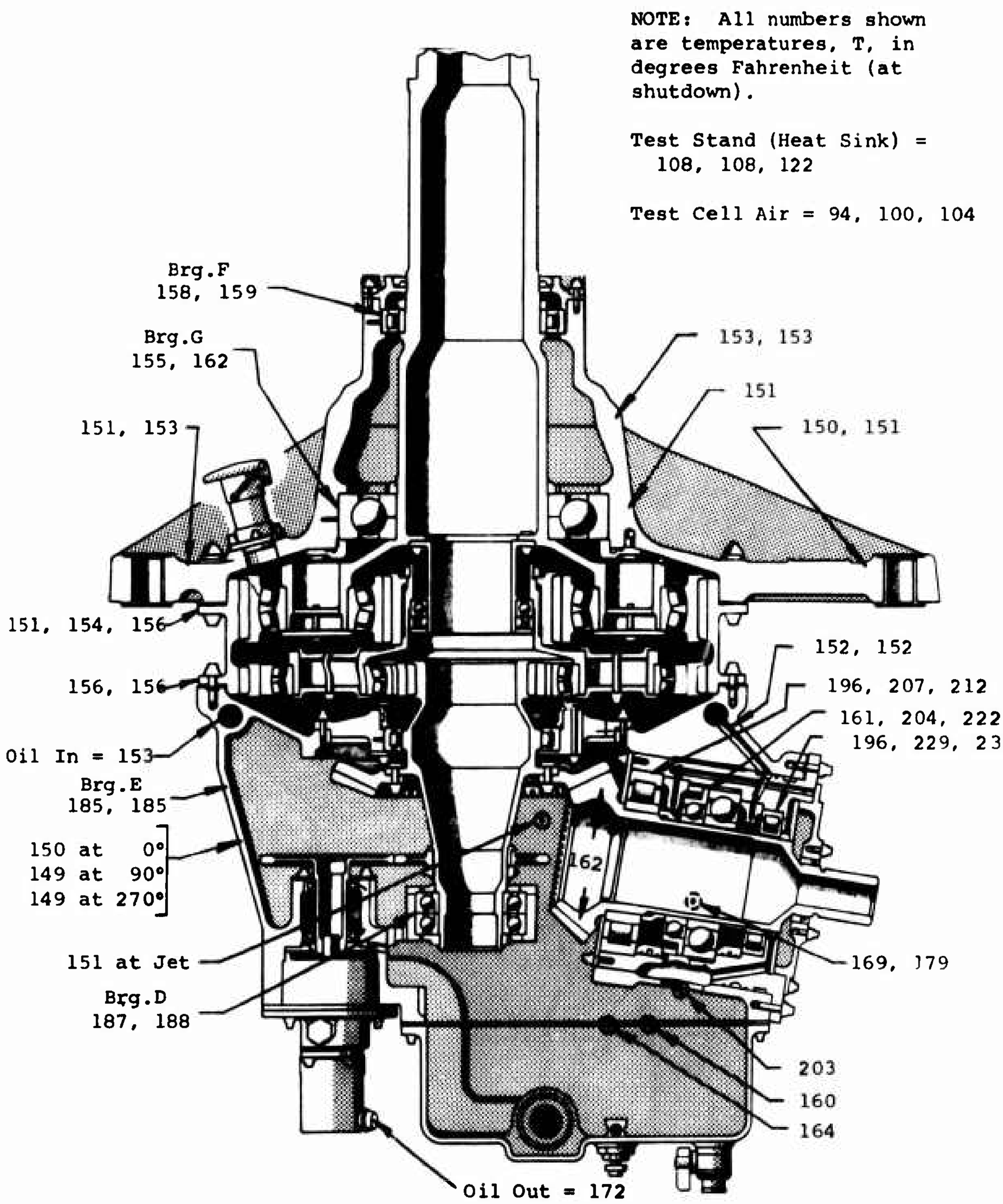


Figure 45. Thermal Map of Test 1 at 75 Percent Torque.

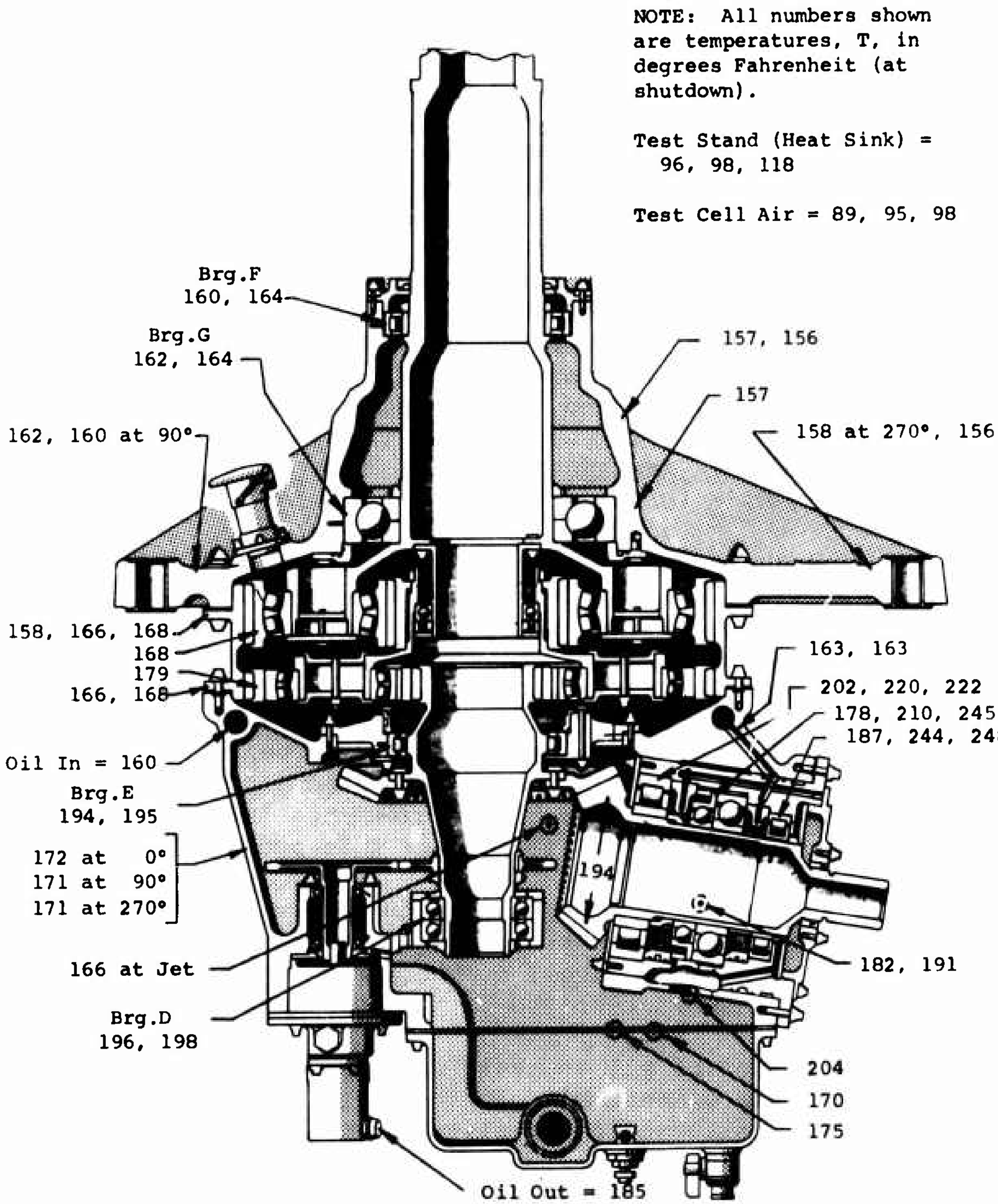


Figure 46. Thermal Map of Test 1 at 100 Percent Torque.

allowed visual inspection and recording of temperature of the first- and second-stage planet gear blanks at shutdown of any numbered test run or segment of a test run. A photograph was made at the end of run 1. Inspection of the magnetic plug and oil sample indicated no irregularities.

Figures 47, 48, and 49 are photographs of the transmission components inspected at the end of all segments of test 1. Figure 47 shows the condition of the spiral bevel pinion. Figure 48 shows the condition of the spiral bevel pinion and the underside of the lower transmission case and spiral bevel gear shaft (with thermocouple leads). Figure 49 shows the condition of the sump, screen, and thermocouple. The first- and second-stage planetary components were visually inspected in the test stand, but no photographs were taken.

TEST 2 THERMAL DATA AND INSPECTIONS
(Oil-out = 286°F ± 10 Percent)

Between test 1 and test 2, the system was purged and recharged with new MIL-L-7808 oil. Reassembly was performed with back-up thermal instrumentation and procedures consistent with the thermal mapping test plan in effect. Figures 50, 51, and 52 are thermal maps indicating the component and/or case temperatures recorded in real-time and/or at shutdown. They represent the 50 percent, 75 percent, and 100 percent torque segments of test 2, respectively. As noted previously, the reader is referred to the section below entitled Data Reduction and Evaluation for a critique of this presented data.

As in test 1, no disassembly inspections between test 2 torque load segments were symptomatically required. A visual inspection was made, however, of the first- and second-stage planetary components after the 75 percent torque load segment.

At the conclusion of all segments of test 2, the specimen transmission was disassembled, in the stand, to inspect the condition of the teeth in the spiral bevel pinion and gear and the first- and second-stage planet gears. Oil from the sump was strained, an oil sample was taken, and additional temperature placards were recovered as debris in the oil sump. The magnetic plug (chip detector) was inspected and the disassembled parts were photographed. No chips were found, and after purging and recharging of the system with new MIL-L-7808 oil, reassembly was performed to run test 3. (No

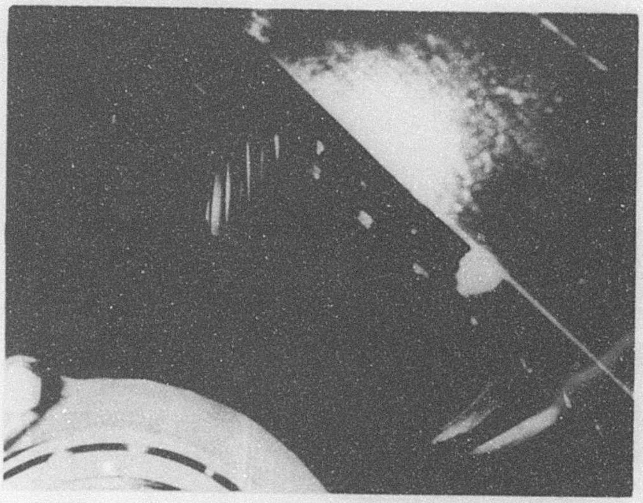


Figure 47. Spiral Bevel Pinion Teeth After Test 1.

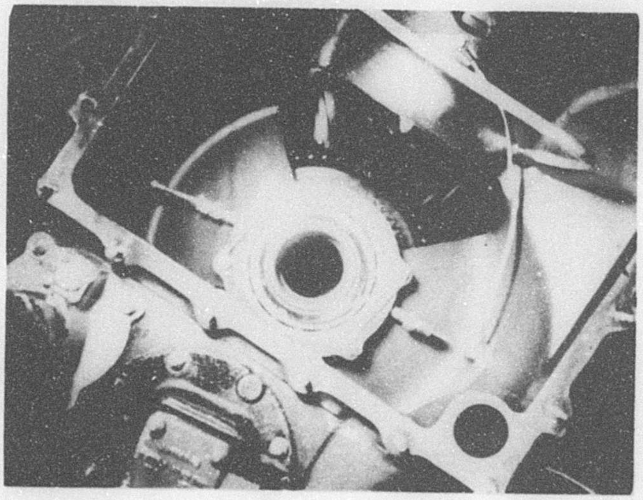


Figure 48. Spiral Bevel Pinion, Gear Shaft, and Bearing Thermocouples After Test 1.

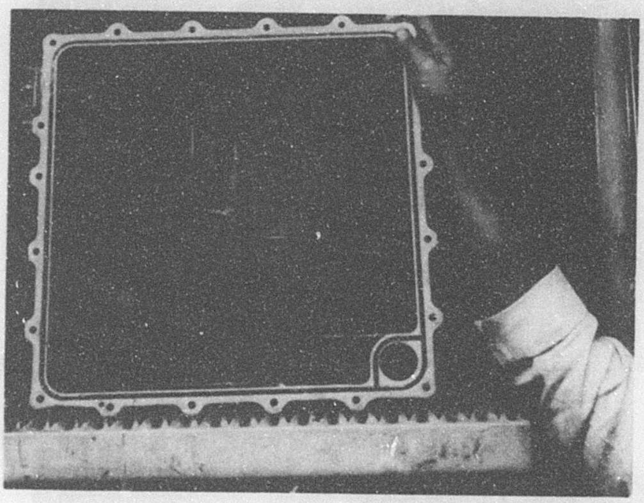


Figure 49. Sump, Screen, and Thermocouple After Test 1.

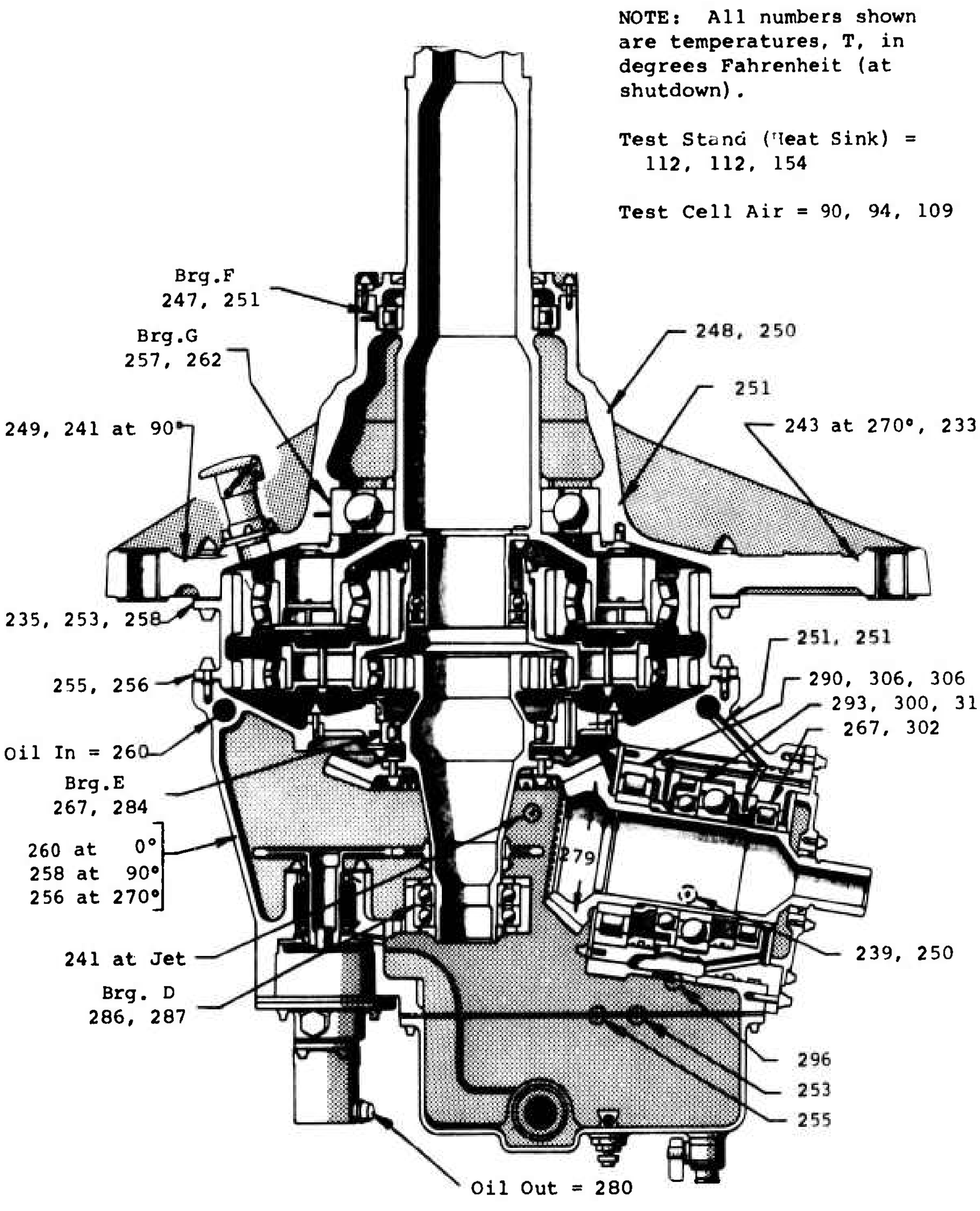


Figure 50. Thermal Map of Test 2 at 50 Percent Torque.

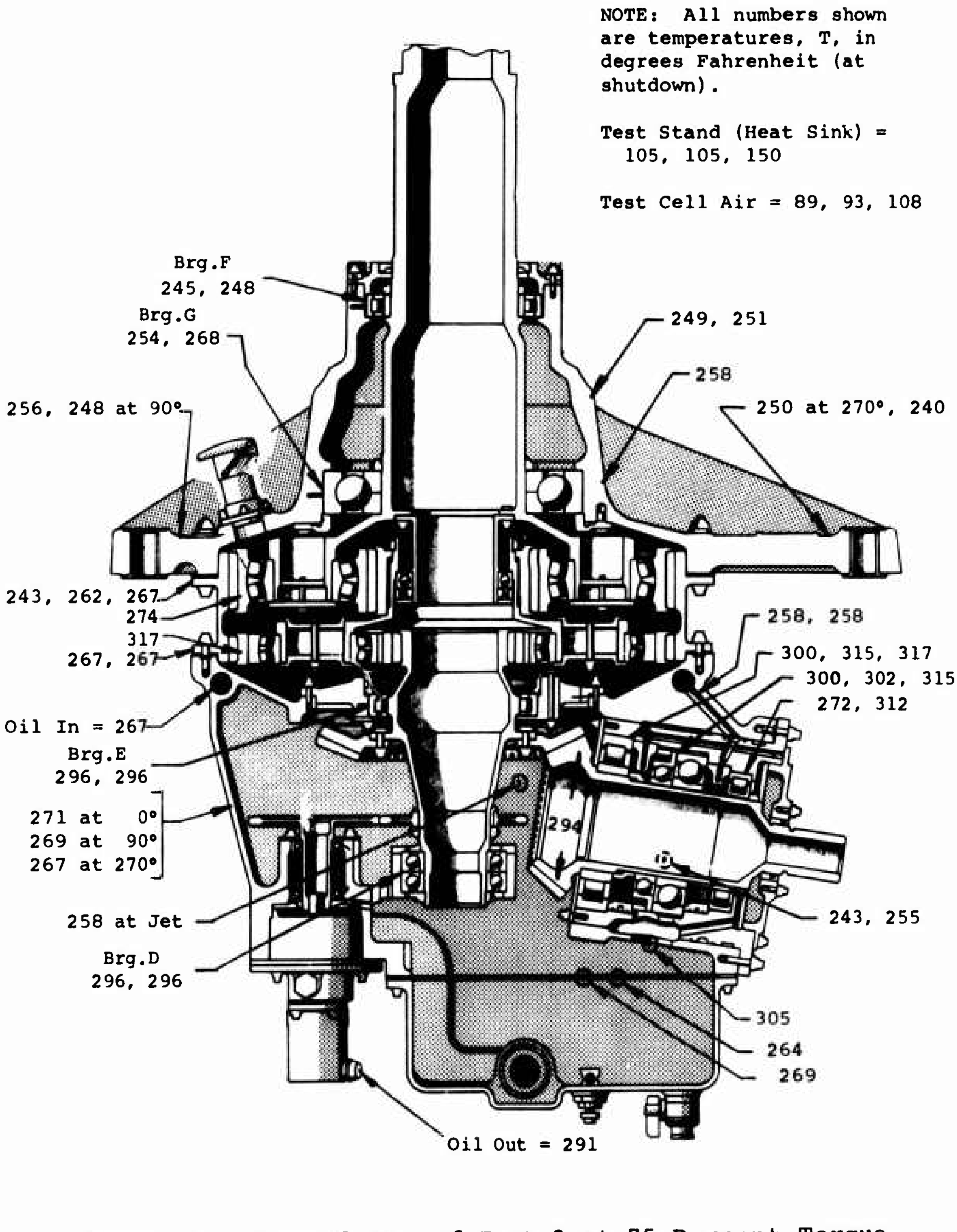


Figure 51. Thermal Map of Test 2 at 75 Percent Torque.

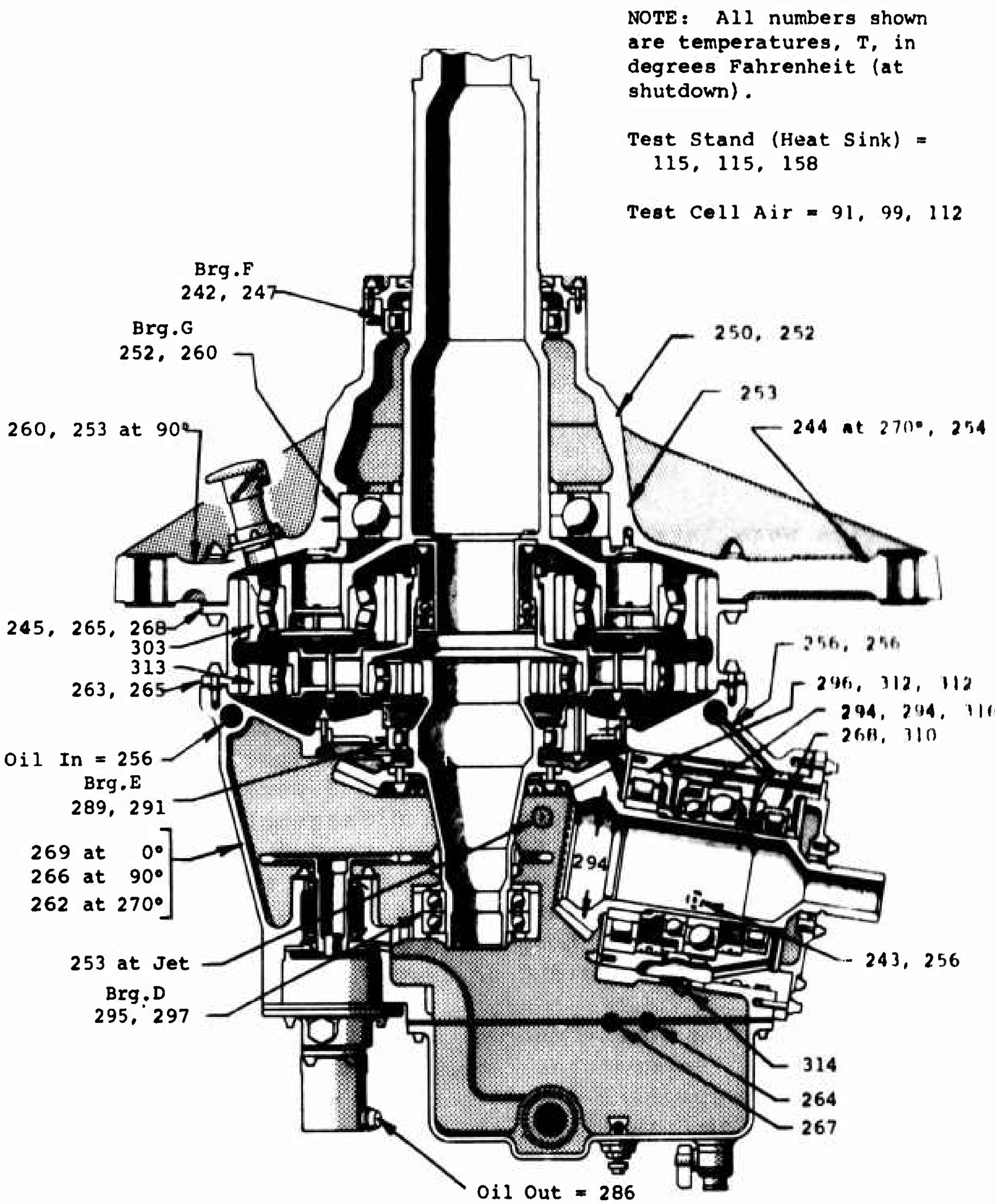


Figure 52. Thermal Map of Test 2 at 100 Percent Torque.

spiral bevel pinion temperature placards remained after test 2, and only one spiral bevel gear temperature placard remained. (The backup thermocouples on the spiral bevel pinion remained intact.) At reassembly, the sump sight gage was masked off with a metal plate in anticipation of plastic failure at higher temperatures for test 3.

Figures 53, 54, and 55 are photographs of the transmission components inspected at the end of all segments of test 2. Figure 53 shows the disassembly state of the specimen transmission in the test stand. Figure 54 shows the acceptable condition of the spiral bevel pinion. Figure 55 shows the condition of the sump, screen, and thermocouple. First- and second-stage planetary components were visually inspected in the test stand, but no photographs were taken.

TEST 3 THERMAL DATA AND INSPECTION
(Oil-out = 400°F ± 10 Percent)

Oil samples were taken at the end of test run 2 and after each test segment (50 percent, 75 percent, and 100 percent torque) of test run 3. Temperature placards recovered from test runs 1, 2 and 3 were retained for review. After test run 2 and after each test segment of test run 3, the system was purged and recharged with new MIL-L-7808 oil. Reassembly after test 2 was performed with backup thermal instrumentation and procedures still in effect. No disassembly inspections of the specimen between torque segments of test 3 were planned, but it was deemed advisable to conduct a disassembly inspection in the test stand after the 50 percent torque run segment (including a visual inspection of the first- and second-stage planetary components), a teardown (out of the stand) inspection after the 75 percent torque run segment, and a complete teardown inspection at the end of test 3.

Figures 56, 57, and 58 are thermal maps indicating the component and/or case temperatures recorded in real-time and/or at shutdown. They represent the 50 percent, 75 percent, and 100 percent torque segments of test 3, respectively. As noted previously, the reader is referred to the section below entitled Data Reduction and Evaluation for a critique of this presented data.

An inspection was made of the disassembled transmission in the test stand after the 50 percent torque run segment. Figures 59, 60, and 61 are photographs of the transmission components

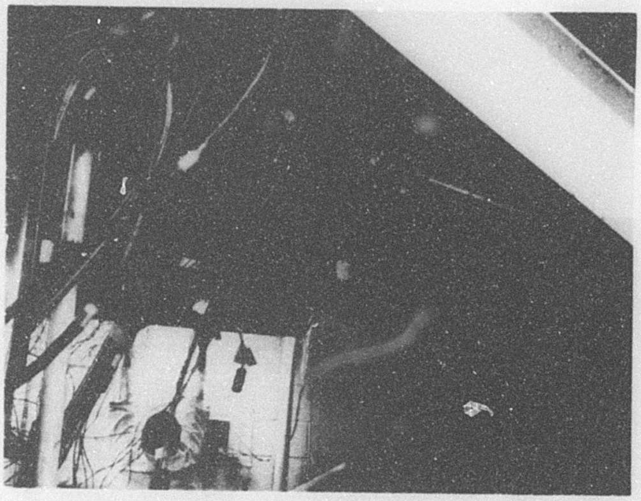


Figure 53. Specimen Transmission Disassembled for Inspection in Test Stand (End of Test 2).

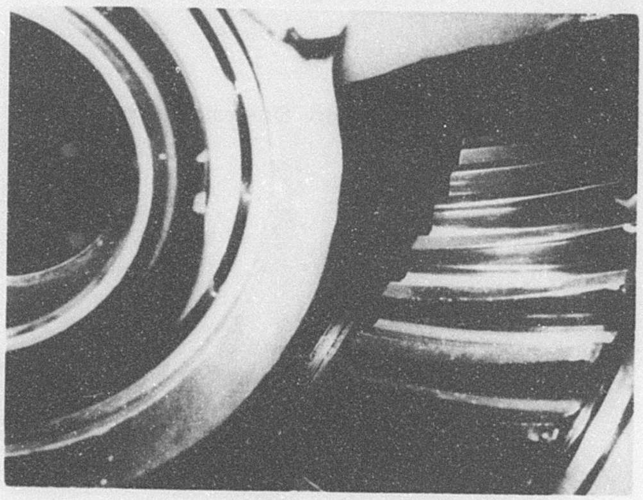


Figure 54. Spiral Bevel Pinion After Test 2.

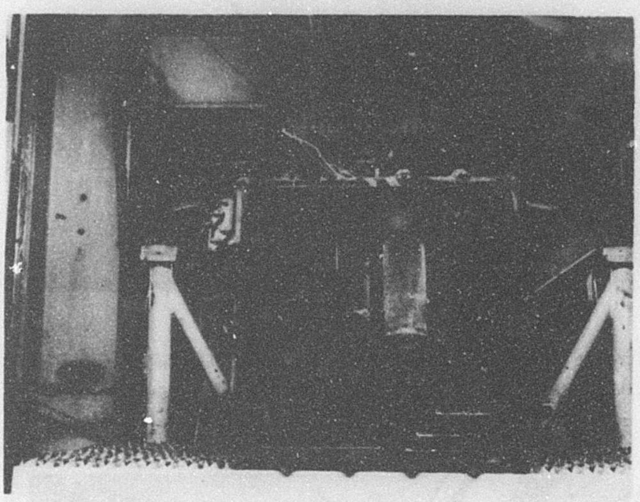


Figure 55. Sump, Screen, and Thermocouple After Test 2.

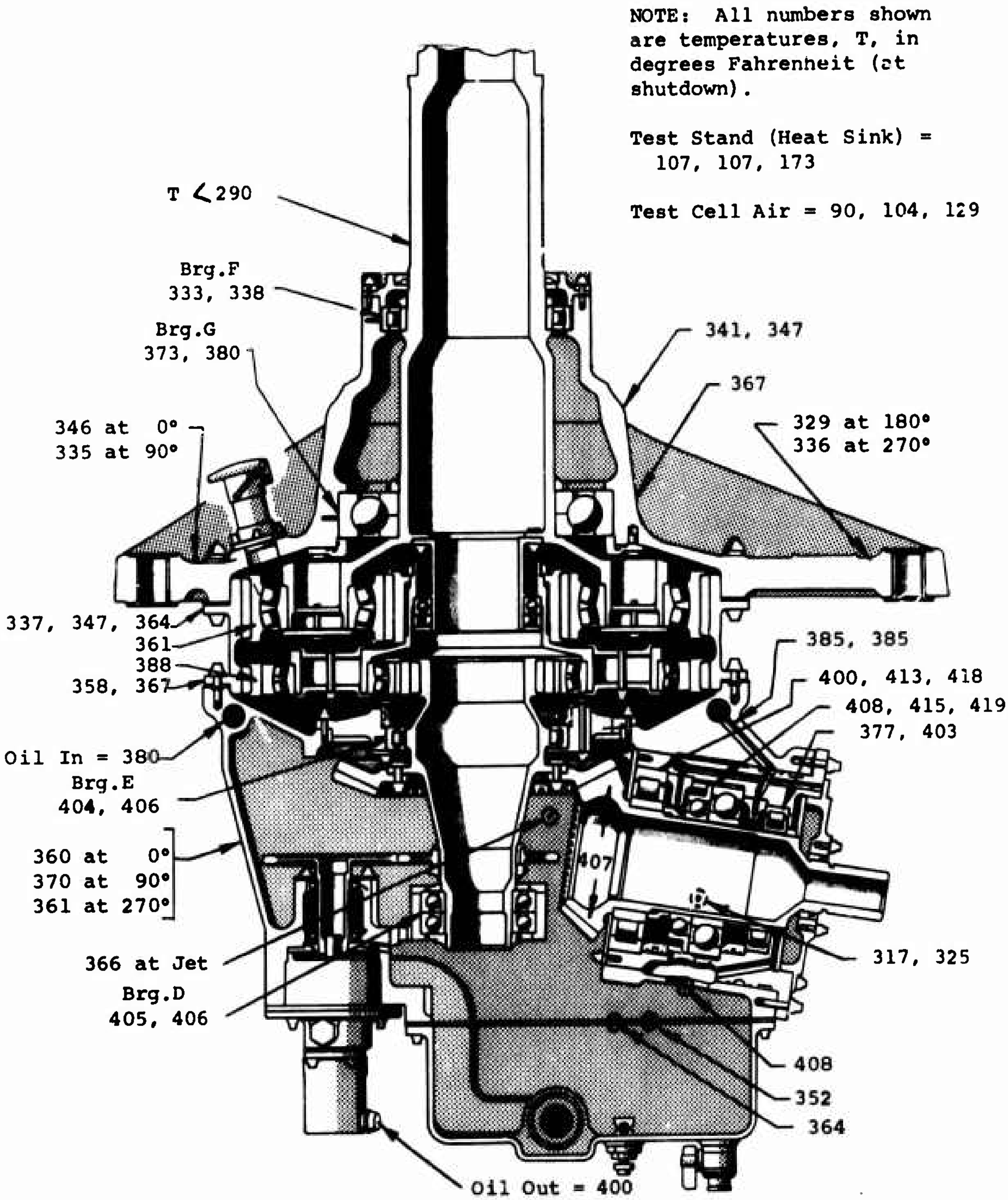


Figure 56. Thermal Map of Test 3 at 50 Percent Torque.

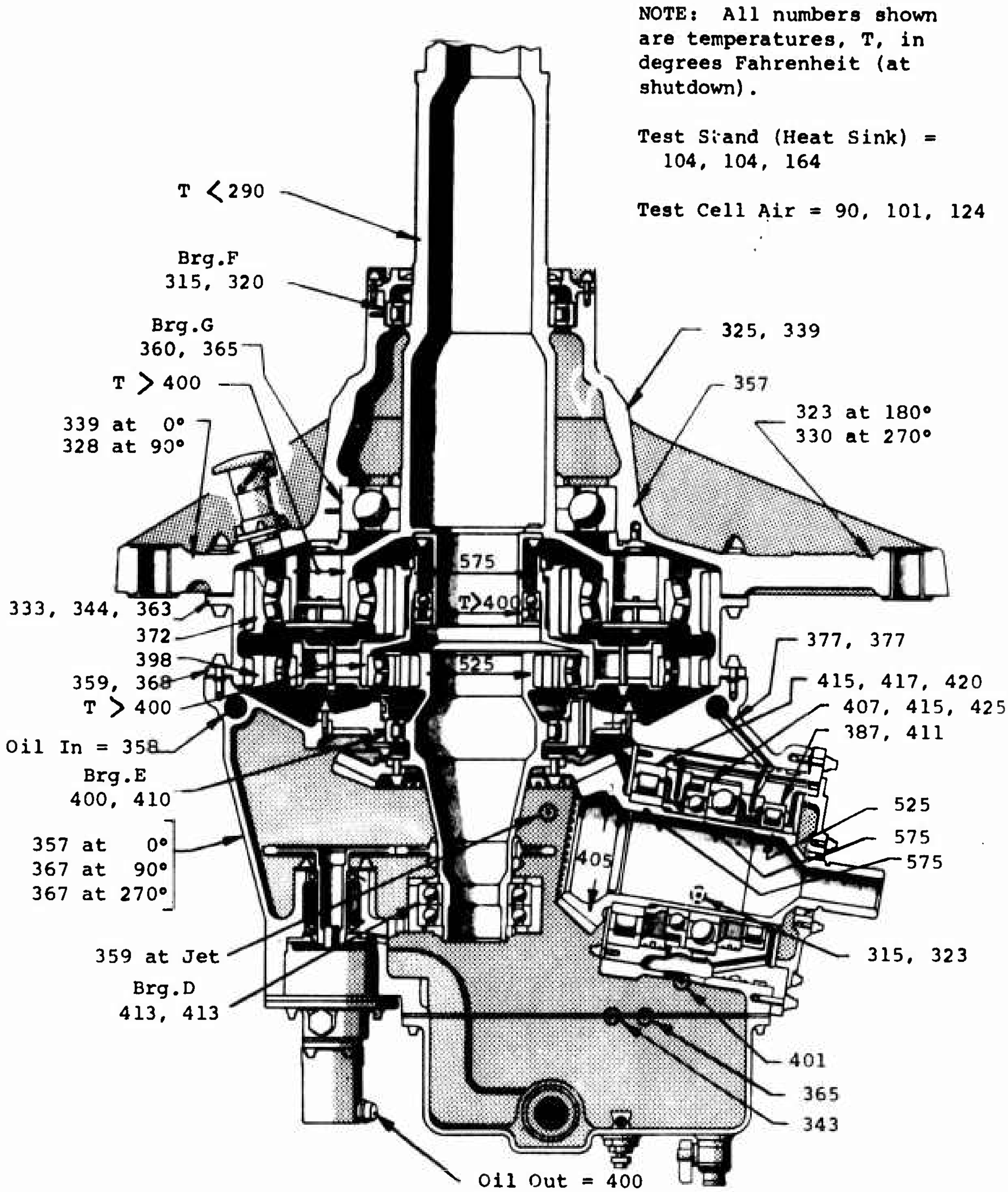


Figure 57. Thermal Map of Test 3 at 75 Percent Torque.

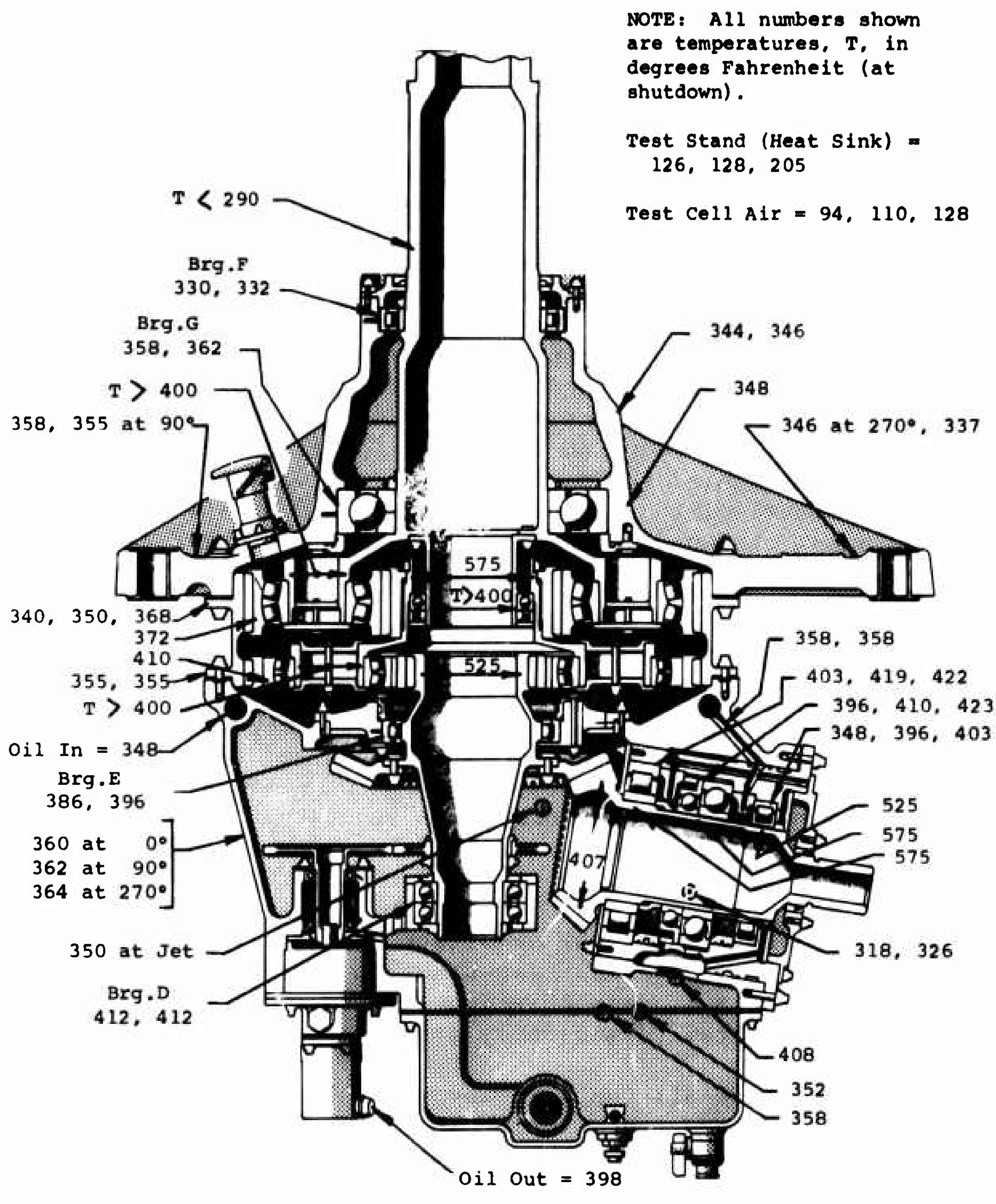


Figure 58. Thermal Map of Test 3 at 100 Percent Torque.

inspected at the end of that segment. Figure 59 shows the state of the disassembled specimen transmission in the test stand. Figure 60 shows the acceptable condition of the spiral bevel pinion. Figure 61 shows the condition of the sump, screen, and thermocouple. First- and second-stage planetary components were visually inspected in the test stand (by removing the quick-disconnect breather standpipe shown in position in Figure 59), but no photographs were taken.

A teardown inspection (out of the test stand) was made after the 75 percent torque run segment of test 3. Figures 62 through 66 are photographs of the acceptable condition of the teeth of the spiral bevel pinion, first-stage sun, first-stage planet, second-stage sun, and second-stage planet gears, respectively. Figure 67 shows the condition of the sump, screen, and thermocouple. Figure 68 shows the installation of new thermoplacards behind the oil dam (dam removed) on the I.D. of the spiral bevel pinion at bearings A, B, and C. (The installation of a new thermoplacard on the conical I.D. under the spiral bevel pinion teeth is out of the photograph field of view.)

As may be seen, the teeth on the flank of the spiral bevel pinion were lightly frosted; classically light frosting was present on all other gears. In addition, three teeth on the first-stage sun gear were lightly pitted and may be seen in Figure 63. After the three pitted teeth on the first-stage sun gear were dressed, all components were deemed acceptable to undergo the 100 percent torque run segment of test 3.

The final teardown inspection (out of the test stand) was made after the 100 percent torque run segment of test 3. Figures 69 through 73 show the final condition of the spiral bevel pinion, spiral bevel gear, first-stage sun, first-stage planet, and second-stage sun, respectively. Figure 74 displays all parts in their detail disassembly state.

All parts survived all tests; however, the spiral bevel gear set shows aggravated tooth surface distress (scoring and pitting). The first-stage sun also shows aggravated tooth surface distress (pitting); the first-stage planet shows light surface distress (pitting, and frosting progressing to light scoring). The second stage shows unprogressed light "classical" frosting. There were no irregularities in the bearings or other major components. The final inspection revealed that the specimen transmission may be used in further tests. It is known

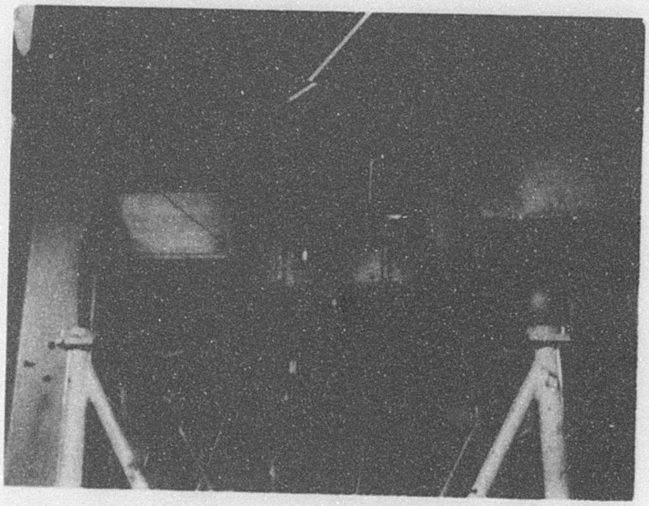


Figure 59. Specimen Transmission Disassembled for Inspection in Test Stand (End of Test 3 at 50 Percent Torque).

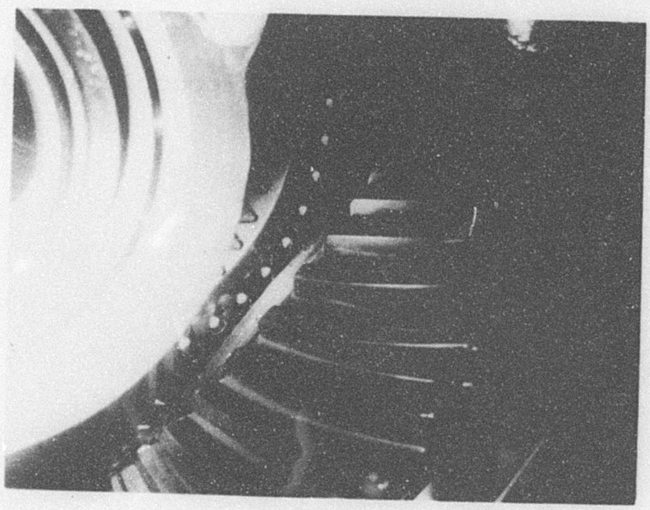


Figure 60. Spiral Bevel Pinion After Test 3 at 50 Percent Torque.

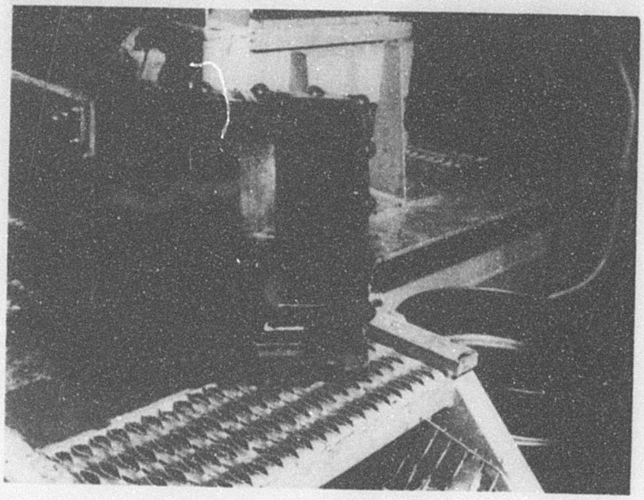


Figure 61. Sump, Screen, and Thermocouple at End of Test 3 at 50 Percent Torque.

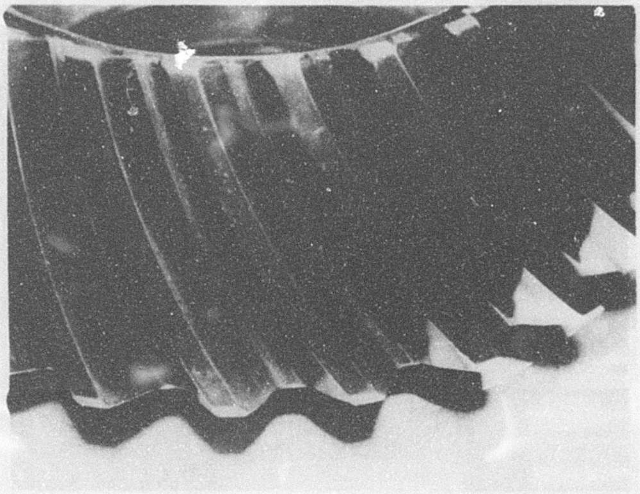


Figure 62. Spiral Bevel Pinion at End of Test 3 at 75 Percent Torque.

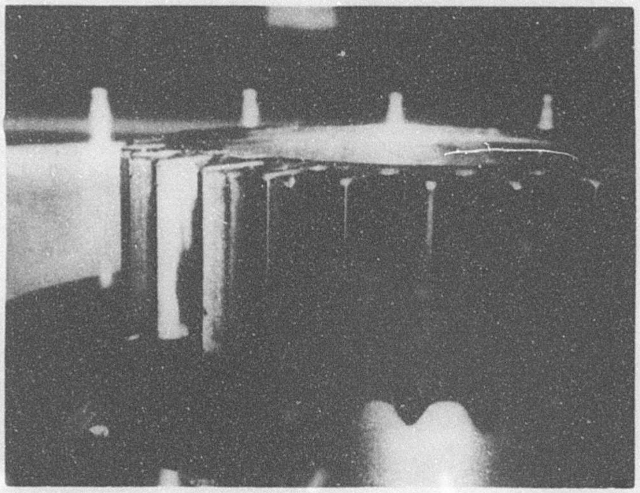


Figure 63. First-Stage Sun Gear at End of Test 3 at 75 Percent Torque.

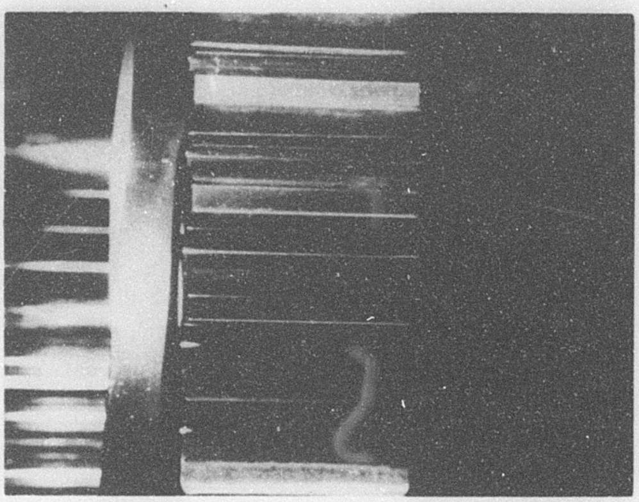


Figure 64. First-Stage Planet Gear at End of Test 3 at 75 Percent Torque.

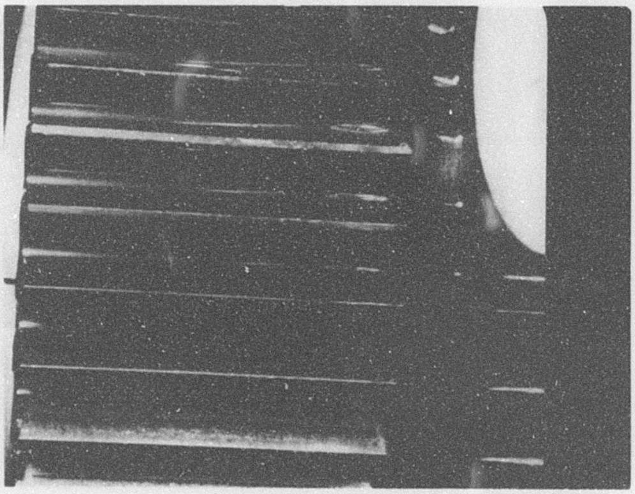


Figure 65. Second-Stage Sun Gear at End of Test 3 at 75 Percent Torque.

Figure 66. Second-Stage Planet Gear at End of Test 3 at 75 Percent Torque.

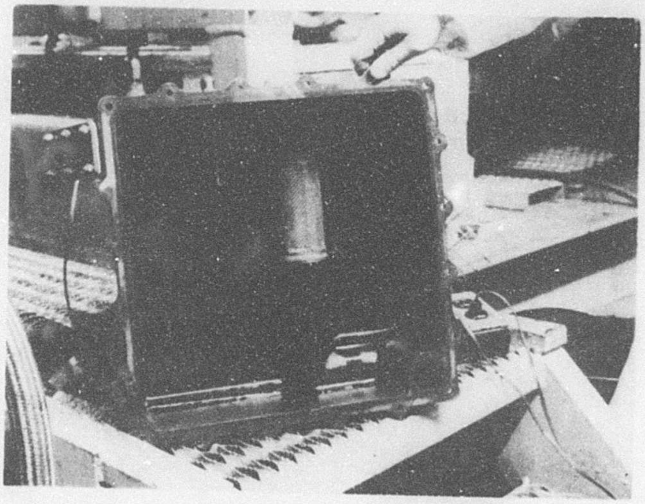


Figure 67. Sump, Screen, and Thermocouple at End of Test 3 at 75 Percent Torque.

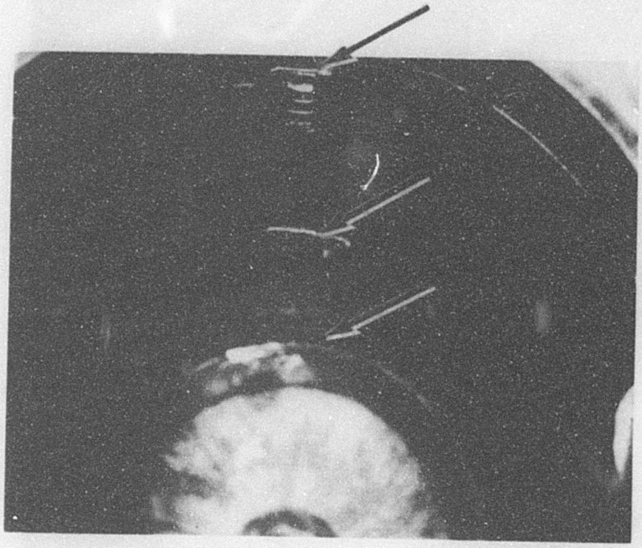


Figure 68. Installation of New Temperature Placard on Spiral Bevel Pinion.

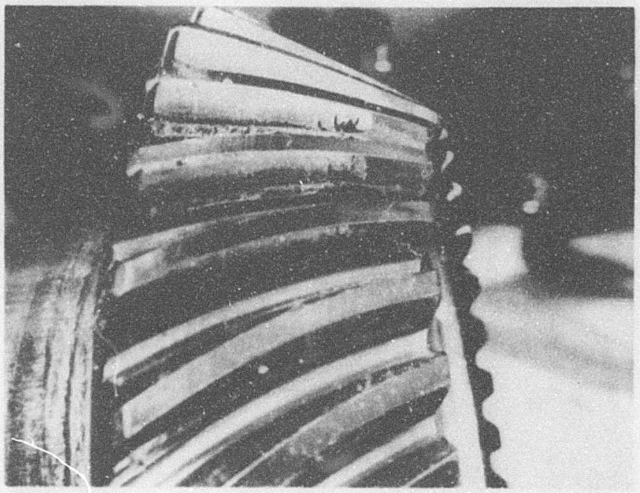


Figure 69. Final Condition of Spiral Bevel Pinion.

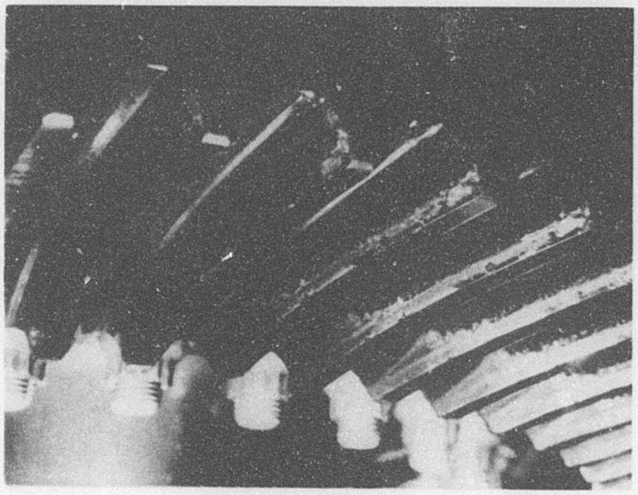


Figure 70. Final Condition of Spiral Bevel Gear.

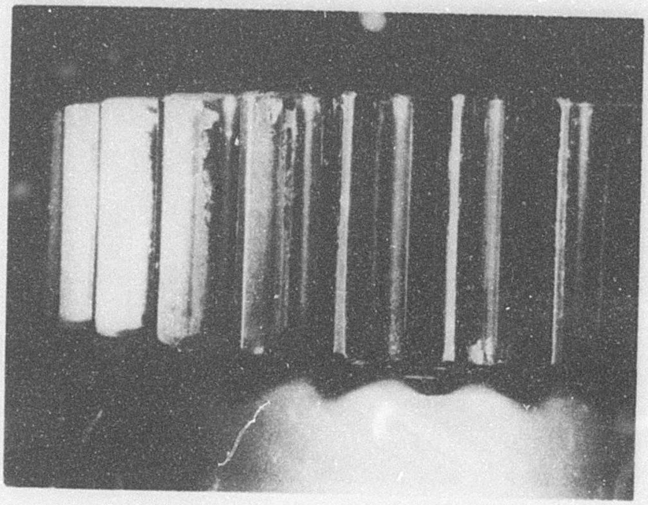


Figure 71. Final Condition of First-Stage Sun Gear.

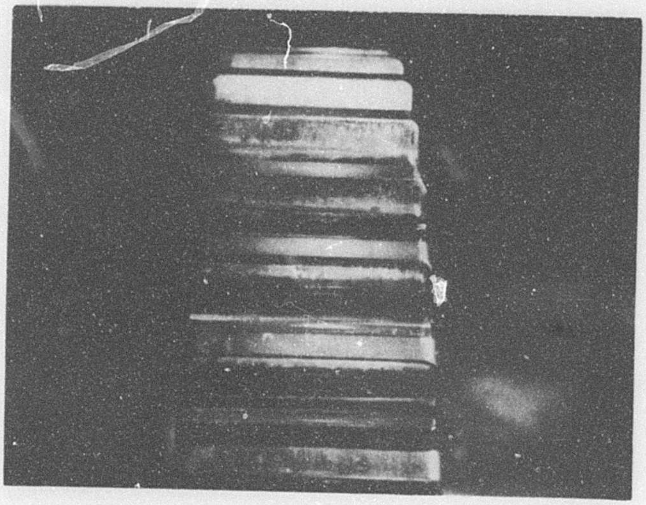


Figure 72. Final Condition of First-Stage Planet Gear.

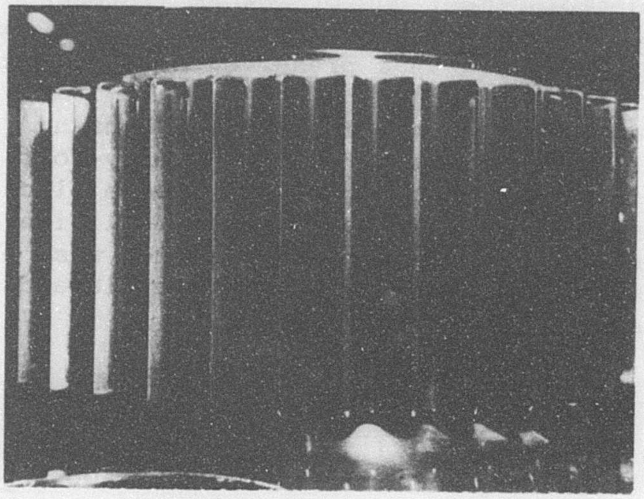


Figure 73. Final Condition of Second-Stage Sun Gear.

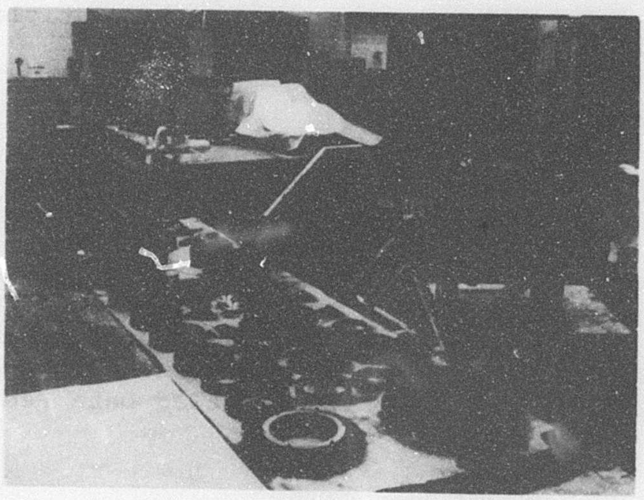


Figure 74. Thermal Mapping Test Specimen Parts in Detail Disassembly State.

that the spiral bevel gear set and the first-stage planet set will require replacement and/or rework (interchanging the drive and coast sides) for further tests. The components were reassembled and placed in a preserved storage state.

Table V is a summary of the temperature sensing (temp-plate) placards which survived the testing. Forty-four sets were applied during the tests. Thirty sets were placed on rotating components inside the transmission (oil side of spiral bevel pinion dam). Seventeen sets did not wash out. In addition, some erratic triggering of the placards was noted and may be seen in Table V.

ADDITIONAL THERMAL DATA GENERATING TEST RUNS

Contrary to expectations, full bypass of the oil cooler did not yield stabilized temperatures of oil-out $\leq 400^{\circ}F \pm 10$ percent at the 50 percent torque level. A limited search was conducted for torque at which thermal equilibrium might be achieved (see Figure 75). In addition, a limited oil-pressure/flow/temperature sensitivity run was conducted to evaluate the limiting thresholds and the relationships of these parameters. These evaluations are found below in the section entitled Data Reduction and Evaluation.

THERMAL GROWTH DATA

Thermal growth data was measured between discrete points on the transmission. These measurements were coupled in real-time to the thermal data that was being generated before and after a run shutdown with oscillographic tapes in recording states. A special dimensional growth run was made and is shown in Figure 76. The thermal growth has been deduced from a combination of this test data and analysis. The growth evaluations are found below, in the section entitled Data Reduction and Evaluation.

INFRARED TECHNOLOGY THERMAL DATA

In order to obtain blanket coverage of transmission lower case skin temperatures between the otherwise discrete thermocoupled points being monitored in real-time, infrared temperature scans were made during at least critical portions on all test runs. When scanning was not recorded, the scanning equipment remained operational in anticipation of surprises. When significant

TABLE V. SUMMARY OF TEMPERATURE SENSING (TEMP-PLATE) PLACARDS SURVIVING TESTS

PLACARD LOCATION (Total Applied = 44 Sets)		WAHL CORPORATION PART NUMBER 430 (290° 300°F 310°F)	430 (380°F 390°F 400°F)	430 (480°F 490°F 500°F)	101-4 (550°F, 600°F 650°F, 700°F)
Behind S/B Pinion Dam	2 (Brg A)	● ● ●	● ○ ●	● ● ●* N/A	□□□□ * N/A
Behind S/B Pinion Dam	3 (Brg B)	● ● ●	● ○ ●	● ● ●* N/A	■□□□ * N/A
Behind S/B Pinion Dam	4 (Brg C)	● ● ●	● ○ ●	● ● ●* N/A	■□□□ * N/A
6 (1st Sun)		● ● ●	● ● ●	● ● ●	□□□□
8 (1st Carrier)		● ● ●	● ● ●	N/A	N/A
9 (2nd Sun) (Shaft I.D.)		● ● ● ● ● ●	● ● ● ● ● ●	○ ● ○	■□□□
11 (2nd Carrier)		● ● ●	● ● ●	N/A	N/A
12 (Shaft Brg. H)		● ● ●	● ● ●	N/A	N/A
14 (Rotor Shaft O.D.)		○ ○ ○	○ ○ ○	N/A	N/A
S/B Pinion on Conical I.D.		Lost	Lost	Lost*	□□□□ *

● Exposed
○ Not Exposed

*Added after Test 3, 75 Percent Torque Run.
(Condition after Test 3, 100 Percent Torque Run.)

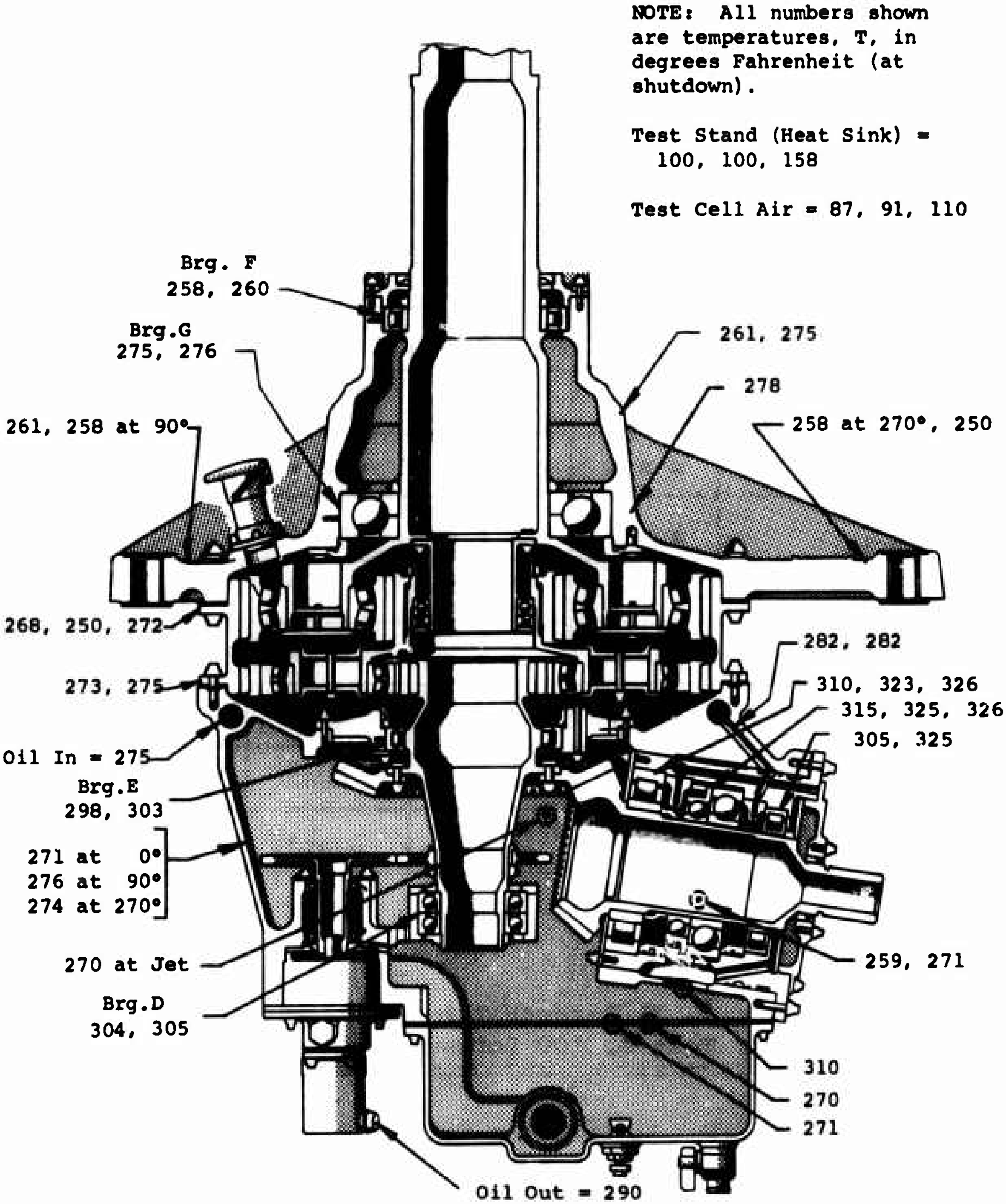


Figure 75. Thermal Map of Hunting/Search Torque (40 Percent Run at Oil-Out = 400°F ± 10 Percent.

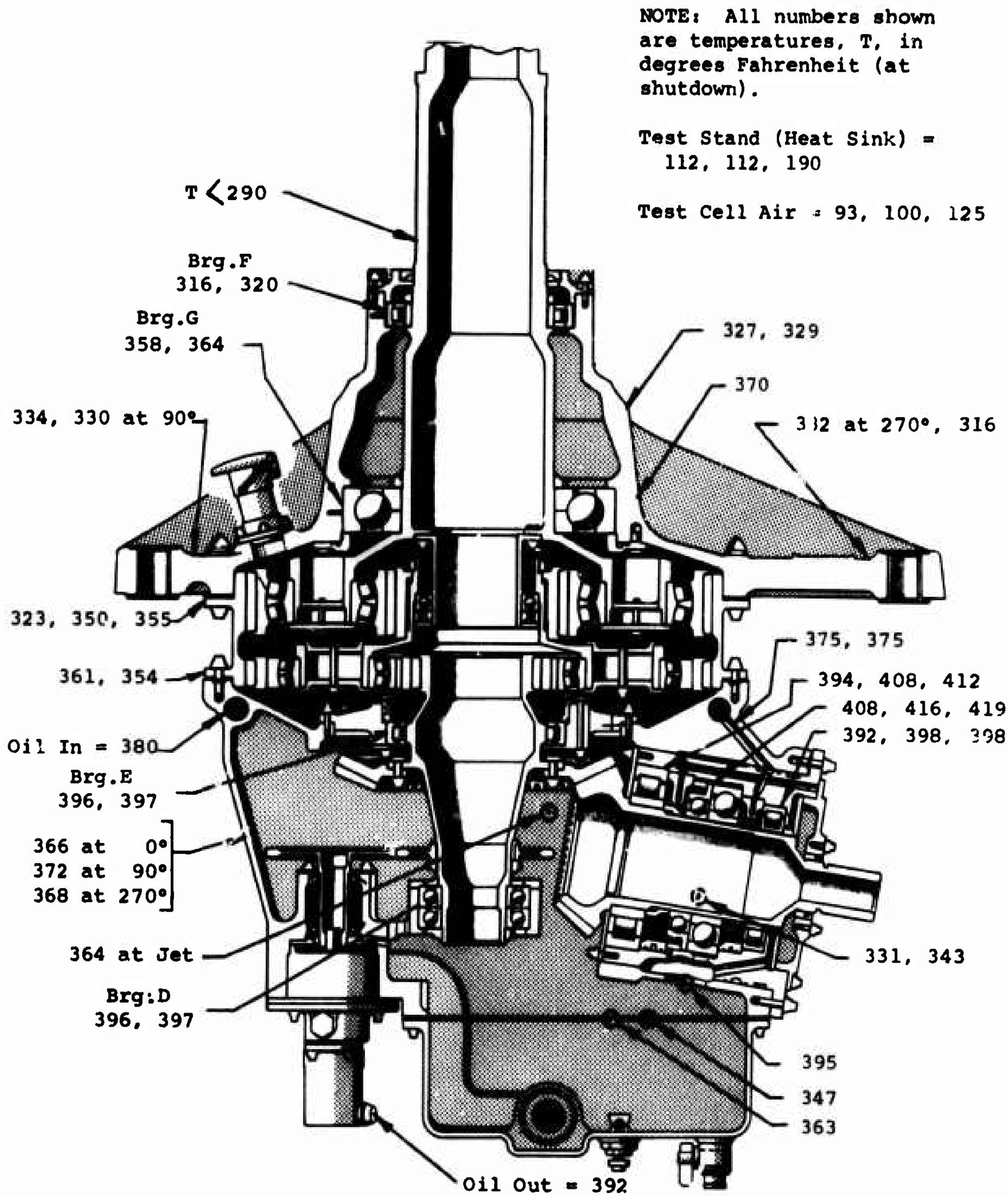


Figure 76. Thermal Map of Dimensional Growth Run.

events were about to occur, records were taken and noted in real-time onto the oscillographic record traces. The reader is referred to the evaluation section below entitled Data Reduction and Evaluation, and Appendix I, Infrared Technology Report.

DATA REDUCTION AND EVALUATION

THERMAL EVALUATION

All thermal maps presented are results of reducing data recorded on two 24-channel (each) time-temperature oscillographs and a dual-channel time-temperature continuous oscillograph, and of pyrometer-millivolt potentiometer readings.

Time Delay Adjustments

The thermal maps give the temperatures of the components at shutdown. It was necessary to adjust planet gear pyrometer-millivolt potentiometer and spiral bevel pinion oscillograph readings for temperature changes due to time delay from shutdown. These were based on the following natural cooling rates:

1. Spiral bevel pinion cooled at 2.0°F per minute (after shutdown).
2. First-stage ring gear cooled at 3.2°F per minute.
3. Second-stage ring gear cooled at 3.2°F per minute.
4. Spiral bevel pinion cartridge housing cooled at 1.4°F per minute.
5. Bearing outer races cooled at 4.0°F per minute.
6. Oil-out cooled at 4.5°F per minute.
7. Oil-in cooled at 4.0°F per minute.

By contrast, the following forced cooling rates were noted during the tests (cooler bypass valve from full closed to full open):

1. Spiral bevel pinion (not monitored prior to shutdown).
2. First-stage ring gear cooled at 15°F per minute.
3. Second-stage ring gear cooled at 15°F per minute.
4. Spiral bevel pinion cartridge housing cooled at 15°F per minute.

5. Bearing outer races cooled at $20^{o}F$ per minute.

6. Oil-out cooled at $30^{o}F$ per minute.

7. Oil-in cooled at $15^{o}F$ per minute.

All temperature adjustments due to time delays after shutdown were based on the above rates. The thermal maps reflect these adjustments.

Heat Paths and the Soakback Phenomenon

The following heat paths can be deduced from review of the thermal maps of the transmission specimen:

Conduction (to a colder heat sink)

1. Torque shaft/synchronizing shaft.

2. Torque shaft/rotor shaft.

3. Transmission mounting pads (4).

4. Intra-transmission (to transmission case walls).

Radiation

This includes the net interraction of emissivity/absorptivity/reflectivity between the transmission specimen surfaces and test cell furnishings and/or walls.

Convection

1. Natural (free) Convection - This includes transfer of heat from the transmission surfaces (including surfaces of shafts) to cell air.

2. Forced Convection - This includes transfer of heat from transmission components to the lubricant/coolant to the test cell cooling water by way of the test cell cooler mounted on the test stand frame (which is itself a heat sink).

Changes of State

This is normally indicative of destructive energy which may be manifested by such things as annealing of otherwise hardened gears, shafts, bearings, or housing elements; and by chemical breakdown of the lubricant and/or metallurgical structures.

Figure 77 is an illustration of the internal conductive heat paths of the specimen transmission. Figure 78 is an illustration of the radiation/natural convection and forced convection heat paths of the specimen transmission. For reference, a selected set of temperatures from Figure 58 (test 3, 100 percent torque run) is shown below that gives the thermal prehistory of pyrometer-potentiometer readings taken of synchronizing shaft components. The listing below gives a time sequence of temperature readings:

COMPONENT	TEMPERATURE	ELAPSED TIME FROM SHUTDOWN
Shutdown Run 3, 100% Torque		0 Minutes
Oil Out	398°F	0 Minutes
Spiral Bevel Pinion	403°F	2 Minutes
Spiral Bevel Pinion	378°F	10 Minutes
Sync Shaft	97°F	12 Minutes
Sync Shaft Adapter O.D.	97°F	13 Minutes
Sync Shaft Adapter Leg	103°F	17 Minutes
Thomas Coupling Plates	114°F	20 Minutes
Pinion Shaft Adapter Leg	120°F	22 Minutes
Pinion Shaft Adapter O.D.	173°F	24 Minutes
Pinion Spline Undercut O.D.	223°F	27 Minutes

Taking the readings in the order shown eliminates the effect of soakback, but reinforces the assumption of the existence of a convective heat path from the rotating components in the Thomas coupling region to air ambient when rotating at full rpm. While it is certain that at least transient amounts of thermal soakback have occurred between elements in the conductive heat paths, they were not discernible within the 24-second oscillographic-switching delay time (two 24-channel recorders), nor were they discernible within the approximately 2 minutes (shortest average time delay) from shutdown to reading the spiral bevel pinion and first- and second-stage planet temperatures.

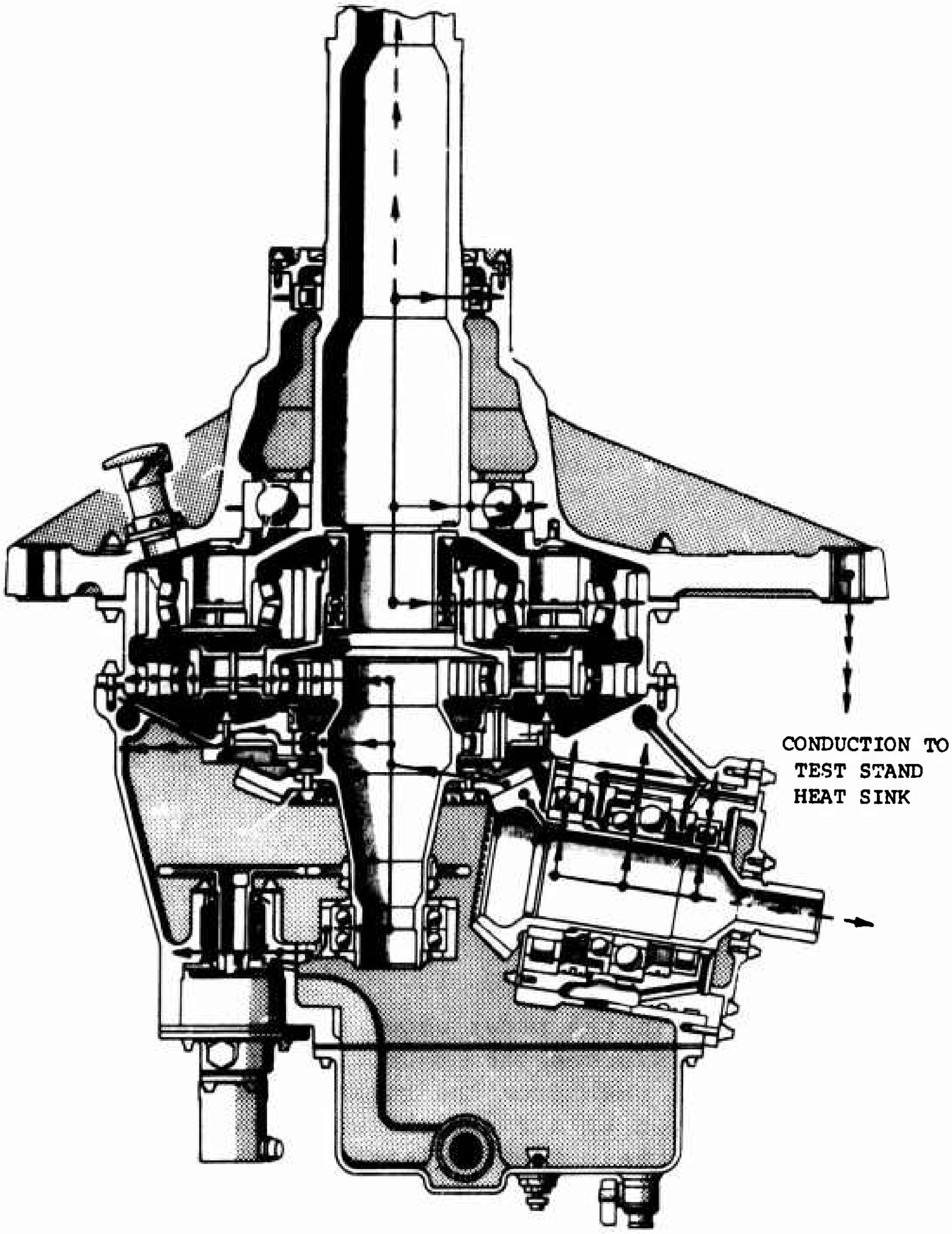


Figure 77. Illustration of Intern 1 Conductive Heat Paths of Specimen Transmission.

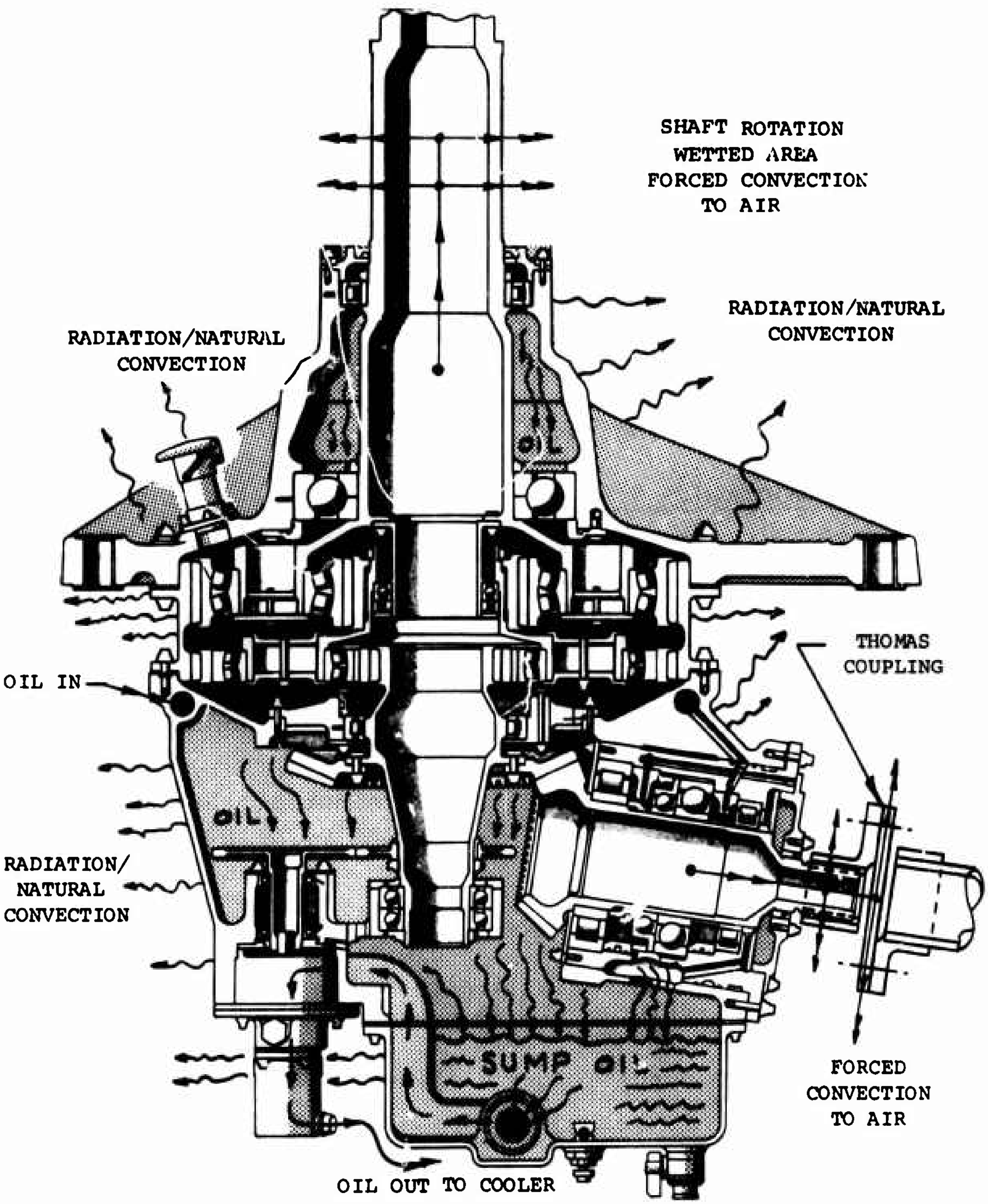


Figure 78. Illustration of Radiation/Natural Convection and Forced Convection (Oil) Heat Paths of Specimen Transmission.

Effects of Oil-Out Temperature Variation

The effects of oil-out upward variation, as expected, serves to raise the temperature of all components of the specimen. Within any target oil-out temperature run, increasing the torque level demands an increase in valve setting for increased water-cooling flow (to maintain the target temperature).

Effects of Torque Variation

Conversely, the effects of torque variation serve to shorten the time that it takes to bring the oil-out temperature within the target range. Within any torque segment run, increasing the oil-out target demands a decrease in valve setting for decreased water-cooling flow.

Infrared Temperature Scans

A detailed discussion of the results, as well as methodology, of IR temperature scanning of the specimen transmission is given in Appendix I of this report. A summary of the IR test data indicated the following:

Run 1, 50 Percent Torque (Oil-out = 186°F ± 10 Percent)

The transmission case surface in the vicinity of the bevel pinion and bearings A, B, and C is hotter than the forward part of the case surface during the major portion of the run.

Run 1, 100 Percent Torque

The temperature distribution is more uniform across the case surface than in the 50 percent torque run.

Run 2, 100 Percent Torque (Oil-out = 286°F ± 10 Percent)

The forward section of the case surface is hotter than the aft side of the case throughout the entire run.

Run 3, 50 Percent, 75 Percent, 100 Percent Torque (Oil-out = 400°F ± 10 Percent)

The results in Run 2, 100 percent torque were repeated during the remainder of all tests.

In general, the infrared temperature scanning results agreed with the results given by the monitoring of the case surface thermocouples. In addition, it gave blanket temperature monitoring of the entire right-side surface of the lower case and sump in real-time. (For additional details refer to Appendix I.)

Design of Experiments Thermal Replication

Replication in the design of experiments in this test has been achieved. While the thermal mapping test plan used the previous aft transmission test as the equivalent of the 50 percent torque at 400°F oil-out test, it is now obvious that a distinction should have been made between the previous aft test segments conducted with and without a thermal (ballistic) blanket. The thermal mapping test plan anticipated residual cooling agents present in the prior tests. This has been verified. Therefore, it is concluded that the 50 percent torque at 400°F oil-out (with no case cooling agent present) test run is a replication of the prior aft transmission test at full bypass of the cooler, but with a thermal (ballistic) blanket that eliminates the effect of cell residual cooling. Figure 79 shows comparative temperature histories of prior and present tests. Full bypass of the cooler is possible at oil-out temperatures of 400°F ± 10 percent at approximately 40 percent torque. Figure 80 is a record of a hunting/search torque run for that oil-out temperature stabilization target.

Qualitative Evaluation of Heat Dissipation

Heat paths follow the dominant heat transfer mechanism(s) in any test segment. The dominant heat dissipation mechanism during tests 1, 2, and 3 is the forced convection provided by MIL-L-7808 oil. This is indicated by noting that the case temperatures are predominately between oil-in and oil-out temperatures during tests 1, 2, and 3. By contrast, the dominant heat dissipation during the hunting-search torque run (Figure 75), oil-cooler completely bypassed, is case radiation and natural convection. This is indicated by noting that the case temperatures are predominately lower than both oil-in and oil-out. In this oil-cooler bypass condition, the dominant heat transfer mechanism internally is conduction. The presence of the lubricant internally serves to modulate spikes of localized temperatures and bathe the inside of the case walls for eventual dissipation by radiation and natural

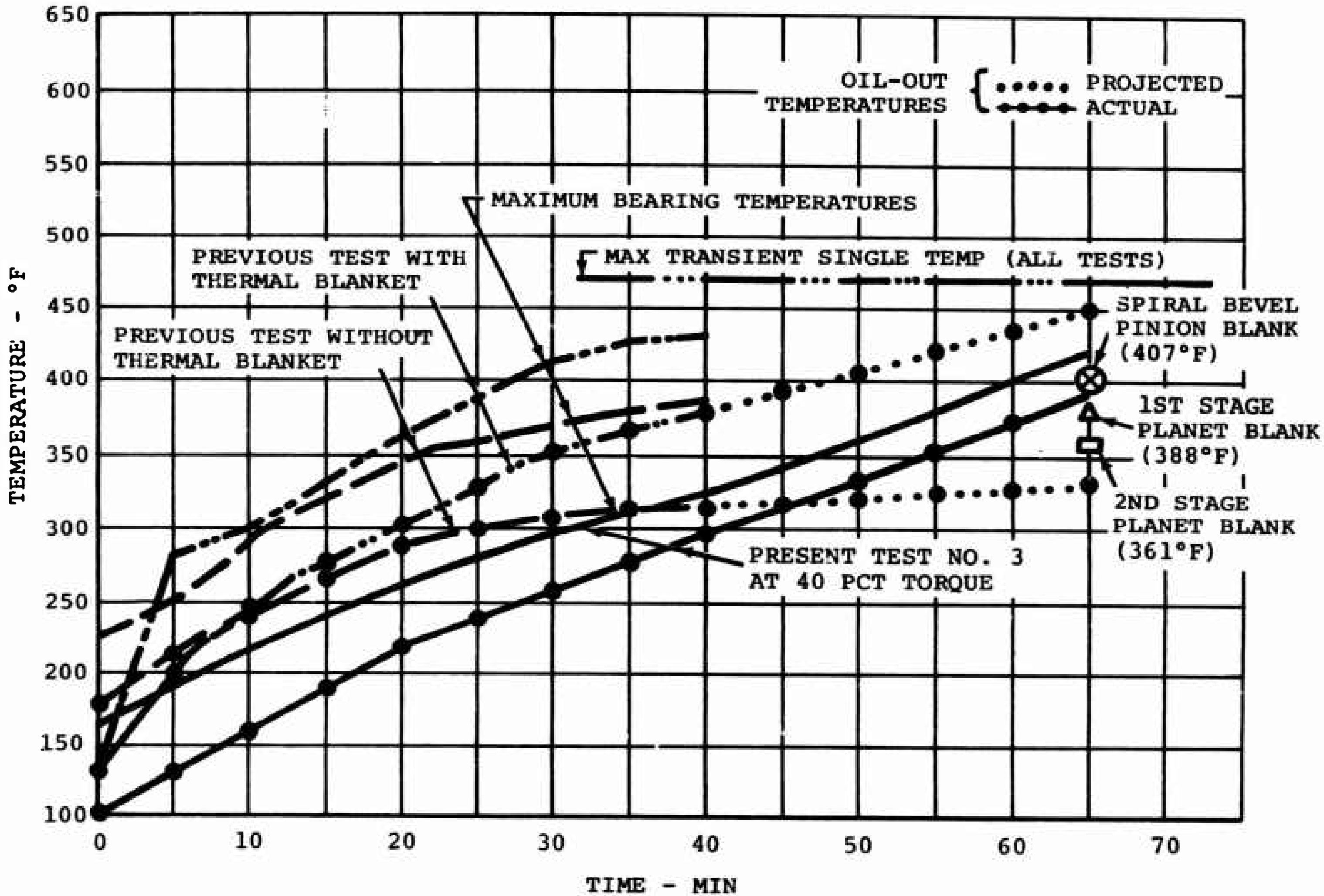


Figure 79. Comparative Temperature Histories of Prior and Present Tests.

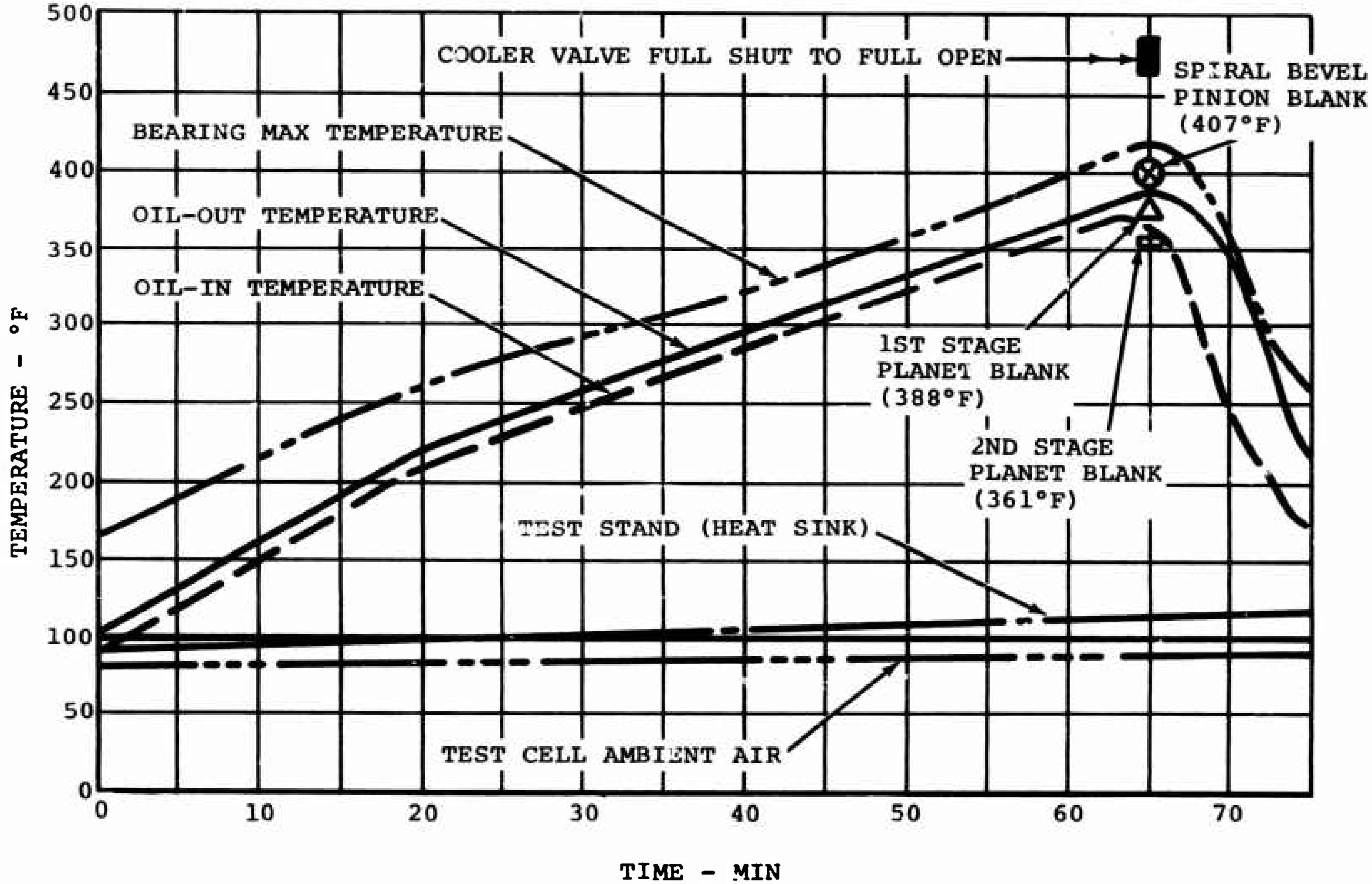


Figure 80. Temperature History of Specimen Components During Hunting/Search Torque (40 Percent) Run.

convection. During these tests, the greater the oil-out control temperature, the more oil-cooler bypass and therefore the more reliance on heat dissipation through the internal conductive paths (Figure 77) and case radiation/natural convection paths.

An examination of each segment of any one numbered test (a single oil-out target test) indicates no significant difference in component temperature pattern with differences of torque.

The one exception to this condition is that, in test 1 (oil-out = $180^{\circ}F \pm 10$ percent), the input end of the transmission case was hotter than the other case surfaces. This was recorded in infrared temperature photographs, and it indicates--especially at low torque--that heat generation, at this end of the low torque/low temperature spectrum, is dominated by input shaft speed.

GROWTH EVALUATION

Case measurement dimensions, l, coupled to average case temperature, T, between respective measurement points are listed in Table VI.

Comparing the listed coefficients of linear thermal expansion of 0.0000151, 0.00000653, and 0.0000131 (inches/inch/degrees F) of magnesium, steel and aluminum alloys, respectively, against the empirical equivalent $\frac{\Delta l}{l_c} / \Delta T$ shows almost complete conformity of classical thermal expansion.

Among the fifteen measurements taken, three measurements remain doubtful. They are X_2, $Z_{2,1}$, and $Z_{2,2}$. Referring to Figure 9, X_2 is a displacement between point 1 (the spiral) bevel cone center) and a diagonally positioned point on the magnesium casting outside surface in line with the neo-vertical plane through bearing C. This dimension was checked twice at room temperature and twice at elevated temperature. The second check at elevated temperature was 10.705 inches, corresponding to the listed 10.718 inches. It is to be noted that the terminal point at the bearing C plane is relatively free to breathe or to distort compared to other casting mass-connected spring rate regions such as ribs and internal supports.

TABLE VI. DIMENSIONAL GROWTH PARAMETER EVALUATION

DIMENSION IDENTITY (See Figure 9)	l_c (inches) at T_c Cool		l_h (inches) at T_h Hot		ΔT $T=T_h-T_c$ (°F)	$\frac{\Delta l}{l_c} / \Delta T$ x 10^6	COEFFICIENT OF EXPANSION k x 10^6
	l_c	T_c(°F)	l_h	T_h			
D1 (Mag.)	24.860	73	24.900	190	117	13.8	15.1
D2 (Steel)	24.826	73	24.842	190	117	5.5	6.53
D3			NOT MEASURED				
D4 See Note	24.877	73	24.940	190	117	21.6	13.1
D5 (Alum.Aly.)	10.500	73	10.516	215	142	10.7	13.1
D6 (Alum.)	5.579	73	5.595	215	142	20.2	13.1
D7 (Mag.)	12.501	73	12.533	230	157	16.3	15.1
D8 (Mag.)	12.444	73	12.470	230	157	13.3	15.1
D9 (Steel)	2.643	73	2.645	180	107	7.07	6.53
X1 (Mag.)	15.520	73	15.558	260	187	13.1	15.1
X2 (Mag.)	10.638	73	10.718	250	177	42.5	15.1
X3 (Mag.)	9.690	73	9.710	250	177	15.2	15.1
Z1 (Mag.)	7.864	73	7.899	240	167	26.6	15.1
Z2, 1 (Steel)	4.275	73	4.261	220	147	22.3	6.53
Z2, 2 (Steel)	3.243	73	3.237	220	147	12.6	6.53
Z3 (Alum.)	15.634	73	15.682	210	137	22.4	13.1

NOTE - Measured on adjacent aluminum.

The $Z_{2,1}$ and $Z_{2,2}$ vertical displacements across the internal ring gear show a negative Δl. These dimensions were checked twice, as were the X_2 dimensions. The analysis of the $Z_{2,1}$ and $Z_{2,2}$ dimensional growth phenomenon is outside the scope of this work.

The thermal growth between points on the specimen is therefore considered as classical thermal growth.

CONCLUSIONS

The following conclusions are drawn from this program:

1. The CH-47C forward rotor transmission specimen survived all tests. The bearings and other dynamic components did not show any signs of visible surface distress after all the torque and temperature runs.

2. Surface distress in the form of light scuffing on the first-stage planet gears, light pitting on the first-stage sun gear, and light scuffing on the spiral bevel pinion flank can be expected when the transmission is operated at 75 percent torque and 400°F oil-out temperature.

3. Operation of the specimen transmission is possible with MIL-L-7808 bulk oil-out temperatures up to 286°F $\pm$ 10 percent with no obvious deleterious effects to the oil and metallurgical distress of the gears, bearings and other components.

4. MIL-L-7808 oil can be expected to show symptoms of accelerated degradation when the specimen transmission is operated with an oil-out temperature of approximately 350°F.

5. Full bypass of the oil cooler is possible at oil-out temperatures of 400°F $\pm$ 10 percent and at approximately 40 percent torque.

6. The linear thermal growth of the specimen transmission is predictable, as evidenced by the close match of the test-derived linear thermal coefficients of expansion and general published values.

7. The use of temperature-sensing placards with current bonding limitations is not practical for most of the critical temperature locations, due to their low reliability in the test specimen's hostile environment.

8. The high-speed input bevel pinion cartridge becomes the dominant heat-generating mechanism at low oil-out controlled temperatures and at low torque levels.

9. The test data indicated that the predominate heat dissipation mechanism was forced convection as provided by the lubricant. This was attributed to the fact that the transmission case temperatures were between oil-in and oil-out temperatures during tests 1, 2, and 3.

10. During the hunt and search torque run test where the oil cooler was completely bypassed, the predominate heat dissipation mechanism was case radiation and natural convection. This was evidenced by the fact that the case temperatures were lower than both the oil-in and oil-out temperatures.

11. It was also determined that, during oil cooler bypass operation, the predominate internal heat transfer mechanism is conduction. The moving lubricant tends to modulate localized temperature spikes by bathing the inside case walls for eventual heat transfer by radiation and natural convection.

12. Careful examination of each numbered test segment result (a single oil-out target test) indicated no significant difference in component temperature patterns due to different torque levels. Test number 1 (oil-out 180°F ± 10 percent) was the only exception, as evidenced by the fact that the input area of the transmission case reached a higher temperature than the other case surfaces.

13. The infrared scanning technique utilized during this program provided an improved surface temperature real-time monitoring and recording capability. This technique permits complete coverage of the entire transmission case. To accomplish this wide area of coverage, a very large number of thermocouples would be required. Since the infrared technique is a noncontact method, it is inherently more reliable than the thermocouple method in a vibrational environment.

RECOMMENDATIONS

Recommendations as to work required to arrive at a self-contained (lubrication) transmission are made based on the evaluation of the experimental test data generated by this program:

1. Experimental thermal/lubricant tests should be conducted utilizing the CH-47C forward rotor transmission and infrared real-time monitoring of surface temperatures in order to evaluate gear load capacity of promising higher temperature lubricants as compared to MIL-L-7808 oil.

2. Experimental thermal/gear material tests should be conducted utilizing the CH-47C forward rotor transmission and infrared real-time monitoring of surface temperatures in order to evaluate load capacity of promising high hot hardness carburizing gear steels as compared to AISI 9310 (AMS6265) steel.

3. Experimental thermal/gear tooth form tests should be conducted utilizing the CH-47C forward rotor transmission and infrared real-time monitoring of surface temperatures in order to evaluate load capacity of promising advanced gear tooth forms as compared to the current standard optimized involute tooth form.

4. Experimental thermal/lubricant, gear material and tooth form tests should be conducted utilizing the CH-47C forward rotor transmission and infrared real-time monitoring of surface temperatures in order to evaluate the interactive effects of a selected optimum advanced lubricant, gear material and tooth form on load capacity as compared to current practice.

5. Experimental thermal/gear and bearing subsystem lubrication methods should be evaluated by implementing tests utilizing the Boeing Vertol R&D Test Stand and the CH-47C forward rotor transmission with infrared real-time monitoring of surface temperatures in order to evaluate and define an optimum (minimum heat generation) lubrication technique for gear and bearing subsystems.

6. An analytical program should be conducted to perform a detailed thermal balance analysis of the CH-47C forward rotor transmission/test stand/test cell interactions in order to fully understand the heat generation/dissipation mechanisms.

7. Utilizing available analytical techniques, a CH-47C rotor transmission gear, bearing, shaft subsystem mathematical model for predicting the effects of thermal (elevated temperature) growth and/or distortion on gear and bearing performance should be developed.

APPENDIX I
INFRARED TECHNOLOGY REPORT

SUMMARY

The infrared scanning technique utilized during this transmission thermal mapping program was provided exclusively by independent research and development funding of the Boeing Vertol Company and therefore was ancillary to the contracted program.

The technique permitted complete coverage of the entire transmission lower case surfaces. To accomplish this wide area of coverage, a very large number of thermocouples would have been required.

Since the infrared technique is a noncontact method, it is inherently more reliable than the thermocouple method in a vibrational environment.

Based upon the successful use of the infrared technique during this program, it appears that further use of this technique may be feasible for the real-time monitoring and recording of rotating and orbiting transmission components such as planet gears and planet gear support bearings.

Note: The emissivity evaluation appearing on pages 109, 110, 111, 112 and 113 in Appendix I is an evaluation which uses conventional laboratory scientific notation. The scientific units of measurement may be made equivalent to the engineering units of measurement, used in the main body of this report, by applying traditional conversion factors.

INTRODUCTION

Combat operations in South East Asia have shown that the helicopter transmission system is highly susceptible to combat damage due to the external location of the lubrication oil cooler. If the supply of oil to the transmission is interrupted, failure will occur within a few minutes. Methods to reduce the vulnerability of this oil cooling system must be developed to overcome this deficiency.

One approach to reduce vulnerability is to design an integral gearbox - lubrication oil system (i.e. delete the external oil cooler and accomplish the heat rejection by radiation through the housing walls). This approach will undoubtedly result in oil temperatures in the range of 400° - 425° F which is a higher temperature range then is currently allowed. To accomplish the long range objective of a self - contained transmission, the first step is to develop an accurate thermal map of existing transmissions operating at elevated oil temperatures to determine placement of required heat transfer paths.

The Advanced Drive System Technology Group has completed an initial program to determine the effect of increased temperatures of all main components and a thermal map of a CH-47C forward transmission under various loads and inlet oil temperatures. This was accomplished by placing thermocouples and thermoplacards in various positions to record local temperatures experienced by the transmission components.

However, using this method, no temperature information is provided for the zones between those points having thermocouple sensors. It has been pointed out above that by deleting the external oil cooler the heat rejection must be accomplished through the housing walls, and therefore it is important to measure the temperature levels across the entire surface of the transmission case. To assist in accomplishing this the Quality Technology Unit has undertaken a program to map the thermal distribution of a CH-47C forward transmission housing using the infrared scanning method. This technique provides a non-contact method of monitoring temperature along a continuous line and thus temperature information can be provided in those zones between the thermocouples on the surface.

The Infrared Scanning Method

Infrared thermal mapping is a non-contact method of displaying the temperature profile across the surface of an object. The technique is based on the principle that all objects radiate infrared energy in an amount proportional to the objects absolute temperature.

The scanner accomplishes this mapping by means of a motor driven optical system which scans the test object in both the vertical and horizontal direction and focuses the infrared energy from small contiguous areas onto a photodetector. The detector generates an electrical signal proportional to infrared radiation intensity which is displayed on a cathode ray tube (CRT) screen. Two types of display are available. In one display, a two dimensional relief map (C-Scan), Figure 1, is generated by modulating the electron beam of the CRT with the signal generated by the photodetector. This display is particularly useful for qualitative identification of hot or cold spots. The hot spots are displayed as lighter (white) areas in the C-Scan presentation.

In the second type of display, the vertical scanning motion of the optical system is stopped and infrared energy is collected from contiguous points on a horizontal line across the surface of the test piece. The signal from the photodetector is applied to the vertical plates of the CRT so that a line trace (A-Scan), Figure 1, representative of temperature along the examined line is displayed. If the CRT vertical amplitude is calibrated, the A-Scan can be used to provide quantitative temperature measurements.

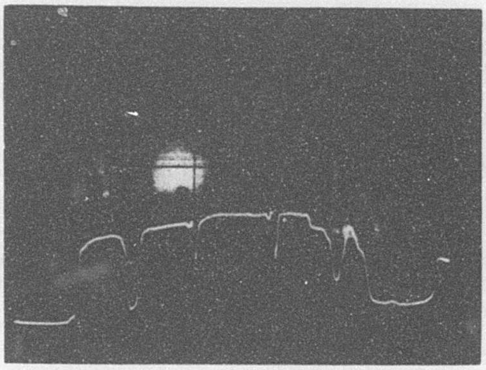


FIGURE 1
C-SCAN AND A-SCAN OF CH-47C TRANSMISSION ACROSS SUMP

Infrared data were recorded in the form of black and white photographs of the CRT display. Both C-Scan and A-Scan data were obtained during the initial phase of this program.

Operation of IR Equipment in Hazardous Environment

The objective of this program was to develop a thermal map of the transmission operating at higher than normal temperatures. When the aircraft "red line" (280°F) has been exceeded, vaporization of oil is in progress and the flash point of the lubricant (MIL-L-7808 = 400°F) is being approached. It was therefore necessary to take proper precautions to reduce the risk of fire when approaching the 400°F limit. For personnel safety the infrared equipment was modified for remote control operation with all of the control units placed outside of the test cell, Figure 2. To accomplish this, 20 ft. cables were attached to each control on the scanning unit and these were monitored by means of a remote

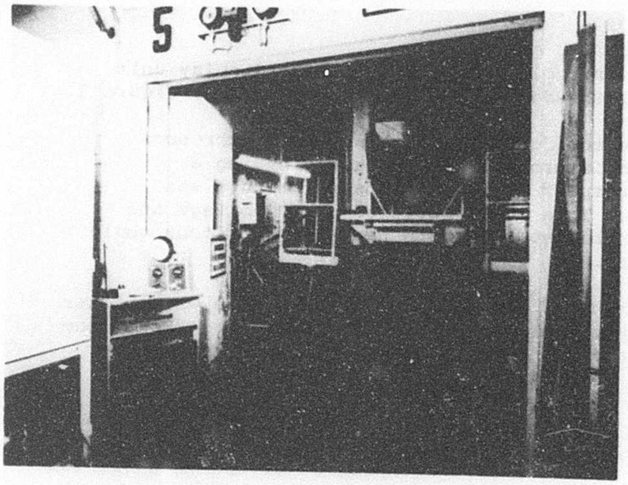


FIGURE 2
XMSN TEST CELL

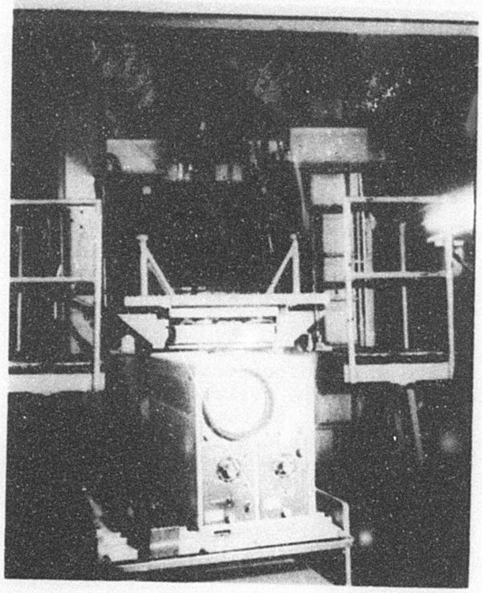


FIGURE 3
IR REMOTE CONTROL UNITS

switching unit placed next to the CRT display unit outside of the doors of the test cell areas, Figure 3.

To operate the focussing mechanism a synchronous motor with internal reduction gears having a revolution speed of 6 1/2 turns per minute was installed. This motor operated on AC voltage and was reversible so that both near and far focus could be achieved.

The amplitude of the A-Scan line increases with higher target temperatures. In order to keep the A-Scan line within the frame of the CRT an electronic attenuator is used. This attenuator was modified for remote operation by relocating it to the remote control switching unit. This was accomplished by incorporating a special circuit in the infrared scanning unit. This was done because the impedance of the transmission line which carries the video signal from the scanner to the CRT display unit should be a constant and it is necessary to match the line impedance with the preamplifier circuit associated with the attenuator circuit. In making these changes it was discovered that the attenuator circuit had been initially improperly matched to the original preamplifier circuit. Therefore an unexpected result of the modification was that a video amplitude gain of approximately a factor of three was obtained.

In addition an investigation was undertaken to ascertain if it was necessary to cool the scanner's electronic components in order to compensate for the potentially high ambient temperatures in the test cell area.

The preamplifier circuit in the scanner incorporates a differential input stage which electronically compensates for ambient temperature variations. Two transistors in close physical contact with each other maintain an electronic balance which is intended to cancel out the effects of temperature variations.

To ascertain whether this temperature compensating device was working correctly a electrofilm heating element was placed in the vicinity of the preamplifier circuit. When the environmental temperature was raised to 110°F only a very small shift in the baseline of an A-Scan of a micro-soldering iron was observed. During the actual test runs the ambient temperature levels in the immediate vicinity of the scanner only reached 93°F even under the most severe test conditions. Therefore the effect of ambient temperature increases on the functioning of the scanner's electronic circuitry is minimal and for the purposes of this study could be disregarded.

Temperature Calibration

All objects above absolute zero emit radiant (infrared) energy. The intensity of this emitted radiation increases in proportion to the fourth power of the objects absolute temperature (Stefan-Boltzmann Law). Since this relationship between radiation intensity and temperature has been established, the surface temperature of an object can be quantitatively determined by calibrating the electrical output of the infrared scanner. To accomplish this the Mac-Iris Calibration Unit, Figure 4, was used.

This calibration unit is a variable infrared source whose temperature can be accurately controlled. The calibrator consists of a long thermal conductor with a heat source connected to one end and a heat dissipator connected to the other end. These develop a temperature differential across the thermal conductor that can be monitored by thermocouples. These were iron-constantan thermocouples attached to a Simpson Thermo-O-Meter model 388-3L which is a self-contained electrically operated temperature indicator. This instrument is accurate to within 1 1/2 scale divisions. Since the scale is not linear, a scale division represents a different number of degrees for various temperature ranges. The number of degrees Fahrenheit per scale division changes from 5° at 200°F to 25° at 400°F.

There are ten black body holes along the length of the calibrator's thermal conductor to provide nine equal

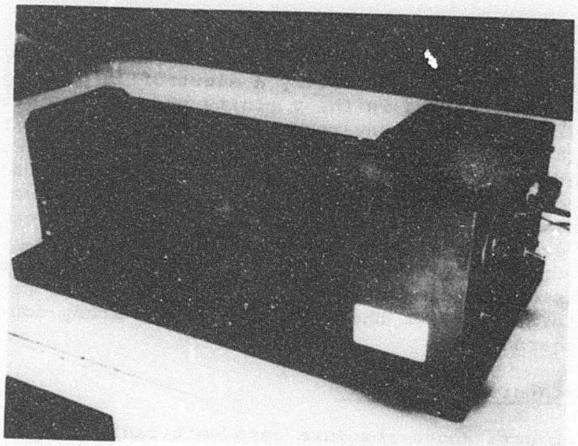


FIGURE 4
MAC-1RIS CALIBRATION UNIT

divisions of temperature gradient, ΔT.

The infrared scanner is calibrated by placing the calibration unit, whose temperature is known, within the field of view of the scanner and noting the amplitude of the A-Scan presentation Figure 5 as it responds to the heat of each black body hole. The difference in amplitude of the A-Scan presentation between two adjacent black body holes represents ΔT. Both the blower speed and applied power can be varied to create any temperature range or temperature gradient that may be desired across the thermal conductor.

The temperature ranges calibrated were approximately equal to the oil-out temperatures encountered under the test cell conditions, i.e. 80°F to 190°F and 80°F to 450°F.

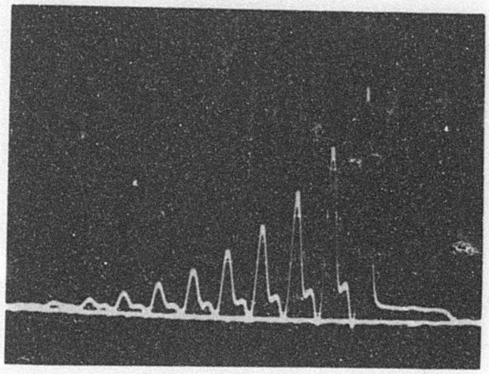


FIGURE 5
A-SCAN LINE OF CALIBRATOR

By measuring the peak height of the A-Scan line and plotting it against the corresponding temperature level of each blackbody hole a calibration curve, Figure 6, was obtained. In both the laboratory environment where the calibration was performed and also in the test cell area the A-Scan line of the ambient temperature was used as the base line from which the A-Scan amplitude measurements were made. In the test cell area the ambient base line was recorded in the morning for the initial test run and was used for all subsequent measurements throughout the day.

It was noted that at temperatures above 150°F the base line immediately to the left of the hot area being scanned was displaced below the initial ambient A-Scan line. This was observed for both the calibration curves, Figure 5 and also for actual test runs on an A-Scan line across the transmission housing, Figures, 16-21. This negative displacement is due to an electronic design limitation in the scanning system. The environmental ambient temperature was used for the base line

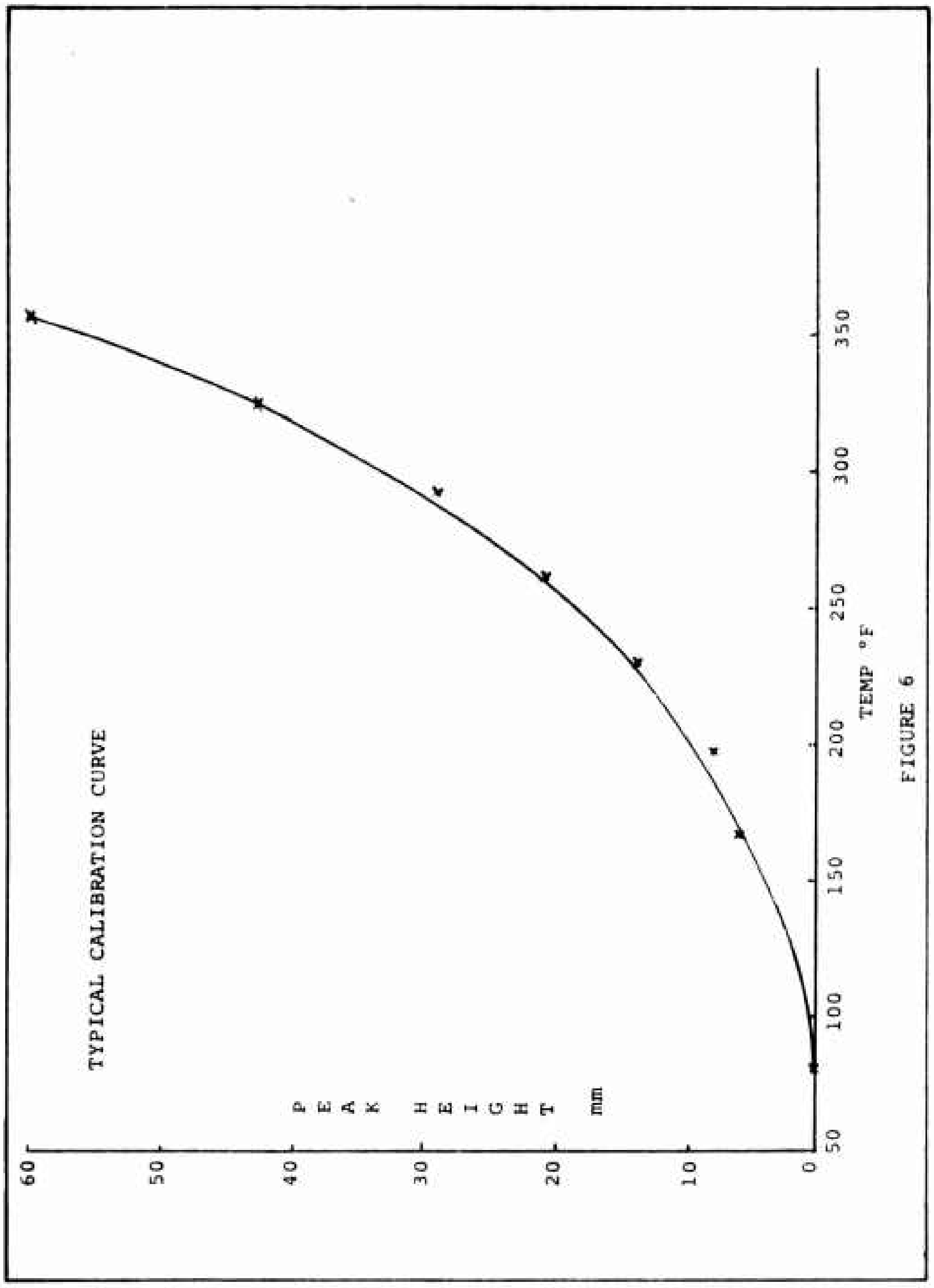

TYPICAL CALIBRATION CURVE
PEAK HEIGHT mm
0
10
20
30
40
50
60
50
100
150
200
250
300
350
TEMP °F

FIGURE 6

in both the test cell area and also for the subsequent backbody calibrations and was approximately the same for both areas (80°F ± 2° F). Therefore this negative displacement can be disregarded in subsequent temperature calculations.

Electronic and Optical Attenuation

To keep the A-Scan presentation within the frame of the CRT as the temperature of the target increases a pre-amplifier variable attenuator is used. The attenuation ranges are in fixed steps marked: 3, 10, 30, 100 indicating the input attenuation factor. In this program attenuation factors of 3, 10 and 30 were required.

In addition, the infrared indium antimonide detector cell saturates above a certain level of radiation. Therefore to measure temperatures in the vicinity of 300°F an optical attenuator is necessary. The lens attenuator has a small hole and it is placed in front of the reflecting lens. It decreases the response of the system by a factor of ten. Therefore it was only used at the higher temperature levels. Temperature calibration curves were established for all combinations of electronic and optical attenuation required in the test cell area.

Emissivity Evaluation

The amount of infrared radiation emitted by an object is dependent not only on the temperature but also the emissivity of the object as shown by the Stefan-Boltzmann Law:

$$W = \varepsilon A \sigma T^4,$$

where

W = Total radiation expressed in watts

σ = Stefan-Boltzman Constant $W/M^2/T^4$

= $5.67 \times 10^{-8} W A^{-1} T^{-4}$

A = Area of the source or limiting aperture, Meter ^{2}

T = Surface Temperature, degrees Kelvin

ε = Emissivity Factor = 1 for a black body } non-dimensional
= < 1 for a gray body

Since the scanner was calibrated for black body radiation it is necessary to compare the surface of the transmission with that of a black body. The only transmission available for this part of the study was a CH-47C engine transmission. Since it is made of the same material, (i.e. A-Z91C magnesium alloy) as the forward transmission the results from the engine transmission could be applied to the forward transmission. A small area of the engine transmission surface was sprayed with 3M Nextel Black Velvet paint of emissivity almost equal to that of a black body (0.99).

The A-Scan presentation Figure 7 taken while the transmission was operating on the test stand at a temperature of 193°F, shows little difference in emissivity between the transmission surface and the black paint. (The small emissivity difference between the black paint and transmission surface can be seen in Figure 7, as the small rise between points X and Y).

X ——→| |←—— Y

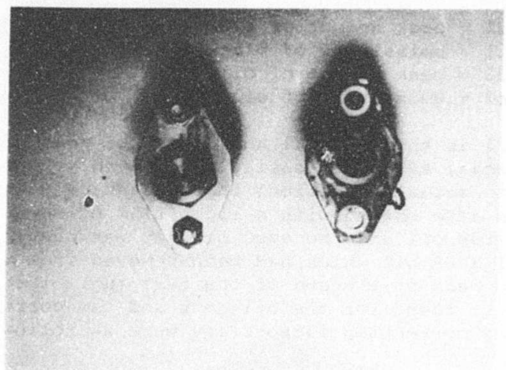
FIGURE 7
TRANSMISSION HOUSING EMISSIVITY EVALUATION

Therefore for the purpose of this study the effects of surface emissivity of the overall transmission housing can be ignored since the emissivity is approximately equal to that of a black body.

Emissivity of Oil Jet

The temperature readings from a iron-constantan thermo-couple attached to an exterior oil jet, part no. 114[illegible]2115, were recorded in an effort to substantiate the independent black body calibrations made in the laboratory. This oil jet exhibited a variety of surface finishes (new and worn anodized aluminum, and cadmium plated steel etc.). None of these seemed to approximate the emissivity of a black body.

The appearance of the oil jet after the final test runs indicated that it had oxidized to a considerable extent in contrast to the shiny finish of a new jet, Figure 8.



NEW USED

FIGURE 8
NEW AND USED OIL JET

It was therefore necessary to obtain emissivity correction factors for both a new and used oil jet. The emissivity of each jet was determined by a comparison with a black velvet coating (3M Nextel 101-C10) which has an emissivity of 0.99. This was accomplished by spraying one half of the oil jet with the black coating Figure 9, and heating it uniformly to 130°F with a forced air blower; an A-Scan line was then taken across the oil jet. In this presentation, the vertical amplitude is directly proportional to the temperature and emissivity across the target according to the Stephan-Boltzmann Law. Thus, if the target temperature is constant across the line being scanned, the vertical amplitude of the A-Scan is directly related to the emissivity of the specimen. A typical A-Scan of the oil jet is shown in Figure 10. The emissivity of the oil jet is given by the formula

$$\frac{d1}{d2} = \frac{\varepsilon 1}{\varepsilon 2} \quad \therefore \quad \varepsilon 2 = \varepsilon 1 \frac{d2}{d1}$$

where d1 = peak height of black velvet
ε1 = emissivity of black velvet = 0.99
d2 = peak height of oil jet
ε2 = emissivity of oil jet

Since ε1 is known and d1 and d2 can be measured from the A-Scan, ε2 can be easily calculated. To better simulate actual conditions in the test cell the new jet was also coated with a light film of new Stauffers MIL-L-7808 oil and the used oil jet was coated with a film of 7808 oil which had been removed from the transmission case at the end of the test run. The emissivity values ε, found for the oil jets and the corresponding backbody correction factors $1/\varepsilon$ were as follows:

	ε	$1/\varepsilon$
New Jet	0.40	2.5
Used Jet	0.62	1.6

Published values of ε for anodized aluminum range from 0.3 to 0.77, and 0.60 for oxidized aluminum, ref. 1, 2, 3.

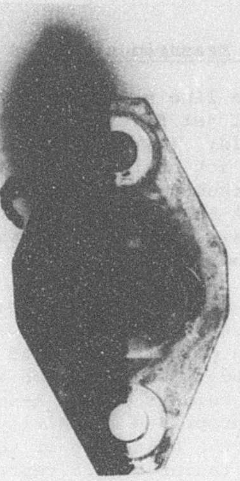


FIGURE 9
EMISSIVITY MEASUREMENT OF OIL JET

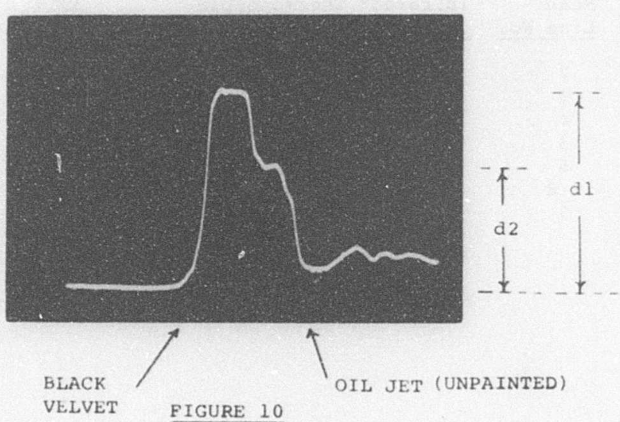


FIGURE 10
A-SCAN OF OIL JET

Oil Jet Temperature Measurements

The principal A-scan line studied in this program was taken across the oil jet fitting, Figure 14. The reasons for this were twofold: (1) The exterior thermocouple attached to the oil jet could be used to substantiate the independent blackbody calibration made in the laboratory, (2) An A-Scan line across the oil jet also passed over other main areas of interest such as the bevel pinion gear and the spiral bevel pinion bearings.

The A-scan line was taken across the oil jet at approximately 5 minute time intervals and each scan line was recorded on polaroid film, at the same time the thermocouple reading was noted on a strip chart recorder. The peak heights of the A-scan line were measured and the appropriate emissivity correction factor applied. At the beginning of the series of runs the correction factor of 2.5 representing a relatively unoxidized oil jet was used. Towards the end of the series of runs the correction factor of 1.6 for an oxidized jet was applied. Actual data for typical test runs are presented below:

Run #1 - 50% Torque Oil Out = 180°F

Scan Line No.	Infrared* Temp.	Thermocouple Temp	ΔT = IR Temp-Thermocouple	% Diff
2	93°F	95°F	-2°F	-2.1
3	104	98	+6	+6.1
4	109	105	+4	+3.8
5	116	104	+12	+11.5
6	124	125	-1	-0.8
7-8	128	118	+10	+8.5
9	128	128	0	0

Run #2 - 100% Torque, Oil Out - 300°F

Scan Line No.	Infrared* Temp	Thermocouple Temp	ΔT	% Diff
2	190°F	182°F	+8°F	+4.4
3	240	228	+12	+5.3
4	270	255	+15	+5.9
5	276	259	+17	+6.5
8	265	250	+15	+6.0
10	230	219	+11	+5.0

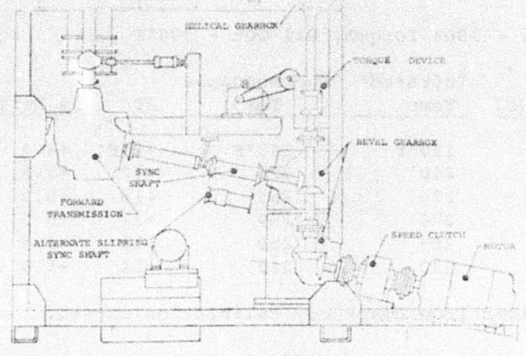
* Derived from blackbody calibration curves.

These results show satisfactory agreement between the two techniques of temperature measurement considering the inherent limitations such as the degree of accuracy in performing the backbody calibration.

Thermal Mapping of Transmission Case

a) Procedure

A 114D1200 forward transmission S/N A7-X101 was disassembled, inspected and instrumented with thermocouples (both externally and internally) by the Advanced Drive Systems Technology Group. The transmission was then installed in a closed loop test stand shown schematically in Figure 11. The Infrared Scanner was positioned in a direct line of sight with the lower case, 114D1089, of the transmission as shown in Figure 12. The transmission was then run with a rotor shaft speed of 243 RPM at various torques and "Target" oil out temperatures as shown in Table I. Target temperature indicates the oil out temperature that was to be achieved during a specific test run.



Closed-Loop Test Stand.

FIGURE 11
CLOSED-LOOP TEST STAND

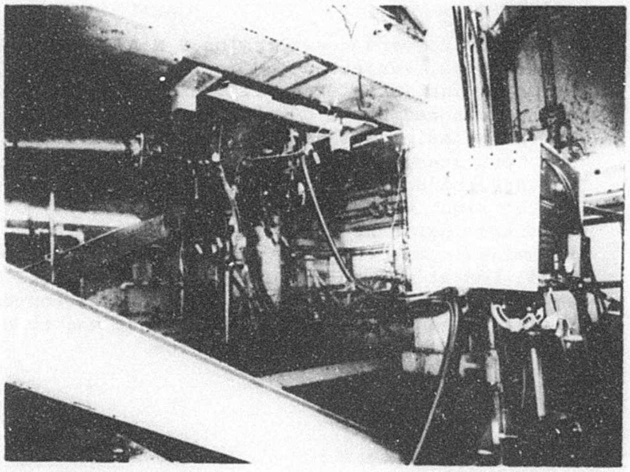


FIGURE 12
CH-47C FORWARD TRANSMISSION
IN TEST STAND

TABLE I
Torque and "Target" Oil Out Temperatures for Specific Test Runs of the Forward Transmission

	Oil Out "Target" Temperature		
TORQUE	186°F	286°F	400°F
	50%*	50%	50%*
	75%*	75%	75%*
	100%*	100%*	100%

*Indicates test runs for which infrared data was obtained.

Infrared data in the form of A and C scan presentations were taken for the transmission housing during the test runs indicated in Table I. A typical example of both displays is shown in Figure 13. The C-scan presentation immediately allows the identification of hot spots across the transmission housing. These appear as whiter areas in the photograph. The amplitude modulated scan (A-Scan) corresponds to a line extending across the oil jet bevel pinion gear, bearings A, B and C and the large open area as shown in Figures 14 and 15. The large "dips" in this A Scan are due to external hoses and thermocouple wires which can be seen as dark areas in the C-Scan of Figure 13.

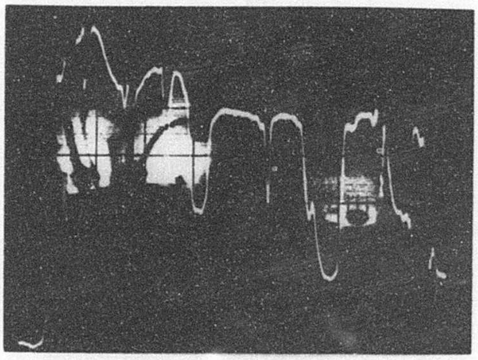


FIGURE 13
C-Scan and A-Scan Showing Large Changes
Due to External Hoses and Thermocouples
(10% Torque, 186°F Oil Out "Target" Temperature)

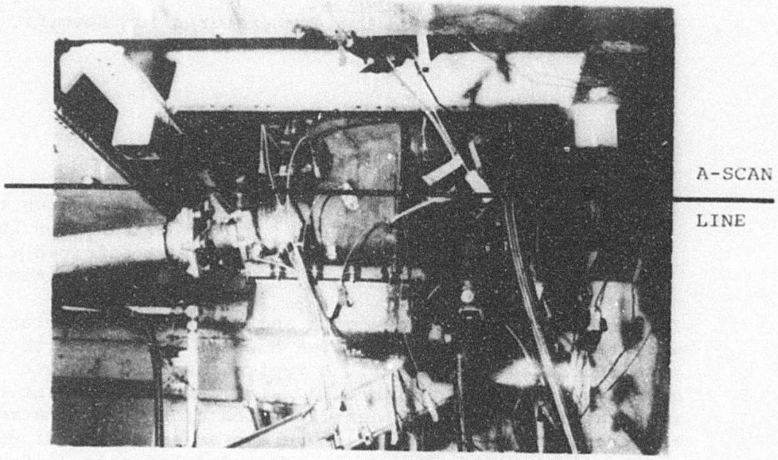


FIGURE 14
A-SCAN LINE ACROSS TRANSMISSION HOUSING

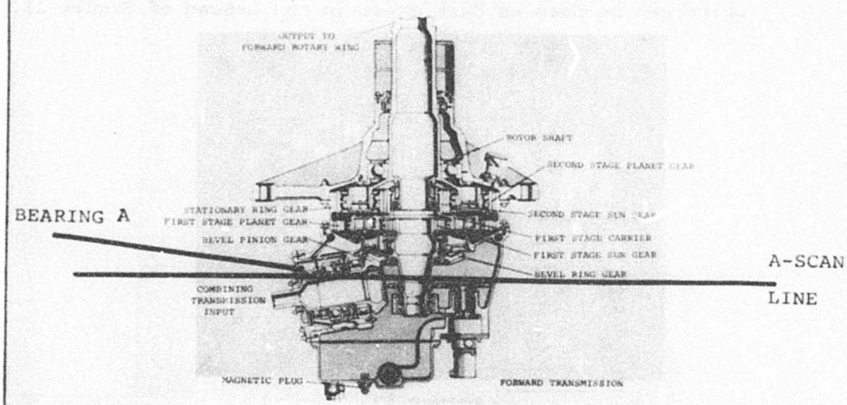


FIGURE 15
SCHEMATIC DIAGRAM OF FORWARD TRANSMISSION

As previously indicated this study was to place emphasis on the temperature behavior of a single line extending across the oil jet and other points of interest. To accomplish this, A-Scan presentations were obtained for the line indicated in Figure 15 at different time intervals during several transmission test runs. Data were recorded in the form of multiple exposed photographs of the line scan indication as it appeared on the infrared scanner's CRT as previously described. Time-temperature relationships could then be obtained for any points of interest across the line by measuring the peak height of the line corresponding to that point and applying the appropriate calibration curve (example Figure 6) and emissivity correction factor.

b. Experimental Results

Multiple exposed photographs showing sequential A-Scans during the indicated transmission test runs appear in Figures 16 to 21. This data conveniently displays the changes that occur across the entire scan line of interest with different oil-out "Target" temperature. Note for example that the left side of the scan line is at a higher temperature (neglecting "dips" due to external hoses and thermocouple wires) then the right side at 50% torque and oil-out "Target" temperature of 186°F. However, this temperature distribution is reversed for 50% torque and oil-out "Target" temperature of 400°F. This effect as a function of time is shown in the time temperature curves of Figures 22 to 27 that were made for a point on the right and left side of the scan line (points 1 and 2 as shown in Figure 16). The temperatures for these points were obtained by converting the infrared data using the appropriate emissivity factor as previously described. In addition the oil-out temperatures and the temperatures of bearing A (located directly below point 1 on the housing) obtained with a thermocouple were also plotted for comparison purposes.

Time-temperature graphs indicate that at oil-out temperatures of 175°F the temperatures of position 1 and 2 are approximately equal. Below this value the temperature of position 1 is less than that of position 2.

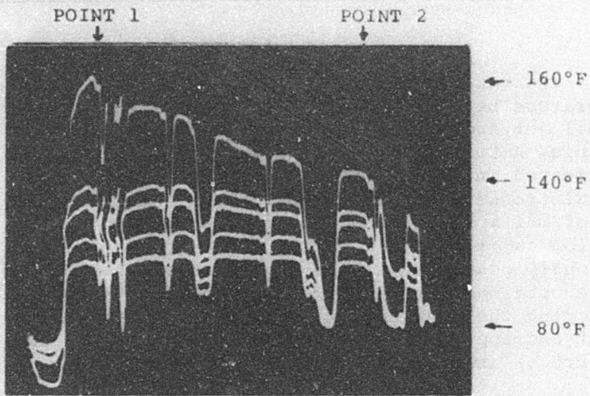


FIGURE 16

RUN #1
50% TORQUE
TARGET TEMP 186°F

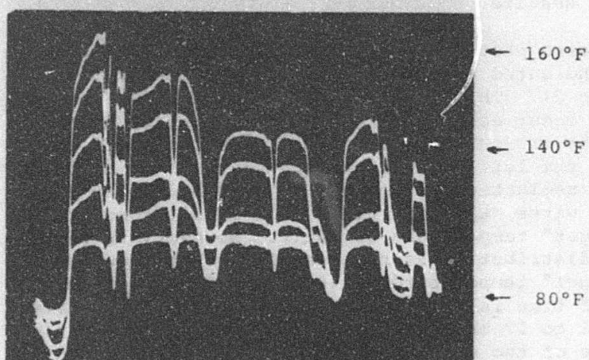


FIGURE 17

RUN #1
75% TORQUE
TARGET TEMP 186°F

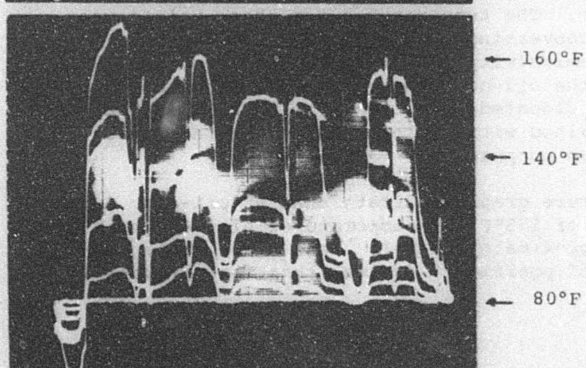


FIGURE 18

RUN #1
100% TORQUE
TARGET TEMP 186°F

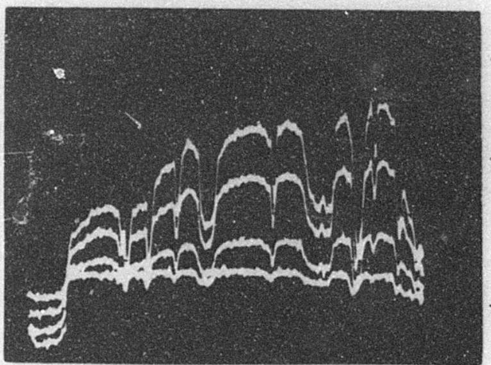


FIGURE 19

RUN #2
100% TORQUE
TARGET TEMP 200°F

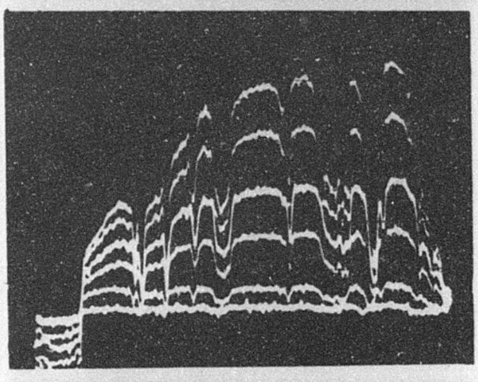


FIGURE 20

RUN #3
50% TORQUE
TARGET TEMP 400°F

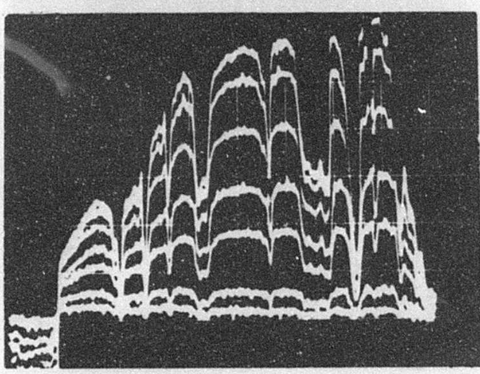
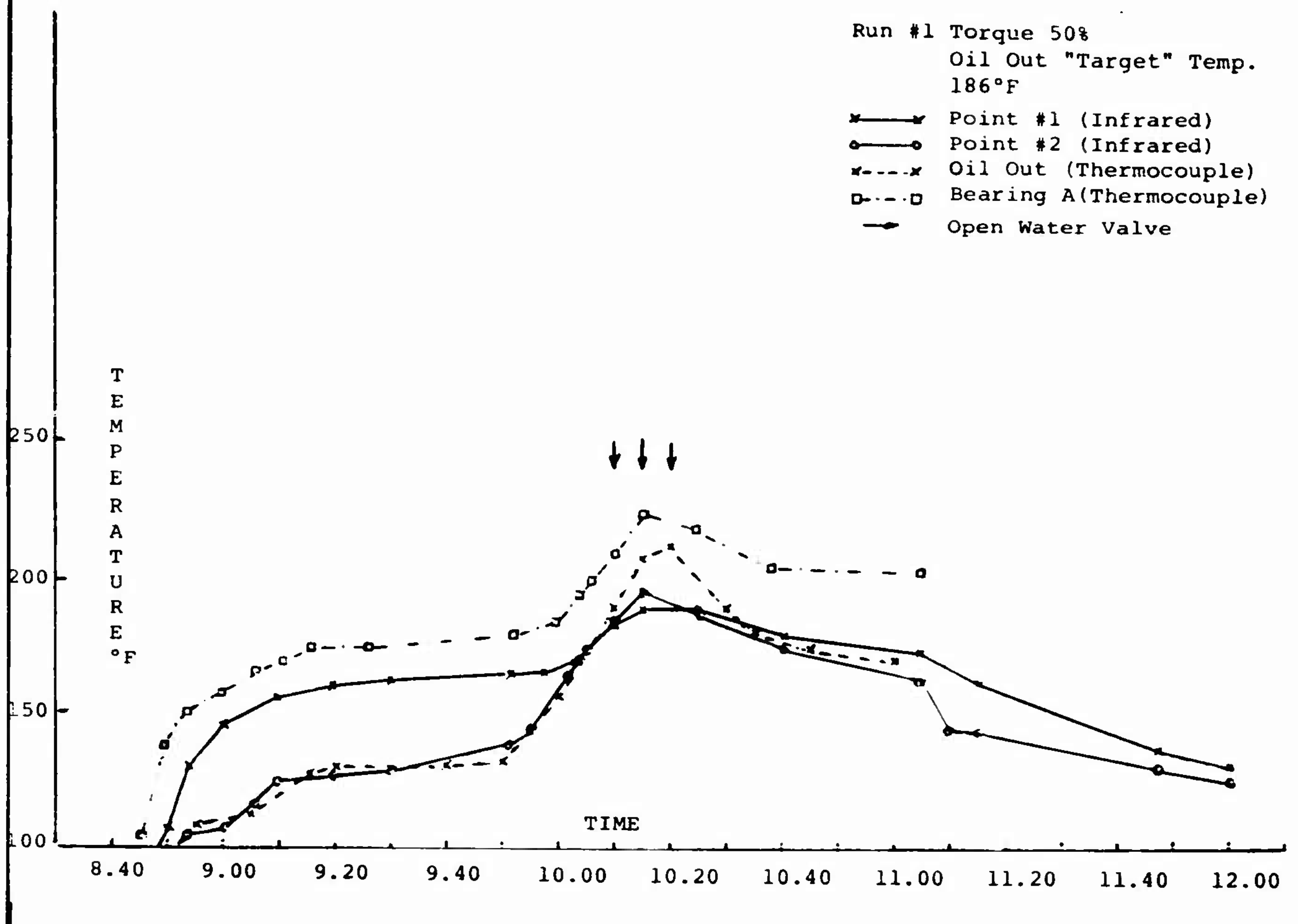


FIGURE 21

RUN #3
75% TORQUE
TARGET TEMP 400°F



Run #1 Torque 50%
Oil Out "Target" Temp.
186°F
Point #1 (Infrared)
Point #2 (Infrared)
Oil Out (Thermocouple)
Bearing A(Thermocouple)
Open Water Valve
TEMPERATURE °F
250
200
150
100
TIME
8.40
9.00
9.20
9.40
10.00
10.20
10.40
11.00
11.20
11.40
12.00

FIGURE 22

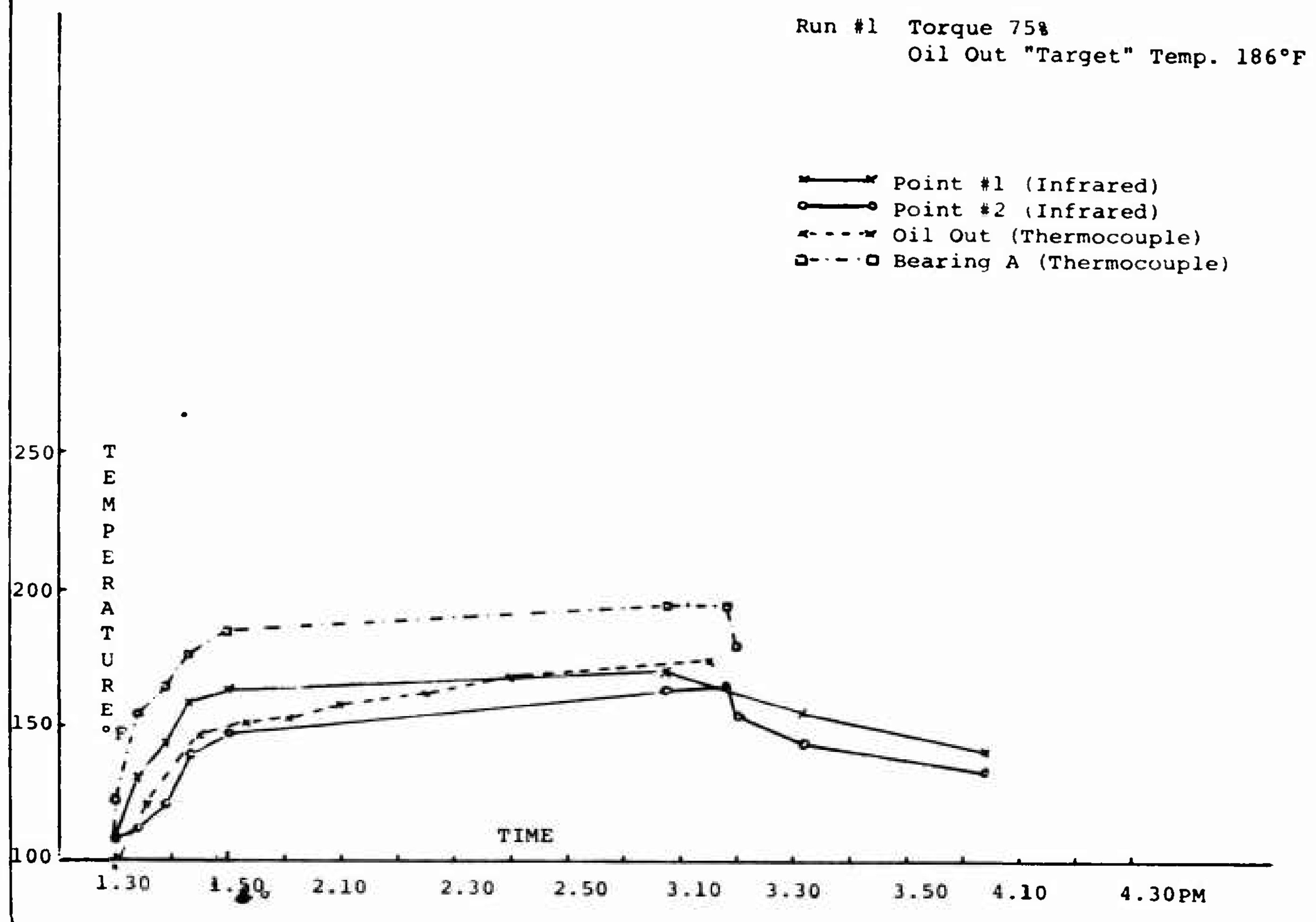
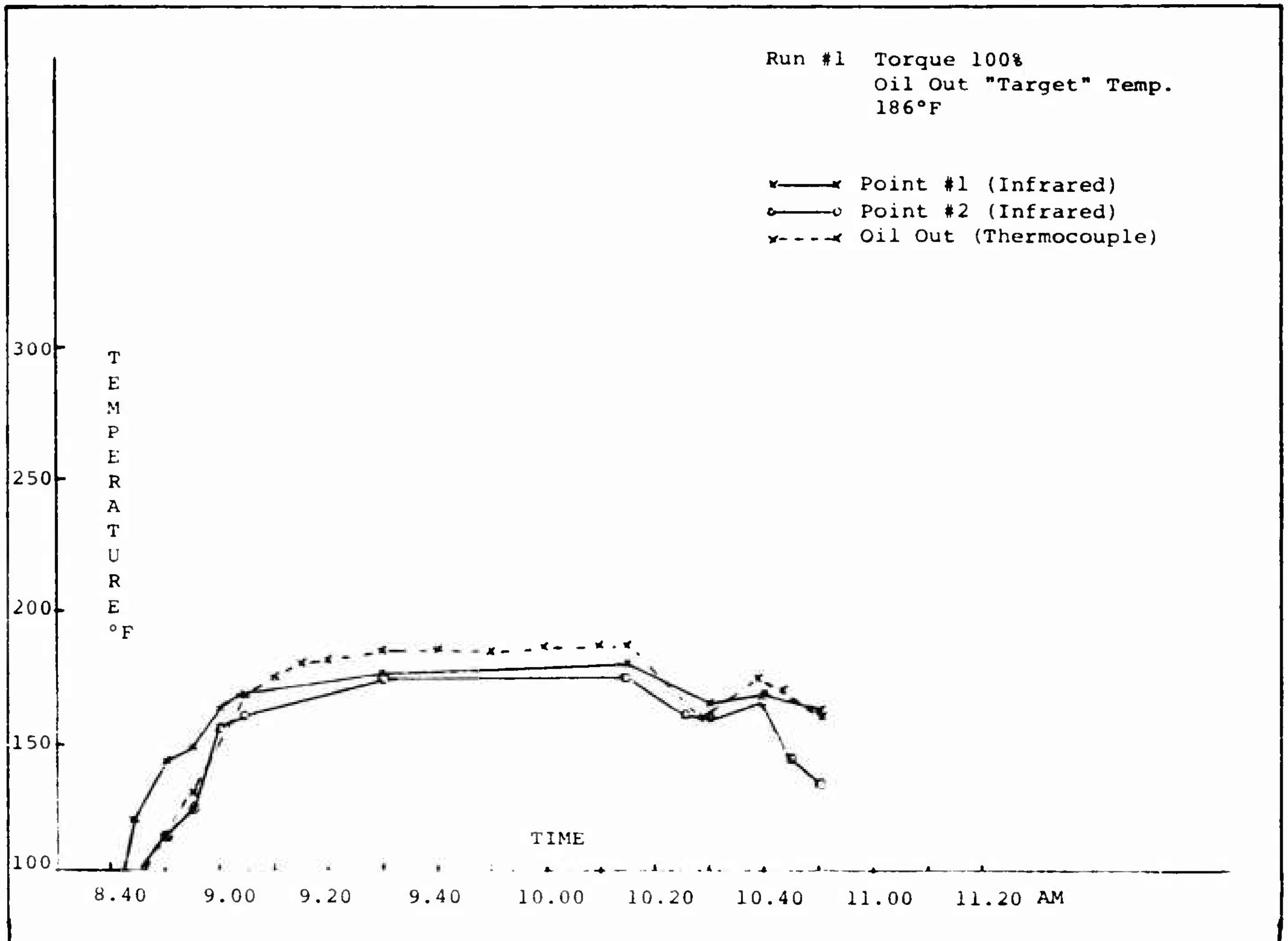

Run #1 Torque 75%
Oil Out "Target" Temp. 186°F
Point #1 (Infrared)
Point #2 (Infrared)
Oil Out (Thermocouple)
Bearing A (Thermocouple)
TEMPERATURE °F
250
200
150
100
TIME
1.30
1.50
2.10
2.30
2.50
3.10
3.30
3.50
4.10
4.30PM

FIGURE 23



Run #1 Torque 100%
Oil Out "Target" Temp.
186°F
Point #1 (Infrared)
Point #2 (Infrared)
Oil Out (Thermocouple)
300
250
200
150
100
TEMPERATURE °F
TIME
8.40
9.00
9.20
9.40
10.00
10.20
10.40
11.00
11.20 AM

FIGURE 24

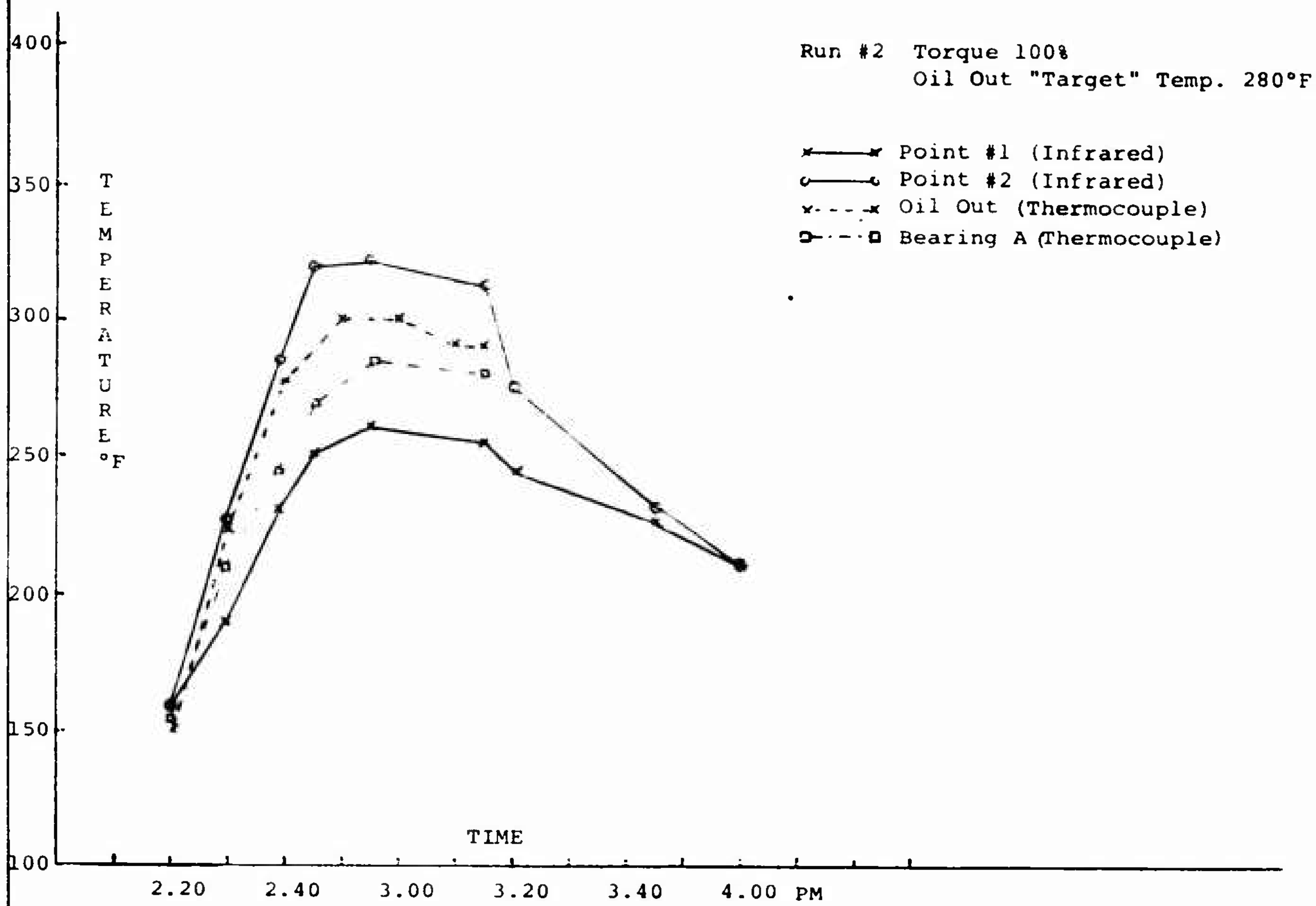

Run #2 Torque 100%
Oil Out "Target" Temp. 280°F
Point #1 (Infrared)
Point #2 (Infrared)
Oil Out (Thermocouple)
Bearing A (Thermocouple)
TEMPERATURE °F
400
350
300
250
200
150
100
TIME
2.20
2.40
3.00
3.20
3.40
4.00 PM

FIGURE 25

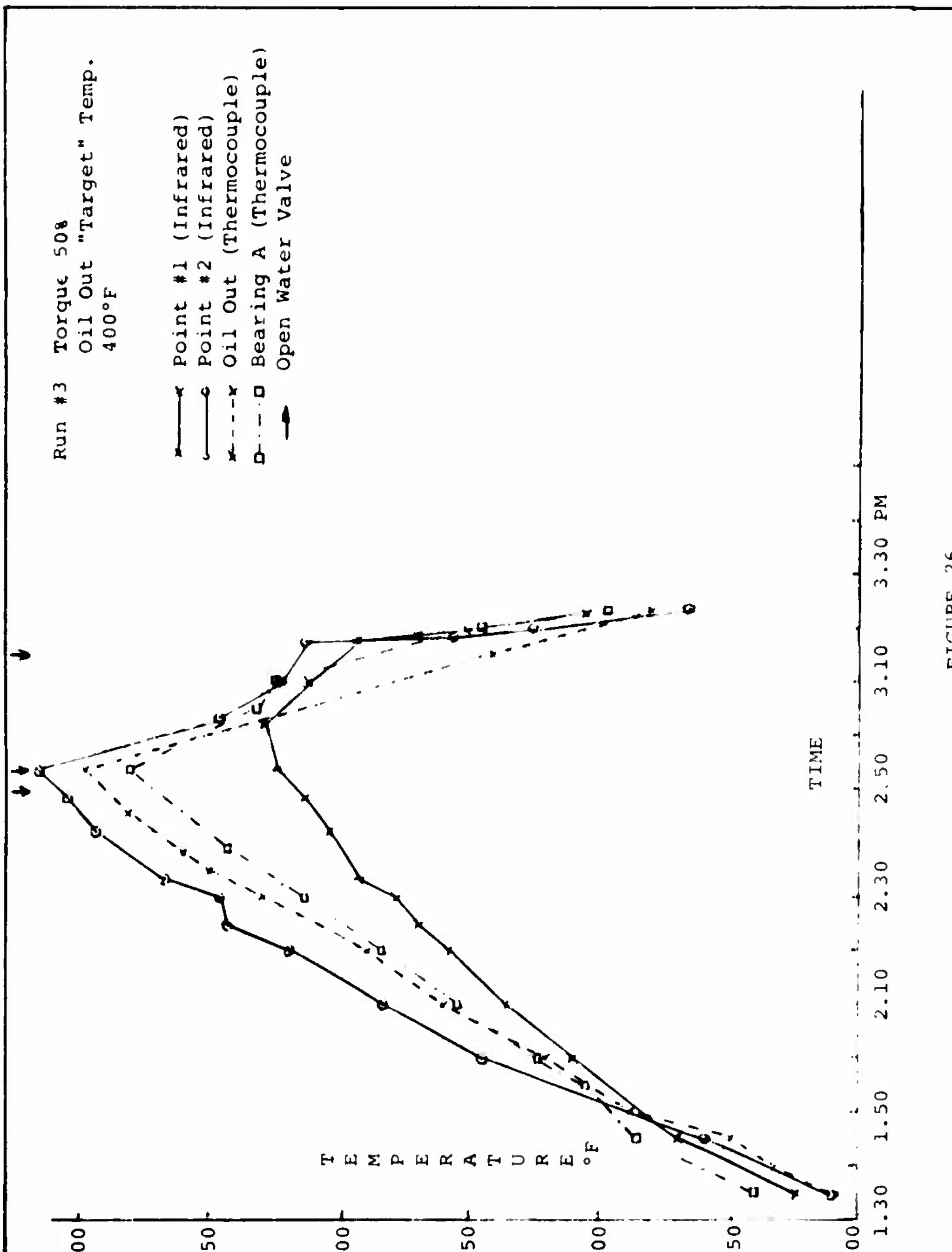

Run #3 Torque 50%
Oil Out "Target" Temp.
400°F
Point #1 (Infrared)
Point #2 (Infrared)
Oil Out (Thermocouple)
Bearing A (Thermocouple)
Open Water Valve
TEMPERATURE °F
400
350
300
250
200
150
100
1.30
1.50
2.10
2.30
2.50
3.10
3.30 PM
TIME

FIGURE 26

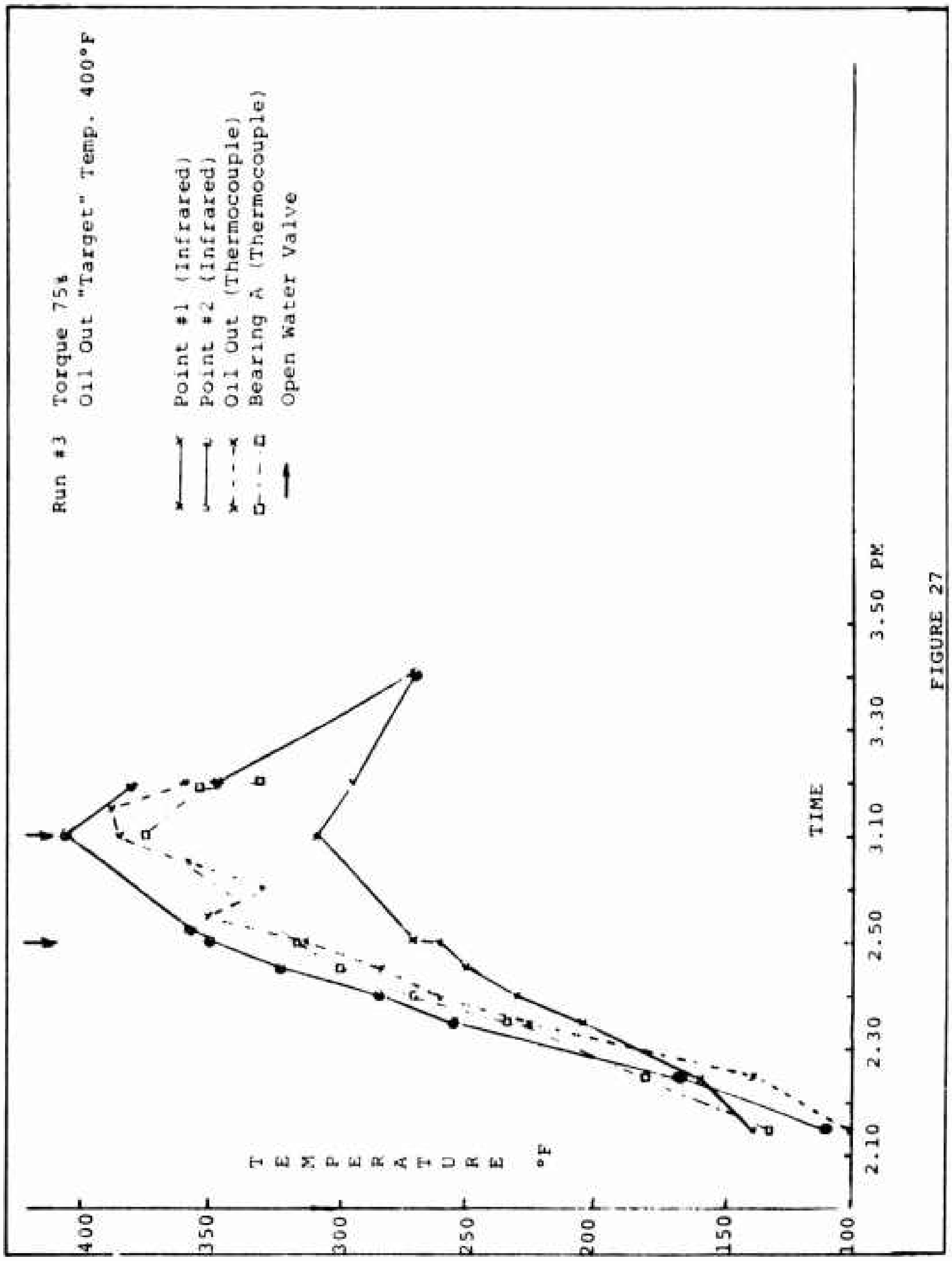

Run #3 Torque 75%
Oil Out "Target" Temp. 400°F
Point #1 (Infrared)
Point #2 (Infrared)
Oil Out (Thermocouple)
Bearing A (Thermocouple)
Open Water Valve
TEMPERATURE °F
400
350
300
250
200
150
100
TIME
2.10
2.30
2.50
3.10
3.30
3.50 PM

FIGURE 27

As the oil-out temperature increases above 175°F the temperature of position 2 is greater than that of position 1, indicating a crossover point at 175°F. At the end of the run after the maximum temperature has been reached and the transmission is cooling down a second crossover point is reached at 210°F when point 1 is equal in temperature to point 2. See graphs for run 1 - 50% torque and run 3 - 50% torque.

The reason for the existence of two different crossover points (one when the transmission is heating up and another when the transmission is cooling down) is not fully understood at this time and should be considered for further study and analysis.

This analysis is complicated by the effects of cooling the inlet oil. This cooling is accomplished by opening the water valve connected to the oil cooler and the times when this operation was performed are noted on the graphs. Not only the timing but also the amount of cooling will affect the overall temperature distribution of the transmission case as shown in Figures 28 and 29. Figure 28 shows the temperature distribution across the housing at the end of Run 3 - 50% torque. Six minutes later the water valve to the oil cooler was fully opened and the results of this sudden cooling are presented in Figure 29 which now shows an assymetric temperature distribution across the case.

In an attempt to obtain additional information concerning this thermal behavior the temperature of bearing A which resides directly below point 1 was plotted along with the infrared temperature data. It appears that for oil-out temperatures below approximately 175°F the bearing temperature correlates fairly well with the housing temperature at point 1. At oil-out temperatures above 175°F the bearing temperature correlates with oil-out temperature.

Further analysis to determine the causes of the observed results could not be accomplished within the scope of this limited program. However, sufficient information was obtained to identify the one area of the transmission housing which is a candidate for location of additional heat transfer paths required for operation of elevated oil temperatures.

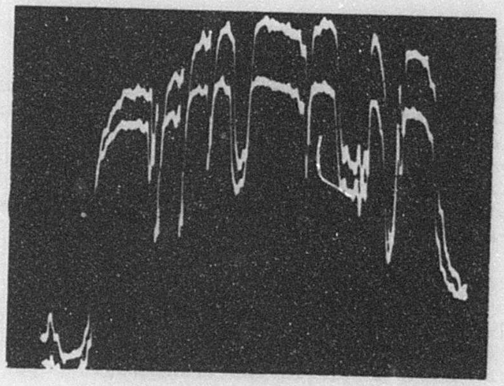


FIGURE 28
TRANSMISSION AT END OF RUN #3
50% TORQUE

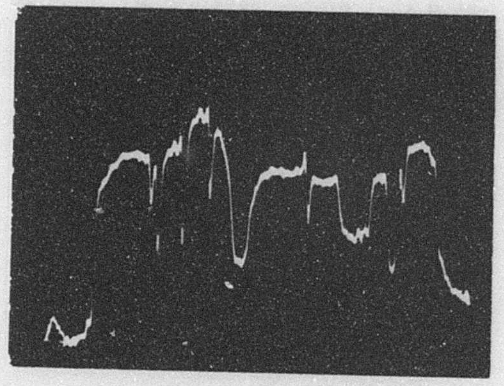


FIGURE 29
TRANSMISSION AFTER OIL
COOLING WAS ABRUPTLY APPLIED

CONCLUSIONS

The results of this program indicate that infrared scanning offers an improved temperature measuring technique which conviently provides data equivalent to several hundred point contact sensors. This capability is directly applicable to the problem of analyzing the temperature distribution across the transmission housing.

Specifically it was found that the temperature distribution across the transmission housing changes with an increase in oil-out temperature. This information is of vital importance for the identification of additional heat transfer paths required for transmission operation at elevated oil temperatures.

RECOMMENDATIONS

Information concerning thermal changes in thermal distribution across the transmission housing at elevated oil temperatures was readily obtained during this program. However, time and budget did not permit a thorough study to determine the causes of this thermal behavior. It is suggested that a more detailed study be performed to ascertain the basis for these changes which may provide information concerning internal design modifications required for optimum transmission operation at elevated oil temperatures.

REFERENCES

(1) "Research Techniques in Nondestructive Testing", R. S. Sharpe Editor, 1970 Academic Press p. 446

(2) "Infrared System Engineering", Richard D. Hudson, Jr. 1969, Wiley-Interscience p. 43, 45

(3) Raytek Rayynger Operation and Maintenance Manual, Raytek Inc. p. 7

(4) "Infrared Evaluation of CH-47C Transmissions" N. W. James, Research and Development Report, 8-243, 1968

(5) "Investigation of the Infrared Method for Measuring Transmission Inner Race Bearing Temperatures". N. W. James, Research and Development Report, 8-257, 1969

APPENDIX II
ENGINEERING TEST 1, 2, AND 3 LABORATORY REPORTS

ENGINEERING TEST LABS

ACCOMPLISHMENT/~~FAILURE~~ REPORT

DATE	MODEL	REPORT NO.
10-11-72	CH-47C	TL-0423

TEST TITLE	
Transmission Thermal Mapping Test	
EWO NUMBER: 7000-52167-11001-000000	LABORATORY: Transmission Test
TEST EVENT: Completion of Phase I - 180°F Oil Out Temperature	

TEST INFORMATION

PART NAME	PART NUMBER	SERIAL NUMBER
--	--	--

SUMMARY:

A 114D1200 forward transmission S/N A7-X101 was disassembled, inspected, modified and instrumented in accordance with the Thermal Mapping Test Plan. The input pinion bearings were replaced by slotted bearings and keys previously used in A7-239 to eliminate thermocouple damage resulting from bearing outer race rotation. Changing the input pinion bearings necessitated the repatterning of the transmission to get the proper gear tooth load pattern.

Thermocouples and thermo-placards were installed in and on the transmission as prescribed in the "Thermal Mapping Test Plan". Deviations from the original test plan in order to facilitate assembly are listed in Tables I and II:

PAGE 1 OF 5

Thermocouples (Table I)

- Thermocouple #4 (change Angle A from 10° to 50°)
- Thermocouple #14 (Change Angle A from 250° to 315°)
- Thermocouple #16 (add words Reverse Thrust)
- Thermocouple #19 (Delete)
- Thermocouple #21 (Change Angle A from 10° to 45°)
- Thermocouple #22 (Change Angle A from 130° to 190°)
- Thermocouple #23 (Change Angle A from 250° to 315°)
- Thermocouple #30 (Change Oil Gallery to Surface)
- Thermocouple #31 (Change Angle A from 240° (Optional) Oil Gallery at Upper Interface) to Angle A = 190° Oil Measurement)
- Thermocouple #32 (Change Angle A from 180° (No Option) (Oil Gallery at Pinion Cartridge) to 170° Oil Measurement
- Thermocouple #33 Change (S/B Mesh Jet) to (Surface at S/B Mesh Jet)
- Thermocouple #41 Add Oil Measurement
- Thermocouple #42 Add Oil Measurement

THERMO-PLACARDS (TABLE II)

All Placards are TEMP-PLATE Part Numbers (#430 and/or #101-4) as fabricated by William Wahl Corp.

PLACARD LOCATION	PART NO. 430			PART NO. 101-4
	(290°F 300°F 310°F	(380°F 390°F 400°F)	(480°F 490°F 500°F)	(550, 600, 650, 700)
#1	X	X	X	X
#2	X	X		
#3	X	X		
#4	X	X		
#5	X	X	X	X
#6	X	X	X	X
#7	X	X		
#8	X	X		
#9	X	X	X	X
#10	X	X		
#11	X	X		
#12	X	X		
#13	(Same as #1 and #5)			
#14	X	X		
#15		Delete		
#16		Delete		
Total Quantity	13	13	4	4

The 430 series thermo-placards were bonded in position using their own self-adhesive, encapsulated in Micro-Measurements M-Bond 600 and cured for two (2) hours at 245°F. The 101 series were bonded with "Temp-Tite", a special high temperature adhesive supplied by Wm. Wahl Corp. and encapsulated in M Bond 600. In some instances during the bonding and encapsulating procedure the 430 series thermo-placards became exposed and had to be replaced. The manufacturer recommended that the 101 series thermo-placards NOT be used in a total oil environment.

In addition to the required instrumentation, two iron-constantant thermocouples were bonded with 2216 epoxy, 180° apart, to the I.D. of the input pinion shaft and brought out through the sync shaft adapter. This allowed recording of gear blank temperature at the bell mouth directly under the spiral bevel gear tooth mesh immediately after shutdown. A method was also devised whereby pyrometric readings of the first and second stage planet gears were taken immediately after shutdown. These back-up methods were installed in anticipation of the thermal placard bonding agent failure due to the hot, agitated oil environment.

The test stand transmission oil system was flushed and refilled with Stauffer's MIL-L-7808 oil as requested. The automatic cooling water system was by-passed and a manual water control valve installed so as to facilitate chill water control from outside of the test cell while the transmission was running.

Test #1 was completed on October 10, 1972. It consisted of four (4) segments which were run at a rotor shaft speed of 243 rpm and a controlled oil-out temperature of 180°F.

- The first segment was at 10% design torque for 0.5 hours
- The second segment was at 50% design torque for 0.5 hours
- The third segment was at 75% design torque for 0.5 hours
- The fourth segment was at 100% design torque (933,702 inch pounds at rotor shaft) for 1.0 hours.

For all segments of the test the following rotor loads were applied to the rotor shaft:

- Lift = 23,000 pounds
- Drag = 4,000 pounds
- Pitch = 157,000 inch-pounds

The test transmission was not torn down and inspected between each segment of the test; however, at the conclusion of all segments of Test #1, the specimen transmission was disassembled, in the stand, to inspect the S/B (spiral bevel) gear mesh teeth condition as well as the 1st and 2nd Stage Planet Gear Blank(s) temperatures and condition. Oil from the sump was strained. Two (550° - 700°F) thermo-placards, and two (380°F - 400°F) thermo-placards were recovered from the oil. In addition, all of the thermo-placards on the spiral bevel pinion and gear indicated "exposure" to "high" temperature even though real-time records including Infra-Red monitoring did not substantiate such "exposure". One thermo-placard (380°F - 400°F) from the S/B pinion was washed-off, one thermo-placard (550°F - 700°F) was washed-off the S/B gear.

It became obvious that back-up means of recording gear blank temperatures (other than thermo-placards) must be used. Consequently the transmission breather was disassembled, its baffle and screen removed, a "standpipe" (venting to atmosphere-rigged for quick removal) fixed to the breather, and the breather reassembled to the transmission. This allows visual inspection and recording of temperature of the 1st and 2nd stage planet gears blanks at shutdown of any numbered and/or segment of a test run. A photographic record was made at the end of Run #1. Inspection of the magnetic plug and oil sample indicated no irregularities.

A and C Scan Infra-Red photographic records were taken during the test segments as well as at shutdown to record any visible "soak-back" phenomena and continuous thermal mapping over the specimen surfaces between surface thermocouples.

Thermal growth dimensional measurements were taken at ambient temperature before test #1 and will be compared with corresponding dimensions at elevated temperatures.

ENGINEERING TEST LABS

ACCOMPLISHMENT/~~FAILURE~~ REPORT

DATE	MODEL	REPORT NO.
10-18-72	CH-47C	TL-0424

TEST TITLE: Transmission Thermal Mapping Test	
EWO NUMBER: 7000-52167-11001-000000	LABORATORY: Transmission Test
TEST EVENT: Completion of Phase II 286°F Oil Out Temperature	

TEST INFORMATION

PART NAME	PART NUMBER	SERIAL NUMBER
--	--	--

SUMMARY:

Phase II of the Thermal Mapping Test was run at a rotor shaft speed of 243 RPM and to a controlled oil-out temperature of 286°F ±10%.

The first segment was at 50% design torque until temperatures stabilized.

The second segment was at 75% design torque until temperatures stabilized.

The third segment was at 100% design torque until temperatures stabilized.

For all segments of the test the following rotor loads were applied:

Lift = 23,000 pounds
Drag = 4,000 pounds
Pitch = 157,000 inch-pounds

At the completion of all segments of Phase II, the transmission sump was removed to facilitate inspection of the spiral bevel gear teeth and the remaining thermo-placards.

The gear teeth exhibited a hard line at the root of the spiral bevel pinion and all but one of the remaining thermo-placards had washed off. The one remaining was on the spiral bevel ring gear. Inspection of the first and second stage planet gears through the oil filler neck indicated no apparent damage to the gear teeth.

PAGE 1 of 2

In preparation for the third and final phase of testing, the oil sump sight glass was replaced with a solid aluminum plate in anticipation of a failure of the plexi-glass at the elevated temperature. The oil in the transmission system was drained and replaced with new MIL-L-7808 oil. While draining, the oil was strained and several thermo-placards recovered.

Prior to start of Phase III the transmission was run up and stabilized at 300°F with 50% torque applied. An entire series of thermal growth dimensions were taken and recorded.

The oil was again drained and replaced with new oil. The spiral bevel gear teeth were inspected. No progression of the hard line was noted. The transmission was readied for Phase III of test.

BOEING VERTOL COMPANY

Test Memorandum Report

SUBJECT: Transmission Thermal Mapping

REFERENCES:

(1) CAP 5430 (Work Statement for RFQ DAAJ02-72-Q-0101)
(2) WPD 7000-52167-11001-000000 dated June 5, 1972
(3) WPD Contract DAAJ02-72-C-0075 dated June 5, 1972
(4) Work Authorization No. 52167 dated June 2, 1972
(5) Thermal Mapping Test Plan dated June 27, 1972
(6) Thermal Mapping Plan of Performance dated June 5, 1972
(7) Engineering Lab Reports TL-0423 and TL-0424
(8) Thermal Mapping Final Report D210-10545-1

ENCLOSURES:

(a) Figure 1 - Map Indicating Locations of Thermocouples and Thermo-placards
(b) Figure 2 - Map of Temperatures recorded during Test #1 - 100% Torque - 180°F
(c) Figure 3 - Map of Temperatures Recorded During Test #2 - 100% Torque - 286°F
(d) Figure 4 - Map of Temperatures Recorded during Test #3 - 100% Torque - 400°F
(e) Figure 5 - Map of Temperatures Recorded during Torque-Temperature Stabilization Run
(f) Figure 6 - Map of Temperatures Recorded as Growth Dimensions were being taken
(g) Table I - Tabulation of Dimensional Growth Parameters

BACKGROUND: This is another in a continuing effort by Boeing Vertol to improve on the vulnerability aspects of the helicopter subsystems in general and the transmission oil cooling subsystem specifically.

PURPOSE: To determine the temperature of all main components and a complete thermal map of a CH-47 forward transmission under various loads and inlet oil temperatures. The results of this test program will provide the U.S. Army (AMRDL) with data indicating the work required to arrive at a thermally-tolerant transmission with self-contained lubrication.

DESCRIPTION OF SPECIMEN:

A CH-47C, 114D1200 forward rotor transmission, S/N A7-X101, previously accountable under Contract DAAJ02-71-C-0020 ("C" model qualification) was disassembled, inspected and deemed acceptable.

The following modifications were incorporated to facilitate dynamic temperature recordings of the internal components.

1. The input pinion bearings were replaced with slotted bearings previously used in a forward transmission S/N A7-239:

P/N	S/N	Replaced by	P/N	S/N	SK-P/N
114DS240-2	K19	" "	114DS240-2	H105	SK22079-4
114DS284-1	K611	" "	114DS241-1	1&2	SK22079-2
114DS262-2	167	" "	114DS262-1	01853	SK22079-3

2. The 114D1045-4 pinion support S/N NJ546 was machined to accept SK22079-5,6,7 positive retention keys.

Modifications 1 and 2 were required to prevent bearing outer race rotation thereby precluding any possibility of damage to the race contact thermocouples.

3. The upper and lower housings were drilled and tapped for thermocouple installations, BMS 544 was used to seal the holes where the internal thermocouples exited the transmission housing.

4. Two iron-constantan thermocouples were bonded (using EC2216 epoxy) 180° apart on the bell mouth of the spiral bevel pinion gear directly under the teeth. The wires were threaded along the I-D of the pinion shaft and brought out at the splined end.

5. Thermo-placards were bonded on the internal components per the test plan.

   a) All surfaces were sanded and solvent cleaned.

   b) The Wm. Wahl Corp. 430 series placards were installed using their own self-adhesive, then encapsulated in Micro-Measurements Inc. M-Bond 600 and cured for two (2) hours at 245°F.

   c) The 101-4 series placards were bonded in place with "Temp-Tite", a special high temperature adhesive (1100°F) supplied by the vendor and encapsulated in M-Bond 600 and cured for two (2) hours at 245°F.

DESCRIPTION OF SPECIMEN: (Continued)

6. The 114D1085 plexi-glass sight gage was removed and replaced with a 1/4" thick aluminum plate in anticipation of high temperature generated distortion. This modification was incorporated prior to start of test three (3) at 400°F ± 10%.

7. The 114D1103 filler neck baffle and the F965 screen assembly were removed to allow access to the first and second stage planet gears with a pyrometer. This also allows for visual inspection of the planet gear teeth. A quick removal stand pipe was installed in the filler neck to negate the possibility of oil spewing from this area while running.

8. The transmission was center punched at measuring points to insure exact repeatability of location when measuring thermal growth.

PROCEDURE:

The test transmission was installed in the FTSJ114D1200 regenerative load stand. The test stand transmission oil system was drained, flushed and recharged with Stauffer's MIL-L-7808G oil.

A manual shut-off valve was installed in the water line to the heat exchanger allowing control of the oil temperature from outside of the test cell. The test stand transmission temperature indicating gages were replaced with high range gages (0°-600°F). Direct reading thermocouples were attached to the stand in strategic locations to determine the effects of the surrounding structure as a heat sink.

The test cell air conditioning and blower systems were shut down and high temperature safety devices were disconnected to preclude any unwanted automatic shut downs.

The rotor loading and torque systems were checked and adjusted as necessary. A test stand and transmission checkout run was performed and all discrepancies corrected prior to start of test.

The following test parameters and limitations were adhered to throughout the course of testing:

1) Applied Rotor Loads

a)	Thrust	=	23,000 lb.
b)	Pitch	=	157,000 in-lb.
c)	Drag	=	4,000 lb.

PROCEDURE: (Continued)

2. Applied Torque at Rotor Shaft (loading as specified for each test segment)

   a) 10% design load = 9,337 in-lb.
   b) 50% design load = 466,850 in-lb.
   c) 75% design load = 700,275 in-lb.
   d) 100% design load = 933,700 in-lb.

   All torque levels to be maintained within +5%, -0%

3. Rotor Shaft Speed

   243 RPM +3% -0%

4. Temperature - Oil Out of Transmission

   Temperature as specified for each test segment

   a) 180°F ± 10%
   b) 286°F ± 10%
   c) 400°F ± 10%

Causes for termination of any segment of the test included but was not limited to:

1. Any component temperature of 450°F.
2. Transmission oil-out temperature does not appear to stabilize below 400°F.
3. Sudden and drastic increases in component or oil temperatures.
4. Any segment of uninterrupted test time exceeding two (2) hours.

The extent of transmission teardown inspections between segments of, and between test runs was at the discretion of the project engineer and/or the program manager. The transmission was completely disassembled and inspected between the 75% and 100% torque runs at 400°F.

The following data was recorded at ten minute intervals throughout all testing, shorter recording intervals were used when deemed necessary.

Rotor shaft thrust load
Rotor shaft pitching moment load
Rotor shaft drag load
Rotor shaft torque
Sync shaft rpm
Transmission oil-in temperature
Transmission oil-out temperature
Transmission oil-in pressure
Transmission oil-out pressure
Test stand motor wattage
Test cell ambient temperature

PROCEDURE: (Continued)

In addition to the above the following data were recorded:

- Temperature vs time of all thermocouples (recorded in real time)
- Test cell temperature in real time
- Temperature range of thermo-placards when obtainable
- Polaroid photograph documentation of spiral bevel gear teeth at the completion of each segment of each run
- Thermal growth measurements prior to start of test (baseline) and end of selected runs

TEST RESULTS:

Test #1

This test included four segments which were run at a rotor shaft speed of 243 rpm and a controlled oil-out temperature of 180°F. The four segments consisted of a 10%, 50%, 75% and 100% design torque run.

Full rotor loads were applied and each segment was run until all temperatures had stabilized. At the end of each segment the transmission oil sump was removed to allow inspection and photographic record of the condition of the spiral bevel gear teeth. A slight hard line on the root of the pinion gear teeth was noted at inspection after the 10% run. The first and second stage planet gears showed no apparent wear at the end of the 180°F run.

Inspection of visible thermo-placards indicated exposure to high temperatures even though real-time records including infra-red monitoring did not substantiate the existance of such temperatures. Several thermo-placards had washed off and were found floating in the oil.

Inspection of the magnetic chip detector and oil filter indicated no discrepancies.

Test #2

This test consisted of three segments, 50%, 75% and 100% design torque, at a rotor shaft speed of 243 rpm with full rotor loads and a controlled transmission oil-out temperature of 286°F ±10%.

TEST RESULTS: (Continued)

Test #2 (Continued)

Inspection of the spiral bevel gear teeth at the completion of each segment revealed minimal progression of the hard line. The first and second stage planet gears showed no abnormal wear when inspected through the oil filler cavity at the end of this test. More thermo-placards were recovered from the oil. Inspection of the magnetic chip detector and oil filter revealed no discrepancies. The transmission oil system was purged and replenished with new MIL-L-7808G oil.

Prior to the start of Test #3 the transmission was run up and the oil-out temperature stabilized at 300°F with 50% torque and full rotor loads applied. Immediately after shutdown thermal growth dimensions were taken. At the exact time that the dimensions were taken the temperature was indicated in real time on an Esterline Angus and a Daystrom twenty-four (24) channel recorder.

The transmission oil was drained and replaced in preparation for the next run.

Test #3

This test consisted of three segments, 50%, 75% and 100% design torque, at a rotor shaft speed of 243 rpm and a controlled transmission oil-out temperature of 400°F ±10%.

Inspection at the end of the 50% torque run indicated a slight progression of the hard line on the spiral bevel gears. The first and second stage planet gears were in satisfactory condition. At the completion of the 75% torque run the hard line had progressed to a light scuff, sufficient to warrant a complete teardown of the transmission. Inspection revealed that three teeth of the first stage sun gear had small spalls and that the first stage planets were lightly frosted. There were no signs of distress in the rest of the transmission.

The spalled sun gear teeth were stoned to remove the sharp edges. New thermo-placards were bonded to the I.D. of the input pinion shaft which is a non-oil washed area. The transmission was re-assembled and the 100% torque run performed. Inspection, through the sump, at the completion of this run indicated severe scuffing of the spiral bevel gear teeth. Light scuffing was noted on the first stage planet gears.

Prior to removal from the test stand and disassembly, a one time run was made to try and determine at exactly what torque level the transmission temperatures would stabilize. Analysis of accrued data indicated a starting point of approximately 40% design torque.

<u>TEST RESULTS</u>: (Continued)

<u>Test #3</u> (Continued)

Disassembly and inspection at the conclusion of all testing indicated that visually the transmission was in satisfactory condition with the following exceptions:

Spiral bevel pinion gear	-	severe scuffing
Spiral bevel ring gear	-	severe scuffing
First stage sun gear	-	advanced spalling
First stage planets gears	-	light scuffing

<u>DISCUSSION OF RESULTS</u>:

Although extreme care was taken in the installation of the required thermo-placards, using the best available technique, it proved to be inefficient in the high velocity oil environment of the transmission. The thermo-placards proved to be unreliable in that exposure occurred out of sequence and high temperature placards were exposed when there was no evidence of the transmission temperatures being in close proximity to those indicated on the placards.

At controlled transmission oil-out temperatures up to and including 286°F ±10%, torque merely serves as a vehicle to increase temperatures more rapidly. At 10% torque speed is the primary heat generator with torque being a secondary factor; however, as the torque is increased this trend is reversed with torque dominating.

There was no noticeable progression of the hard line on the spiral bevel gears nor was there any indication of surface distress on the other gears up to and including the 50% torque run at 400°F. At a point between 50 and 75% torque in the 400°F temperature range, there occurred a crossover in which the gear tooth surfaces begin to deteriorate rapidly. This condition could possibly be due to a chemical breakdown of the oil, a metallurgical breakdown of the gear tooth load surface or a combination of both; however, the explanation of this phenomena is not in the scope of this testing.

At the completion of all testing, a limited search was performed to determine at what torque level the oil-out temperature would most nearly stabilize. After careful analysis of the accrued data, it was decided to start at 40% torque. At this torque level the temperature rate of climb began to level off, although the temperature was still increasing. The continual increase in temperature could in part be the result of heat generated due to the advanced and continuing state of deterioration of the spiral bevel and first stage sun gears.

DISCUSSION OF RESULTS: (Continued)

Figure 1 indicates the location and number of thermocouples and/or thermo-placards as installed on and in the transmission. Figures 2, 3, and 4 are a mapping of the actual temperatures recorded at each location monitored during the 100% torque runs at 180°, 286° and 400°F (±10%) respectively. The analysis and any hypothesis derived from the temperature data will be fully documented in the Thermal Mapping Report No. D210-10545-1.

Temperatures reached during the limited torque vs stabilized temperature search are documented on Figure 5. Cut-off point for this test was established at 400°F in view of the previously discussed condition of the spiral bevel gear teeth.

A separate run was performed at 50% torque and an oil-out temperature of 300°F to determine the thermal expansion of the transmission. The exact temperature in the local of the dimension being taken was recorded in real time. Table I is a tabulation of the dimensional growth. Some of the dimensions required were very difficult to obtain due to interference of the surrounding test stand structure.

CONCLUSIONS:

Recorded data indicates three heat paths in the transmission as it is running. When the oil temperature is being maintained by controlled cooling the main heat path is the circulating oil, the rotor shaft and input pinion shaft also act as heat paths. When there is no cooling the oil has very little affect as a heat path. Under these conditions the transmission is dependent on radiation and conduction through the skin into the surrounding atmosphere and test stand structure plus the rotor and input pinion shafts as heat paths to dissipate the heat.

There is a cross-over point where at elevated temperatures there is a rapid deterioration of the gear tooth load surfaces. The conformation and evaluation of the phenomena should be pursued with more extensive testing.

To further refine the exact torque level at which the transmission temperatures stabilize, additional testing is necessary.

NUMBERS IN PARENTHESES ARE NUMBER OF THERMOCOUPLE AND TEMPERATURE PLACARD READINGS

TEST STAND (HEAT SINK) (3)

TEST CELL AMBIENT AIR (3)

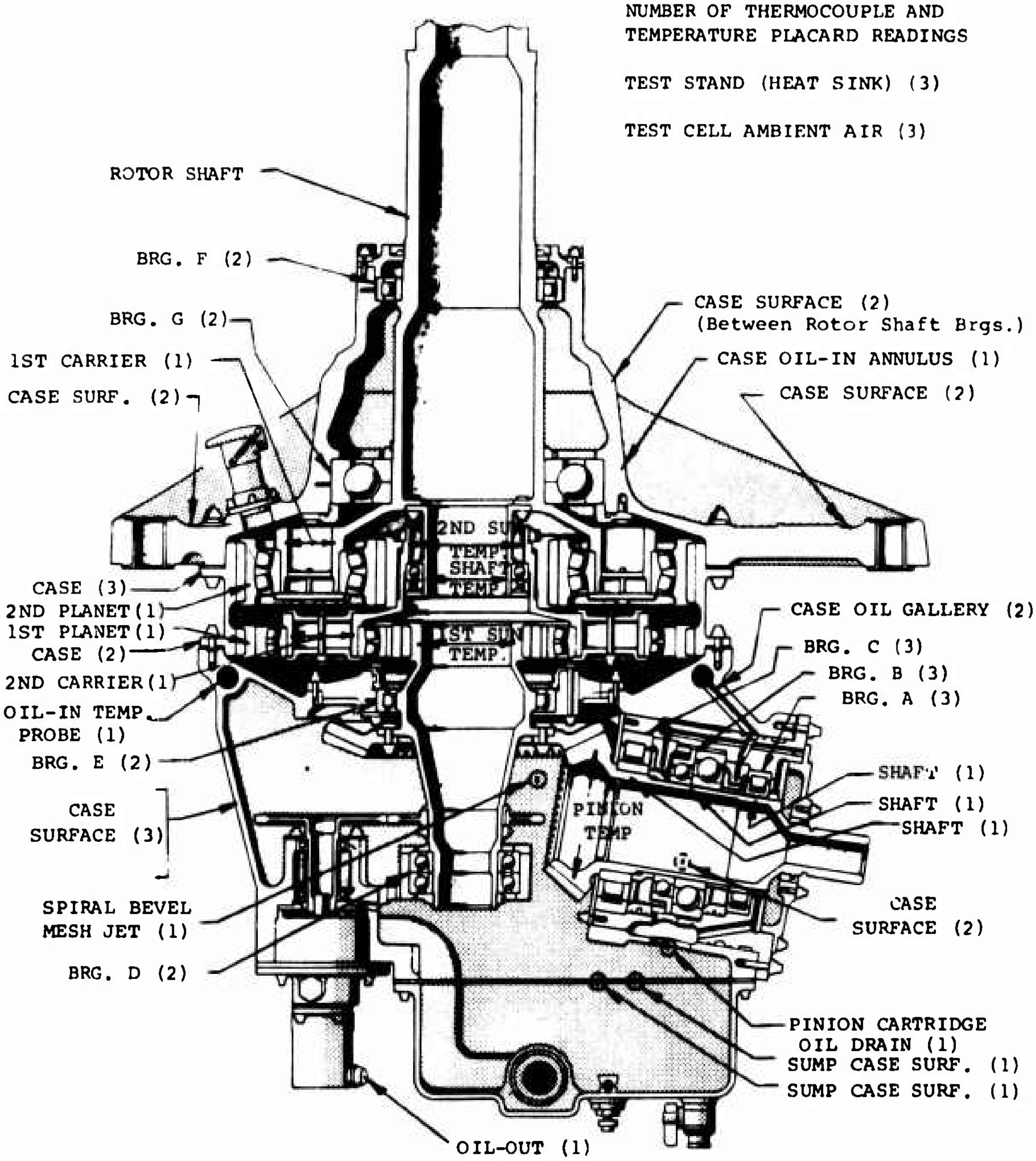


Figure 1: Thermal Mapping Component Temperature Legend.

SHEET 9

Ref. No.: TMR 1372

NOTE: All numbers shown are temperatures, T, in degrees Fahrenheit (at shutdown).

Test Stand (Heat Sink) = 96, 98, 118

Test Cell Air = 89, 95, 98

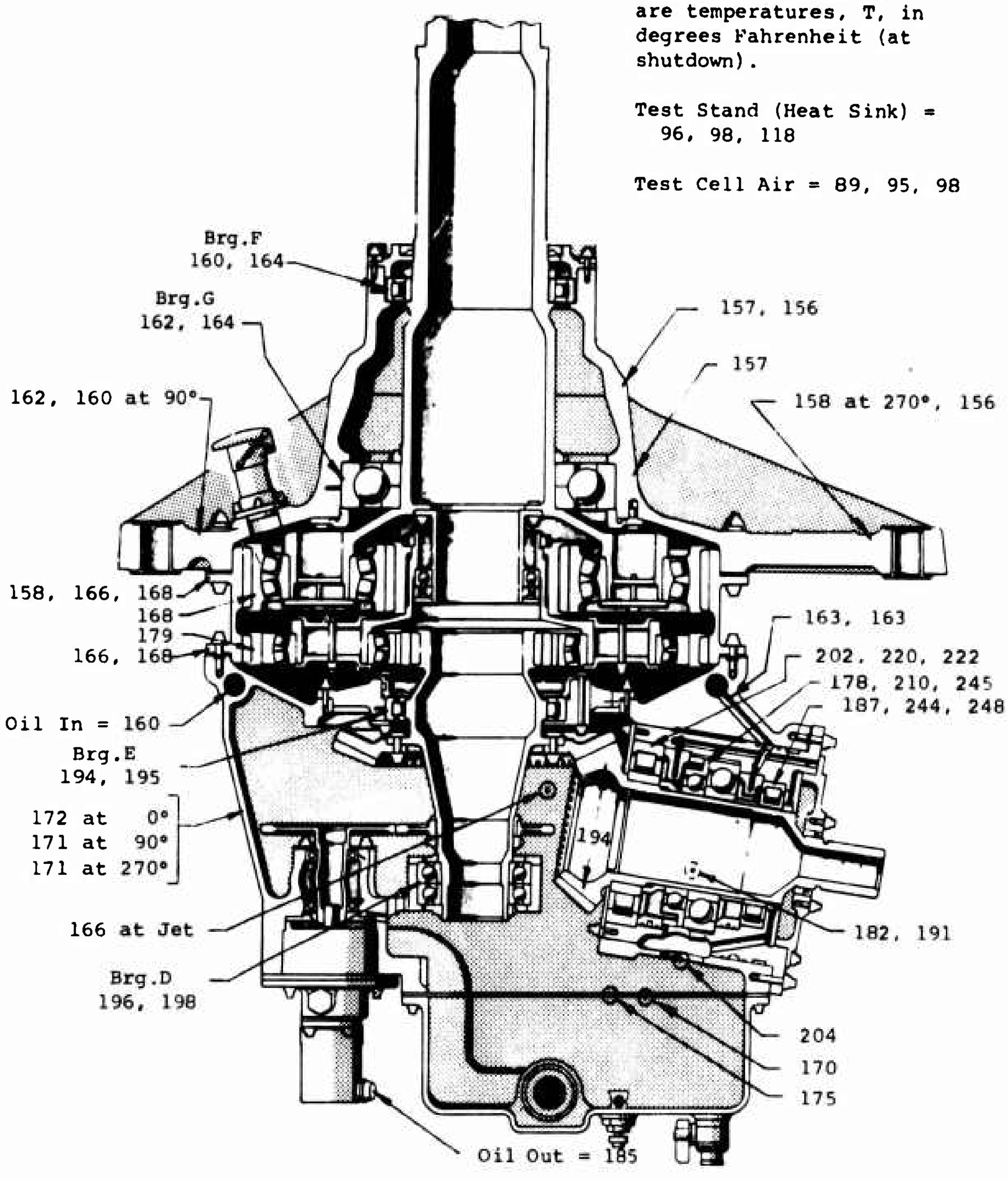


Figure 2: Thermal Record at 100% Torque - 180°F Oil-Out Temperature.

SHEET 10

Ref. No.: TMR 1372

NOTE: All numbers shown are temperatures, T, in degrees Fahrenheit (at shutdown).

Test Stand (Heat Sink) = 115, 115, 158

Test Cell Air = 91, 99, 112

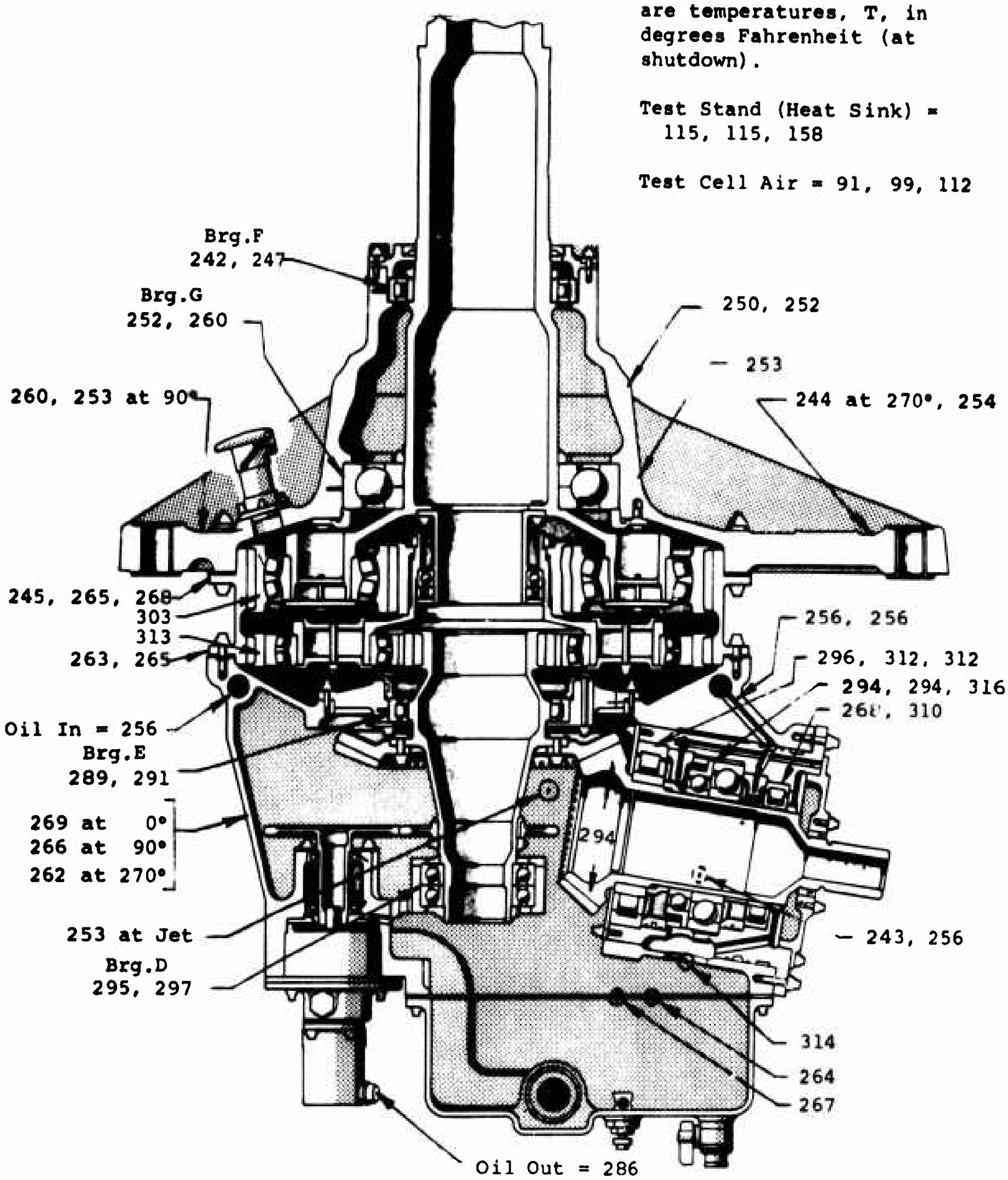


Figure 3: Thermal Record at 100% Torque - 286°F Oil-Out Temperature.

SHEET 11

NOTE: All numbers shown are temperatures, T, in degrees Fahrenheit (at shutdown).

Test Stand (Heat Sink) = 126, 128, 205

Test Cell Air = 94, 110, 128

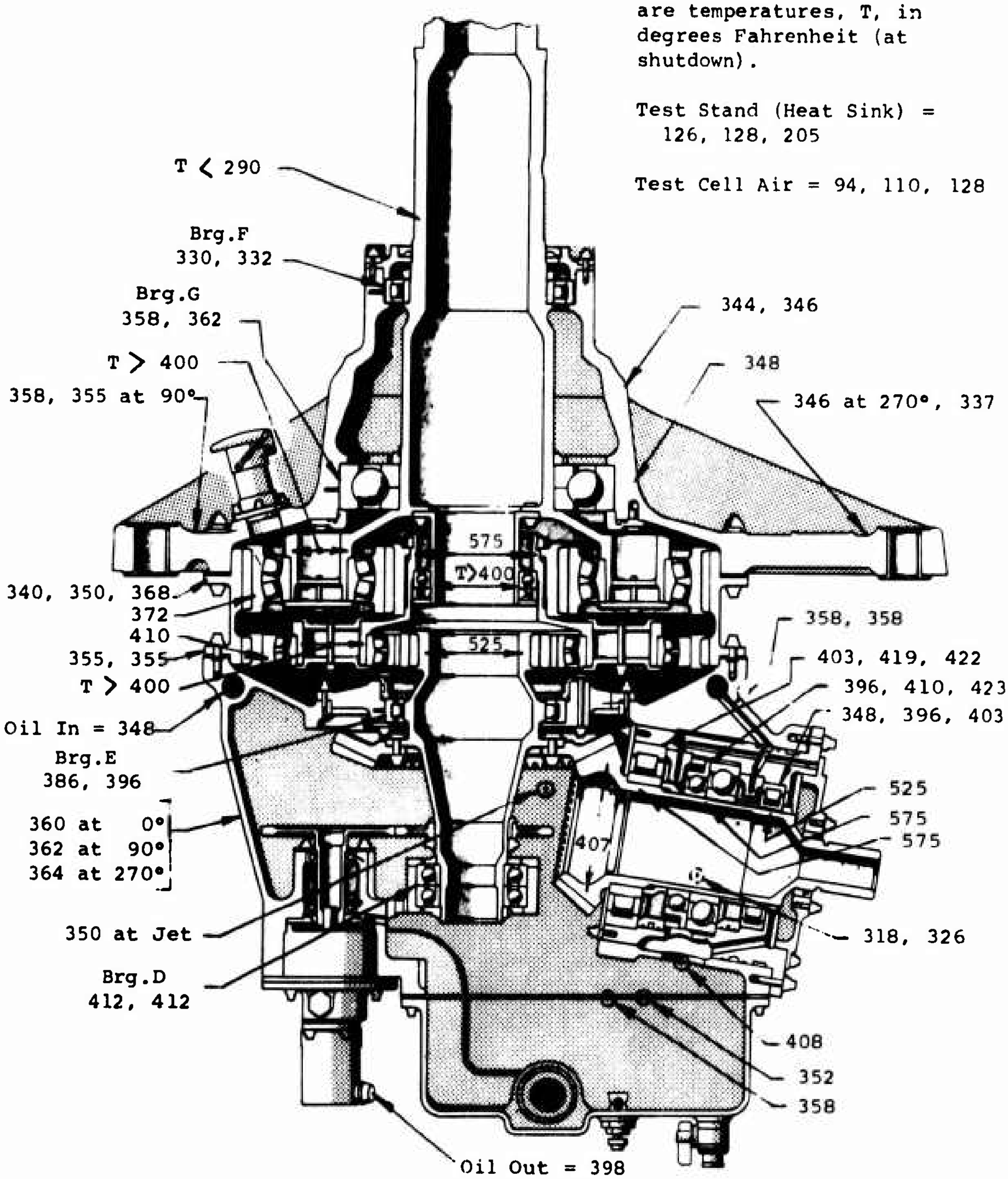


Figure 4: Thermal Record at 100% Torque - 400°F Oil-Out Temperature.

NOTE: All numbers shown are temperatures, T, in degrees Fahrenheit (at shutdown).

Test Stand (Heat Sink) = 112, 112, 190

Test Cell Air = 93, 100, 125

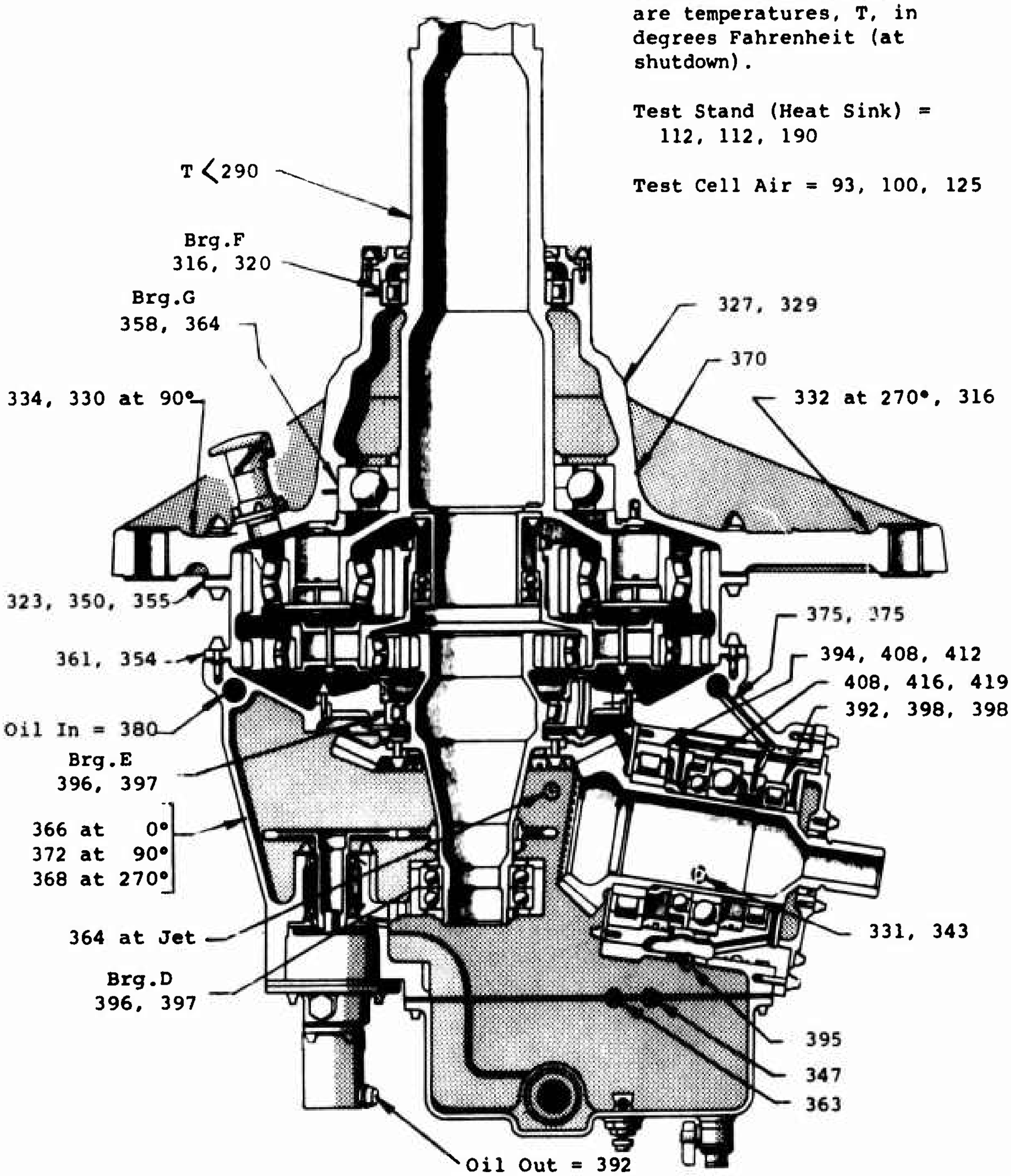


Figure 5: Thermal Record at 40% Torque - 400°F Oil-Out Torque Search.

SHEET 13

NOTE: All numbers shown are temperatures, T, in degrees Fahrenheit (at shutdown).

Test Stand (Heat Sink) = 100, 100, 158

Test Cell Air = 87, 91, 110

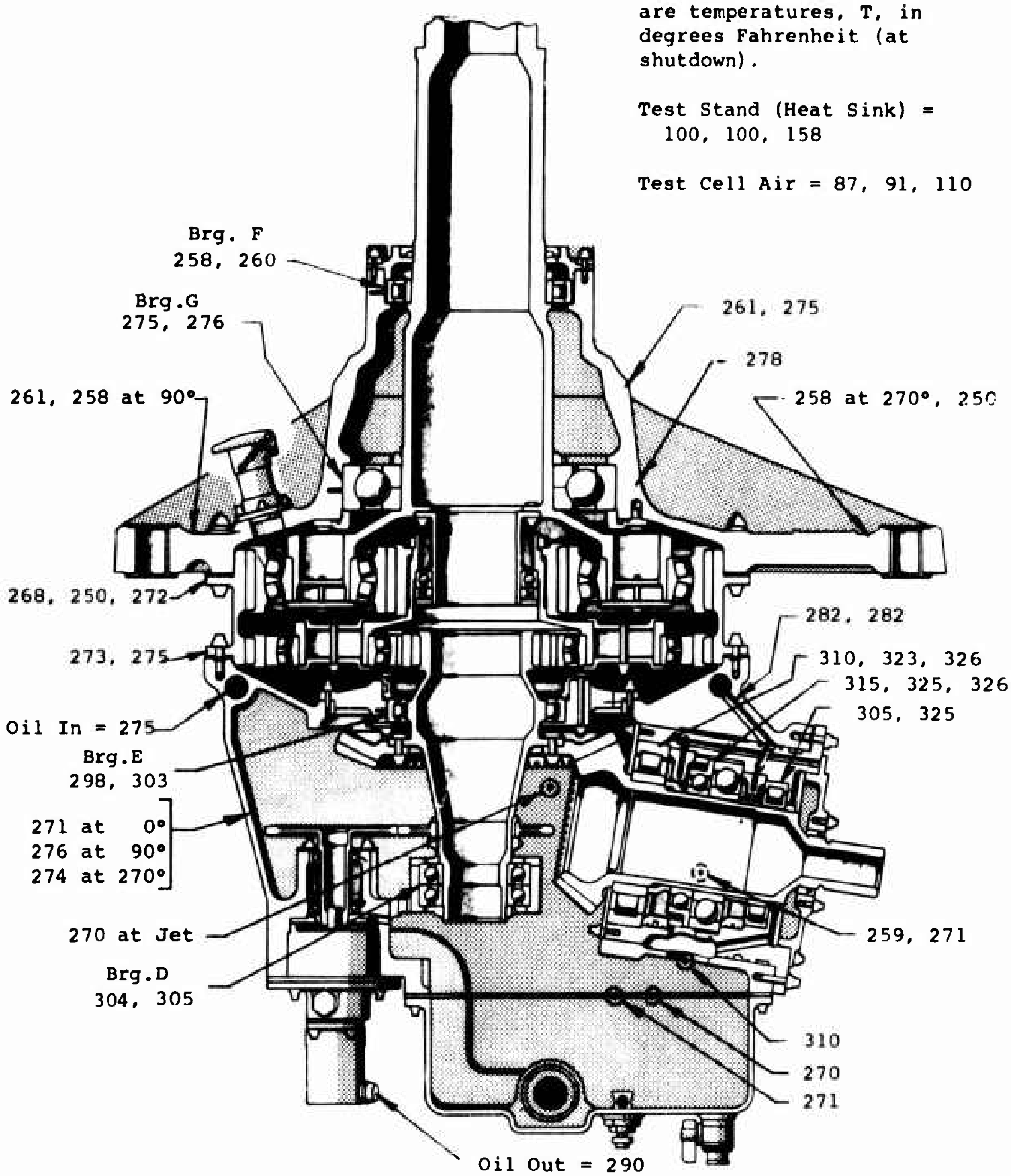


Figure 6: Thermal Record of Temperatures During Dimensional Mapping.

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TABLE I: DIMENSIONAL GROWTH PARAMETER EVALUATION

DIMENSION IDENTITY	l_c (inches) at T_c Cool		l_h (inches) at T_h Hot		ΔT $T=T_h-T_c$ (°F)	$\frac{\Delta l}{l_c} / \Delta T$ x 10^6	COEFFICIENT OF EXPANSION k x 10^6
	l_c	T_c(°F)	l_h	T_h			
D1 (Mag.)	24.860	73	24.900	190	117	13.8	15.1
D2 (Steel)	24.826	73	24.812	190	117	5.5	6.53
D3			NOT MEASURED				
D4 See Note	24.877	73	24.940	190	117	21.6	13.1
D5 (Alum.Aly.)	10.500	73	10.516	215	142	10.7	13.1
D6 (Alum.)	5.579	73	5.595	215	142	20.2	13.1
D7 (Mag.)	12.501	73	12.533	230	157	16.3	15.1
D8 (Mag.)	12.444	73	12.470	230	157	13.3	15.1
D9 (Steel)	2.643	73	2.645	180	107	7.07	6.53
X1 (Mag.)	15.520	73	15.558	260	187	13.1	15.1
X2 (Mag.)	10.638	73	10.718	250	177	42.5	15.1
X3 (Mag.)	9.690	73	9.710	250	177	15.2	15.1
Z1 (Mag.)	7.864	73	7.899	240	167	26.6	15.1
Z2, 1 (Steel)	4.275	73	4.261	220	147	22.3	6.53
Z2, 2 (Steel)	3.243	73	3.237	240	147	12.6	6.53
Z3 (Alum.)	15.634	73	15.682	210	137	22.4	13.1

NOTE - Measured on adjacent aluminum.