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CH-54B MAIN GEARBOX THERMAL MAPPING PROGRAM

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13. ABSTRACT

This report contains the procedures and results of a thermal mapping program conducted on the CH-54B main gearbox. The gearbox was analyzed to determine heat paths and heat sources and was instrumented to measure housing and dynamic component temperatures as well as thermal growth. Thermal maps of the gearbox were made at oil-outlet temperatures of 242°F, 280°F, 325°F, and 372°F. MIL-L-7808G oil was used for all tests. The temperatures measured indicated that the present method of analyzing the gearbox is adequate. Thermal growth measurements indicated that the handbook values for thermal coefficient of expansion are adequate for analysis. Recommendations are made for additional research required to develop a self-contained, more survivable gearbox design.

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DEPARTMENT OF THE ARMY
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This report was prepared by the United Aircraft Corporation, Sikorsky Aircraft Division under the terms of Contract DAAJ02-72-C-0072. 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-54B main gearbox under 100 percent load and speed, varying the outlet oil temperatures. Thermal growth of the casing was also measured.

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
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CH-54B MAIN GEARBOX THERMAL MAPPING PROGRAM

Final Report

By

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Prepared By

United Aircraft Corporation
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Stratford, Connecticut

for

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U.S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

SUMMARY

The work performed under Contract DAAJ02-72-C-0072 was directed toward providing data on the thermal characteristics of the CH-54B helicopter main gearbox. This data would provide some insight into heat flow paths and possible methods of making a gearbox less susceptible to loss of lubrication as a result of ballistic damage to lubrication system components such as oil coolers and lines.

As part of this program, the CH-54B main gearbox was analyzed to determine heat sources and paths and possible component temperature ranges which could be anticipated within the gearbox. This information was used to select a range of temperature sensing devices to measure the temperatures of these components. Methods were developed to secure the temperature sensors both on the gearbox components and on the housing. The selection tests included testing of methods of retaining the sensors on rotating dynamic components, protection from oil contamination, and calibration. Methods for measuring the thermal growth of the gearbox were also tested.

A CH-54B main gearbox was subjected to a series of four tests during which the gearbox component temperatures on gears, shafts, and bearings were measured with both thermocouples and irreversible sensors. The thermal growth of the gearbox housing was also measured with LVDT's and a trammel bar.

The baseline test was run under normal operating conditions with an oil-in temperature of 160°F. The oil-out temperature was 242°F. The three subsequent tests were run with oil-out temperatures of 280°F, 325°F, and 372°F respectively. After each test, the gearbox was disassembled to determine the temperatures experienced by the components.

The temperature data obtained from the tests verified the analysis of the primary heat sources and indicated that the current methods of analysis are satisfactory for future gearbox designs. The thermal growth measurements indicated that the handbook values for the coefficient of thermal expansion are satisfactory for use in calculating gearbox growth.

The tests and analysis indicated several areas of research which require increased technology in the advance toward the development of a self-contained gearbox. Among the areas to be considered are: methods of improving convection (both free and forced), development of higher heat stabilized bearings and gears, development of lubricants with high vaporization temperatures which can also provide good lubricating characteristics throughout the operating range of the gearbox, the use of heat pipes, the design of thin wall housings, and investigation of baffling and scavenging of gearboxes to integral sumps.

FOREWORD

This report covers analysis and test of a CH-54B main transmission to determine thermal characteristics such as heat flow and expansion. The program was conducted for the Eustis Directorate of the U. S. Army Air Mobility Research and Development Laboratory under Contract DAAJ02-72-C-0072. The task number is 1G162207AA7201.

Eustis Directorate technical direction was provided by Mr. R. Givens.

The principal contributors for Sikorsky Aircraft were Messrs. D. Wilson, Project Manager; L. Burroughs, Transmission Design Supervisor; H. Frint, Senior Designer; and R. Stewart, Test Engineer.

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a	gear addenda, in.
A	area, ft^2
A_I	input housing area, ft^2
A_M	main housing cone and rear cover area, ft^2
A_S	sump area, ft^2
c_p	heat capacity, Btu/lb-°F
C_s	bearing basic static capacity, lb
d_m	mean diameter, in.
F_B	equivalent bearing load, lb
F_R	radial bearing load, lb
F_S	static equivalent load, lb
f	coefficient of friction
FHP	total gearbox friction, hp or BTU/min
h	heat transfer coefficient, Btu/ft^2-°F-min
i	number of rows of rolling elements
m	gear ratio
$\dot{m}$	mass flow rate, lb/min
M_l	bearing friction torque due to applied load, lb-in.
M_v	bearing friction torque due to viscous effects, lb-in.
N	number of teeth
N_p	number of teeth, pinion
N_s	number of teeth, sun gear
N_r	number of teeth, ring gear
n	rotational velocity, rpm
Q	heat flow, hp or Btu/min

Q_c	heat rejected by convection, hp or Btu/min
Q_{cI}	heat rejected by convection from input sections, hp or Btu/min
Q_{cM}	heat rejected by convection from main housing and rear cover, hp or Btu/min
Q_{cS}	heat rejected by convection from sump, hp or Btu/min
Q_{EX}	heat rejected through oil cooler, hp or Btu/min
Q_R	heat rejected by radiation, hp or Btu/min
Q_{RI}	heat rejected by radiation from input sections, hp or Btu/min
Q_{RM}	heat rejected by radiation from main housing and rear cover, hp or Btu/min
Q_{RS}	heat rejected by radiation from sump, hp or Btu/min
R	gear pitch radius, in.
R_b	base circle radius, in.
R_i	inside radius, in.
R_o	outside radius, in.
R_v	pitch radius of equivalent spur gear, in.
S	specific gravity
T_A	temperature, ambient air, °F or °R
T_I	mean temperature, input housing surface, °F or °R
T_i	gearbox oil-in temperature, °F
T_M	mean temperature, main housing and rear cover surface, °F or °R
T_o	gearbox oil-out temperature, °F
T_S	mean temperature, sump surface, °F or °R
ΔT	oil temperature drop across oil cooler, °F

V	pitch line velocity, ft/min
V_s	average sliding velocity, ft/min
z	number of elements per row
α	bearing contact angle, deg
β_a	arc of approach, rad
β_r	arc of recess, rad
γ	bevel gear pitch angle, deg
ϵ	emissivity
η	efficiency
ρ	density, lb/gal
σ	Stefan-Boltzmann constant
ϕ	pressure angle in plane of rotation, deg
ϕ_n	normal pressure angle, deg
ψ	helix angle at pitch line
F_A	axial bearing load, lb

INTRODUCTION

As a result of operations in which helicopters have performed duties exposing them to combat, the helicopter power transmission has been shown to be susceptible to combat damage. One of the primary causes of this damage has been loss of lubrication due to oil cooler damage.

Research into the area of reducing the helicopters' susceptibility to loss of lubrication has been a continuing effort by the Eustis Directorate and Sikorsky Aircraft. As part of this research, the determination of gearbox temperatures and growth characteristics under elevated temperatures was undertaken. This is an initial step toward a goal of designing a gearbox with an integral lubrication system and a corresponding reduction in the gearbox vulnerability.

The CH-54B, Figure 1, was selected as one model helicopter from which a thermal map of the main gearbox would be determined. Since a gearbox with an integral lubrication system will probably encounter higher operating temperatures than presently encountered under today's normal operating conditions, a program was undertaken by the Eustis Directorate and Sikorsky Aircraft to identify major heat sources and heat paths within the CH-54B main gearbox. In this program, the main gearbox was analyzed to determine heat paths and then tested at various oil outlet temperatures to determine thermal characteristics.

Figure 1. CH-54B Helicopter.

PROGRAM SCOPE

The subject of study under Contract DAAJ02-72-C-0072 was the CH-54B main transmission. Work performed under this contract included the following:

1. An analysis to predict temperatures and heat paths within the gearbox.

2. Four tests to determine stabilized operating temperatures under normal and elevated lubricant temperature conditions. The lubricant oil-in temperature was approximately 160°F for the baseline (normal operation) test. For successive tests, the oil-out temperatures were increased to 275°, 325°, and 360°F. Irreversible temperature sensing tapes and labels and thermocouples were used to monitor temperatures during each test. The gearbox was disassembled at the completion of each test for inspection of internal temperature sensors.

3. Measurements to determine thermal expansion of the transmission.

4. Identification and quantitative evaluation of the primary heat rejection paths of the transmission based on the temperature data obtained in Step 2.

DESCRIPTION OF TEST ARTICLE

The main gearbox of the CH-54B is powered by two JFTD-12A engines. Power is transmitted by each engine directly into the four-stage main transmission which reduces the 9000 rpm engine speed to 185 rpm at the main rotor, a 48.54 to 1 reduction. Power is also transmitted from the tail/accessory drive section of the main transmission through the tail drive shaft at 3016 rpm and into the intermediate and tail gearboxes, which reduce speed to 850 rpm at the tail rotor. Figure 2 shows the dynamic components of the CH-54B.

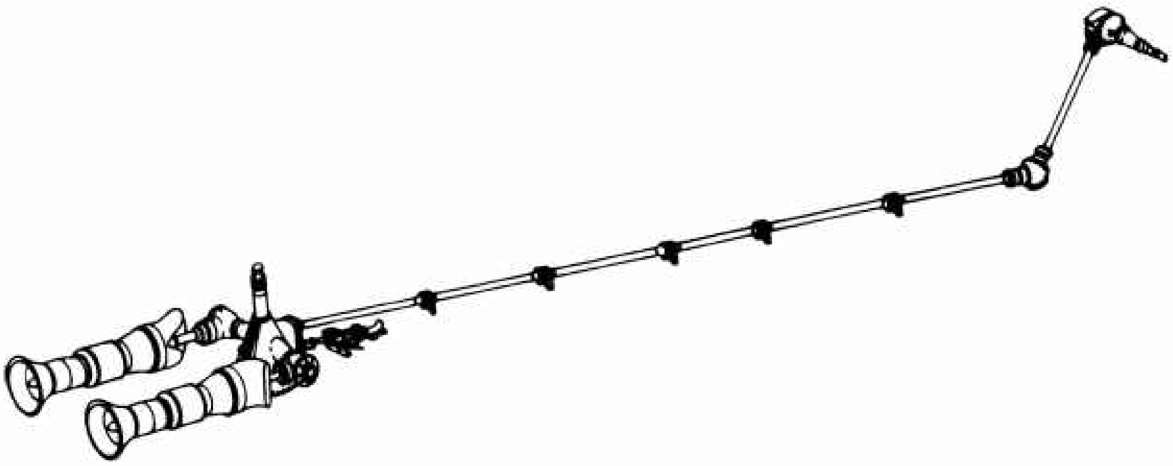
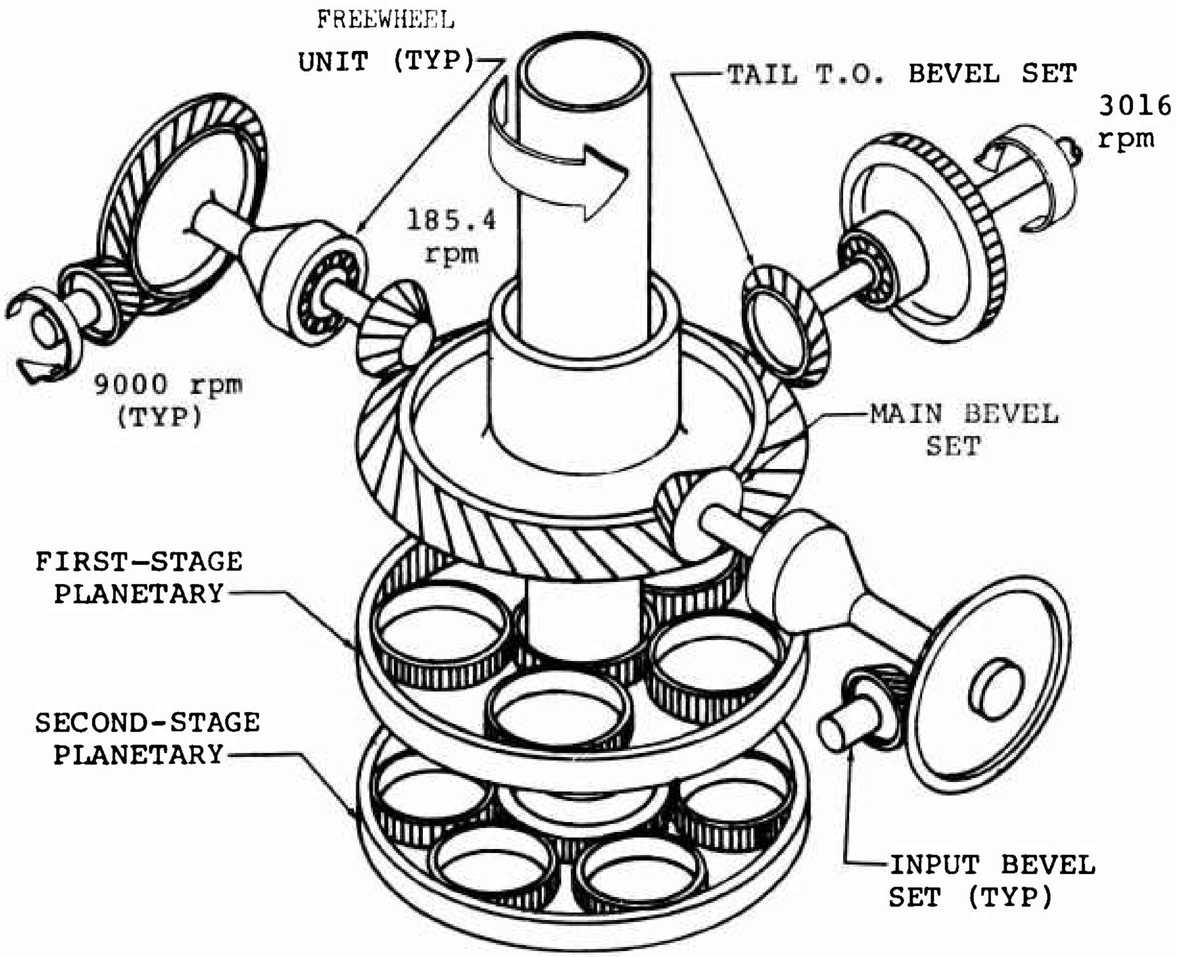


Figure 2. Isometric of Drive Train Components of the CH-54B Aircraft.

A schematic arrangement of the CH-54B main transmission is presented in Figure 3. This figure also contains numbers of teeth, reduction ratios, and speeds of the main transmission major reduction stages. CH-54B accessories are mounted on the rear cover of the main transmission and on the right-hand input bevel.

The gearbox is shown in Figure 4.



GEAR MESH	REDUCTION	INPUT rpm	OUTPUT rpm
INPUT BEVEL SET	27/53	9000	4585.9
MAIN BEVEL SET	25/76	4584.9	1508.2
1ST-STAGE PLANETARY	78/55/188	1508.2	442.3
2ND-STAGE PLANETARY	166/32/230	442.3	185.4
TAIL T.O. BEVEL SET	76/38	1508.2	3016.4

Figure 3. CH-54B Main Transmission Schematic.

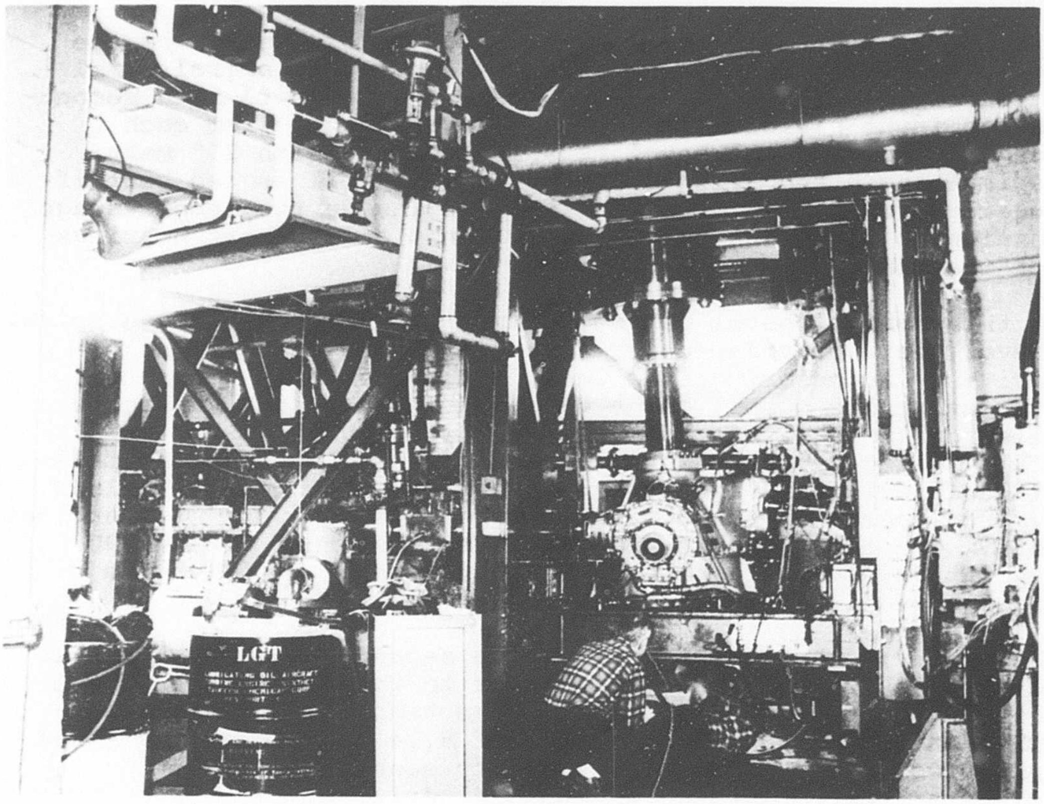


Figure 4. CH-54B Main Transmission Shown in Test Stand.

Power is transmitted from the engines to the first-stage spiral bevel mesh of 27 to 53 reduction. The gears of this stage are designed to transmit 4800 hp continuously at a 9000 rpm engine input speed. The 2.875-inch face width spiral bevel gears used a spiral angle of 25° and are of 3.313 diametral pitch. The left-hand and right-hand first-stage spiral bevel gears are identical in design and are interchangeable.

A ramp roller type overrunning clutch is located between the first-stage output gear and the second-stage spiral bevel input pinion. This clutch is arranged with a driving outer housing and an overrunning cam, which assures good lubrication to rollers, cage, cam, return springs, and outer housing. The relatively low speed of operation (4585 rpm) of this unit compared with other production freewheel units reduces centrifugal load of the rollers on the outer housing during overrunning.

The cam output member of the ramp roller clutch drives the second-stage pinion of the 25 to 76 reduction spiral bevel mesh. The bevel gear of this stage is common to both second-stage input pinions and combines power inputs from each engine. The spiral bevel mesh is designed with 25° mean spiral angle and 3.125 diametral pitch. Oil is fed centrifugally from an oil distribution tube inside the second-stage pinion to lubricate the freewheel unit and support bearings of the pinion.

A third spiral bevel pinion, driven by the second-stage spiral bevel gear, provides power for accessories and tail rotor drives. Accessory drives include those for two generators, two hydraulic pumps, and a tachometer generator. There is also drive gear from the accessory power unit (APU). A ramp roller-type freewheel unit is mounted between the tail-takeoff drive and accessory drive gear. This design allows ground operation of accessories from the APU with main engines off. The tail takeoff freewheel unit overruns during APU operation, so that the APU does not attempt to drive the main or tail rotors.

Attached to the output gear of the second-stage bevel set is a quill shaft that transmits power to the lower part of the housing containing the planetary section of the main transmission. The overall reduction of 8.14 to 1 is accomplished with two stages of simple planetary meshes, a simple planetary being defined as sun gear driving, carrier output, and ring gear fixed. The first-stage planetary of 3.41 to 1 reduction ratio contains seven pinions. The first-stage planetary pinion is mounted on a two-row roller bearing connected to the straddle-mounted carrier plates through pinion shafts. The ring gear, which is rigidly bolted to the main transmission lower housing, contains both first-stage and second-stage internal gear members. Connected to the lower carrier plate of the first-stage planetary and driven through dowel pins is the sun gear of the second-stage planetary. The 2.39 to 1 reduction second-stage planetary is similar in design to the first-stage and contains 18 planetary pinions. The lower carrier plate is splined to the main rotor shaft, which transmits torque to the main rotor.

PRETEST THERMAL ANALYSIS

INTRODUCTION

The objective of this analysis is an analytical prediction of the stabilization temperatures of gearbox components. These predictions will be subsequently verified in the testing portion of this report.

The frictional heat produced in the gearbox is caused by the following effects:

- The rolling/sliding action of the gears as they pass through mesh.
- Friction of bearings caused by load and viscous effects.
- Windage and oil churning.

The total heat generated by these effects is removed from the gearbox by any or all of the following heat-rejection modes:

- Free connection from the transmission housing.
- Thermal radiation from the housing.
- Heat transfer through an external oil/air heat exchanger.
- Conduction through test cell mounting.

HEAT LOSS ANALYSIS

The heat produced by the gears and bearings can be estimated by calculating efficiency factors or heat losses for these components. The following sample calculations will illustrate this procedure.

High-Speed Input Spiral Bevel Gear Mesh

The efficiency of a spiral bevel gear mesh is given by

$$\eta = 1 - \frac{\cos\phi}{\cos\phi_n \cos\psi}\left[\frac{1 + 1/m}{(\beta_a + \beta_r)\cos\psi}\right]\left[\frac{f}{2}\right]\left[\beta_a^2 + \beta_r^2\right] \qquad (1)$$

For the high-speed input bevel mesh,

$\phi_n = 20°$

$\psi = 25°$

$R_p = 4.075$

$R_g = 7.999$

$\gamma_p = 27°$

$\gamma_g = 63°$

$a_p = .344$

$a_g = .167$

$F = 2.875$

$n_p = 9000$

$\phi = \tan^{-1}\left[\tan\phi_n \,/\cos\psi\right] = 21° \, 52.8'$

$R_{vp} = R_p \,/\cos\gamma_p = 4.573$

$R_{vg} = R_g \,/\cos\gamma_g = 17.619$

$R_{bp} = R_{vp} \cos\phi = 4.244$

$R_{bg} = R_{vg} \cos\phi = 16.350$

$R_{op} = R_{vp} + a_p = 4.917$

$R_{og} = R_{vg} + a_g = 17.788$

$$\beta_a = \frac{\sqrt{R_{og}^2 - R_{bg}^2} - R_{vg}\sin\phi}{R_{bp}}$$

$$\beta_r = \frac{\sqrt{R_{op}^2 + R_{bp}^2} - R_{vp}\sin\phi}{R_{bp}}$$

$$m = \frac{R_{vg}}{R_{vp}} = 3.852$$

$R_{mp} = R_p - F\sin\gamma_p = 2.770$

$V = \frac{\pi}{6} R_{mp}\, n_p = 13053$ fpm

$V_s = V\cos\phi\left(1 + \frac{1}{m}\right)\left(\frac{\beta_a + \beta_r}{4}\right) = 1095$

$$f = \frac{2}{3}\left(\frac{.050}{e^{.125 V_s}} + .002\sqrt{V_s}\right) = .0441$$

substituting in equation (1)

$$\eta = 1 - \left[\frac{.92796}{(.93969)(.90631)} \left(\frac{1 + \frac{1}{3.852}}{(.28721)(.90631)} \right) \left(\frac{.044}{2} \right) \times (.10375^2 + .18346^2) \right]$$

$$= .99484$$

Second-Stage Planetary

The efficiency of a conventional planetary (sun gear input, cage output, fixed ring gear) is given by

$$\eta = 1 - \frac{N_R}{N_R + N_S} (1 - \eta_{sP} \eta_{sR}) \qquad (2)$$

for the sun/pinion mesh:

$\phi = 22.5^\circ$

$R_S = 10.375$

$R_P = 2.000$

$P_D = 8$

$\eta_S = 166$

$N_R = 442$

$N_P = 32$

$R_{oS} = 10.375 + .100 = 10.475$

$R_{oP} = 2.000 + .100 = 2.100$

$R_{bS} = R_S \cos\phi = 9.585$

$R_{bP} = R_P \cos\phi = 1.848$

$$\beta_a = \frac{\sqrt{R_{op}^2 - R_{bp}^2} - R_p \sin\phi}{R_{bs}}$$

$$= .02426$$

$$\beta_r = \frac{\sqrt{R_{os}^2 - R_{bs}^2} - R_s \sin\phi}{R_{bs}}$$

$$= .02655$$

$$m = \frac{N_P}{N_S} = \frac{32}{166}$$

$$= .1928$$

$$V = \frac{\pi}{6} R_S \frac{N_R}{N_R + N_S} n_S$$

$$= 1395$$

$$V_S = V \cos\phi \left(1 + \frac{1}{m}\right) \frac{\beta_a + \beta_r}{4}$$

$$= 101.3$$

$$f = \frac{2}{3}\left[\frac{.050}{e^{.125 V_s}} + .002\sqrt{V_S}\right]$$

$$= .01342$$

$$\eta_{SP} = 1 - \left(\frac{1 + 1/m}{\beta_a + \beta_r}\right)\left(\frac{f}{2}\right)\left(\beta_a^2 + \beta_r^2\right)$$

$$= 1 - \left(\frac{1 + \frac{1}{.1928}}{.05081}\right)\left(\frac{.0134}{2}\right)\left(.02426^2 + .02655^2\right)$$

$$= .99894$$

for the pinion/ring mesh:

$R_P = 2.000$

$R_R = 14.375$

$V = 1395$

$N_R = 230$

$R_{OP} = 2.100$

$R_{iR} = 14.276$

$R_{bp} = 1.848$

$R_{bR} = 13.281$

$$\beta_a = \frac{R_R \sin \phi - \sqrt{R_{iR}^2 - R_{bR}^2}}{R_{bp}} = .14323$$

$$\beta_r = \frac{R_{op}^2 - R_{bp}^2 - R_p \sin \phi}{R_{bp}} = .12559$$

$$m = \frac{N_R}{N_p} = \frac{230}{32} = 7.188$$

$$V_s = V \cos \phi \left[1 - \frac{1}{m}\right] \frac{\beta_a + \beta_r}{4} = 74.56$$

$$f = \frac{2}{3}\left[\frac{.050}{e^{.125 V_s}} + .002\sqrt{V_s}\right]$$

$$\eta_{PR} = 1 - \left[\frac{1 - \frac{1}{m}}{\beta_n + \beta_r}\right] \frac{f}{2} \left(\beta_a^2 + \beta_r^2\right)$$

$$= 1 - \left(\frac{1 - \frac{1}{7.188}}{.26882}\right)\left(\frac{.01152}{2}\right)\left(.14323^2 + .12559^2\right)$$

$$= .99933$$

The overall planetary efficiency is thus

$$\eta = 1 - \frac{230}{396}\left[1 - (.99894)(.99933)\right] = .99900$$

High-Speed Input Triplex Ball Bearing

For bearings, the viscous and friction torque effects are calculated and converted to horsepower losses:

$$M_l = z\left(\frac{F_s}{C_s}\right)^y F_\beta\, d_m$$

where $F_\beta = 0.9\, F_a \cot\alpha - 0.1\, F_r$ or (3)

F_r whichever is larger

$$M_v = 1.42 \times 10^{-5} f_o (\nu_o n)^{2/3} dm^3 \text{ and} \qquad (4)$$

for this ball bearing

$F_a = 4038$	$f_o = 8$
$F_r = 3768$	$\nu_o = 7.5$
$\alpha = 25°$	$n = 9000$

$d_m = 5.235$

$i = 3$

$Z = 15$

$D = \frac{15}{16}$

$f = .544$

$z = .001$

$y = .33$

$F_s = F_r = 3768$

$$C_s = 400 i Z D^2 \cos\alpha \sqrt{\frac{2f(1-\gamma)}{2f-1}}$$

$$\gamma = \frac{D\cos\alpha}{dm} = .1623$$

$$C_s = (400)(3)(15)\left(\frac{15}{16}\right)^2 \cos 25° \sqrt{\frac{1.088(1-.1623)}{.088}} = 46140$$

$$F_B = 0.9(4038)(\cot 25°) - 0.1(3768) = 7417$$

$$M_\ell = .001\left(\frac{3768}{46140}\right)^{.33}(7417)(5.235) = 16.99$$

$$M_v = (1.42 \times 10^{-5})(12)\left[(7.5)(9000)\right]^{2/3} 5.235^3 = 40.53$$

$$\text{total hp loss} = \frac{(M_\ell + M_v)}{(12)(33000)} 2\pi n = 8.21 \text{ hp}$$

Main Input Section Cylindrical Roller Bearing

$$M_\ell = f_1 F_B d_m$$

$$M_v = 1.42 \times 10^{-5} f_o (\nu_o n)^{2/3} d_m^3$$

for this bearing

$$F_r = 2344$$

$$d_m = 7.199$$

$$f_1 = .0003$$

$$f_o = 5$$

$$F_B = F_r = 2344$$

$$M_\ell = (.0003)(2344)(7.199) = 5.062$$

$$M_v = (1.42 \times 10^{-5})(5)\left[(7.5)(4585)\right]^{2/3} 7.199^3 = 28.01$$

$$\text{total power loss} = \frac{(M_\ell + M_v)(2\pi n)}{(12)(33000)} = 2.41 \text{ hp}$$

The results of the heat loss calculations for all the gears and bearings are summarized in Table I.

HEAT REJECTION ANALYSIS

Heat generated within the gearbox by the heat-producing elements (gears and bearings) is ultimately rejected to the atmosphere by radiation, by convection, and by an oil/air heat exchanger. The assumption is that conduction through the test stand mounting is negligible.

The heat rejected by radiation is given by

$$Q_R = \epsilon \sigma A (T_S^4 - T_A^4) \tag{5}$$

where Q_R = heat rejected by radiation
ϵ = emissivity of gearbox surface
σ = Stefan-Boltzmann constant
T_S = gearbox housing temperature
T_A = ambient air temperature
A = effective gearbox surface area

The heat rejected by convection is given by

$$Q_c = hA (T_S - T_A) \tag{6}$$

where Q_c = heat removed by convection
h = the average heat transfer coefficient

The heat removed by the heat exchanger can be represented by

$$Q_{EX} = \dot{m} c_p \Delta T \tag{7}$$

where Q_{EX} = heat removed by the oil cooler
$\dot{m}$ = oil flow rate through cooler
ΔT = temperature drop across the cooler

The total heat removed from the gearbox is thus

$$\begin{aligned} Q_T &= Q_R + Q_c + Q_{EX} \,^{*} \qquad (8) \\ &= \sum \epsilon \sigma A (T_S^4 - T_A^4) + \sum hA(T_S - T_A) + \dot{m} c_p \Delta T \end{aligned}$$

From Table I, the total heat generated by the gears and bearings is 5640 Btu/min. In addition, 10 horsepower (424.4 Btu/min) is assumed for windage and seal friction losses. Thus, the total gearbox heat loss is estimated to be

$$Q = 5640 + 424 = 6064 \text{ Btu/min}$$

---

*Heat loss by conduction through the mounting is considered trivial.

TABLE I. PREDICTED HEAT LOSSES, CH-54B MAIN GEARBOX

Component	Transmitted Horsepower	Efficiency	Horsepower Loss	Total Horsepower
Gears				
High-Speed Bevel	3300	.99484	17.03	34.06
Main Bevel Input	3300	.99491	16.80	33.59
Tail Takeoff Bevel	600	.99663	2.02	2.02
First-Stage Planetary	6000	.99983	1.02	1.02
Second-Stage Planetary	6000	.99900	6.00	6.00
Bearings				
High-Speed Triplex Ball	3300		8.21	16.42
High-Speed Roller	3300		1.44	2.88
Input Section Duplex Ball	3300		4.10	8.20
Input Section Roller	3300		2.41	4.82
Input Bevel Timken	3300		4.48	8.96
Input Bevel Roller	3300		.89	1.78
Outer Shaft Timken	3300/600		3.16	3.16
Outer Shaft Roller	3300/600		.98	.98
First-Stage Planetary	6000		.60	4.50
Second-Stage Planetary	6000		.16	2.96
Main Rotor Shaft Thrust Ball	6000		.76	1.52
Main Rotor Shaft Roller	6000		0	0
Tail Takeoff Timken	600		.01	.01
Tail Takeoff Roller	600		.01	.01
				132.89

SKIN TEMPERATURE CALCULATION

At this point some assumptions must be made or information obtained from previous test as to the temperature distribution over the housing surface and how much heat is to be absorbed by the oil cooler before equation (8) can be solved for skin temperatures.

In Table IV of Reference 1, mean surface temperatures are given for the CH-54A main gearbox operating at 195°F inlet oil temperature. The same relative temperature distribution will be used in this analysis. This table is reproduced in part herein as Table II. Note that the average coefficient of heat transfer (h in equation 6) calculated in Reference 1 is .108 Btu/min.

In the thermal mapping program, increased operating temperature will be accomplished by diminishing the amount of heat rejected by the oil cooler, thus increasing the amount rejected from the housing surface by radiation and convection.

In the limiting case where the cooler would absorb 100% of the heat generated,

$$Q_R = Q_c = 0$$

$$Q_t = \dot{m} C_p \Delta T = 6064 \text{ Btu/min}$$

and

$$\Delta T = \frac{6064}{(19.8)(.1337)(.86)(62.4)(.54)} = 79°$$

where 19.8 is the assumed oil flow through the cooler in gpm
.86 is the specific gravity
.54 is the specific heat

For the condition where the oil cooler is inoperative or, in effect, bypassed, all of the heat is rejected from the gearbox by radiation and convection. Substituting the values of Table II into equation (8),

$$\begin{aligned} Q_t = {} & .288 \times 10^{-10} \{[[(.60)(19.7) + .60(9.0) + .60(18.4)][T_s^4 - T_a^4] \\ & + [(.60)(12.6) + (.44)(4.2) + .44(1.6) + (.96)(5.2)][(1.22T_s)^4 - T_a^4] \\ & + [(.44)(0.9) + (.44)(2.6)][(.98T_s)^4 - T_a^4]\} + .108[(19.7 + 8.0 + \\ & 18.4)(T_s - T_a) + (4.2 + 1.6)(1.22T_s - T_a) + (0.9 + 2.6)(.98T_s - T_a) \\ = {} & 6064 \text{ Btu/min} \end{aligned}$$

TABLE II. RADIATION AND CONVECTION PROPERTIES, CH-54B MAIN GEARBOX

Nomenclature	Total Radiative Surface Area* (ft^2)	Total Convective Surface Area* (ft^2)	Mean-Skin Temperature** (^oF)	**Emissivity*****
Main Conical Housing Less Sump	19.7	19.7	T_s	0.60
Rear Housing Boss and Rear Cover	9.0	8.0	Ts	0.60
Engine Input Housing (2)	18.4	18.4	T_s	0.60
Bottom of Gearbox and Sump	12.6	-	1.22 T_s	0.60
Oil Drain Lines From Engine Inputs (2)	4.2	4.2	1.22 T_s	0.44
Oil Line From Cooler to Manifold	0.9	0.9	.93 T_s	0.44
Oil Line From Gearbox to Cooler	1.6	1.6	1.22 T_s	0.44
All External Lubrication Lines	2.6	2.6	.98 T_s	0.44
Oil Cooler Radiator	5.2	-	1.22 T_s	0.96
Total	74.2	55.4	-	-

TABLE II. CONTINUED.

*The bottom portion of the gearbox and the sump are not considered to be good convectors because free convection cannot occur in the stagnant hoist-well area. Radiation, however, will occur to other bodies such as the airframe, hoist, etc. The oil cooler itself is not considered to be a free convector, because all significant heat transfer occurs through forced convection induced by the blower.

**Actual skin temperature distribution from CH-54B power transmission test-bed test results.

***Emissivity values: All housings and covers are magnesium alloy painted with olive-drab flat matte lacquer. All plumbing is bright stainless steel, unfinished. The radiator is brass painted with black flat matte lacquer.

Solving this equation for T_s,

$$T_s = 670°F$$

Similar calculations can be made for various percentages of utilization of the oil cooler (between 0 and 100%). The results of these calculations are shown in Figure 5.

In Figure 5, another mode of heat rejection comes into play when the temperature of the oil (roughly equal to skin temperatures) reaches the vaporization temperature. Heat of vaporization would reduce the skin temperature in the upper portion of the curve.

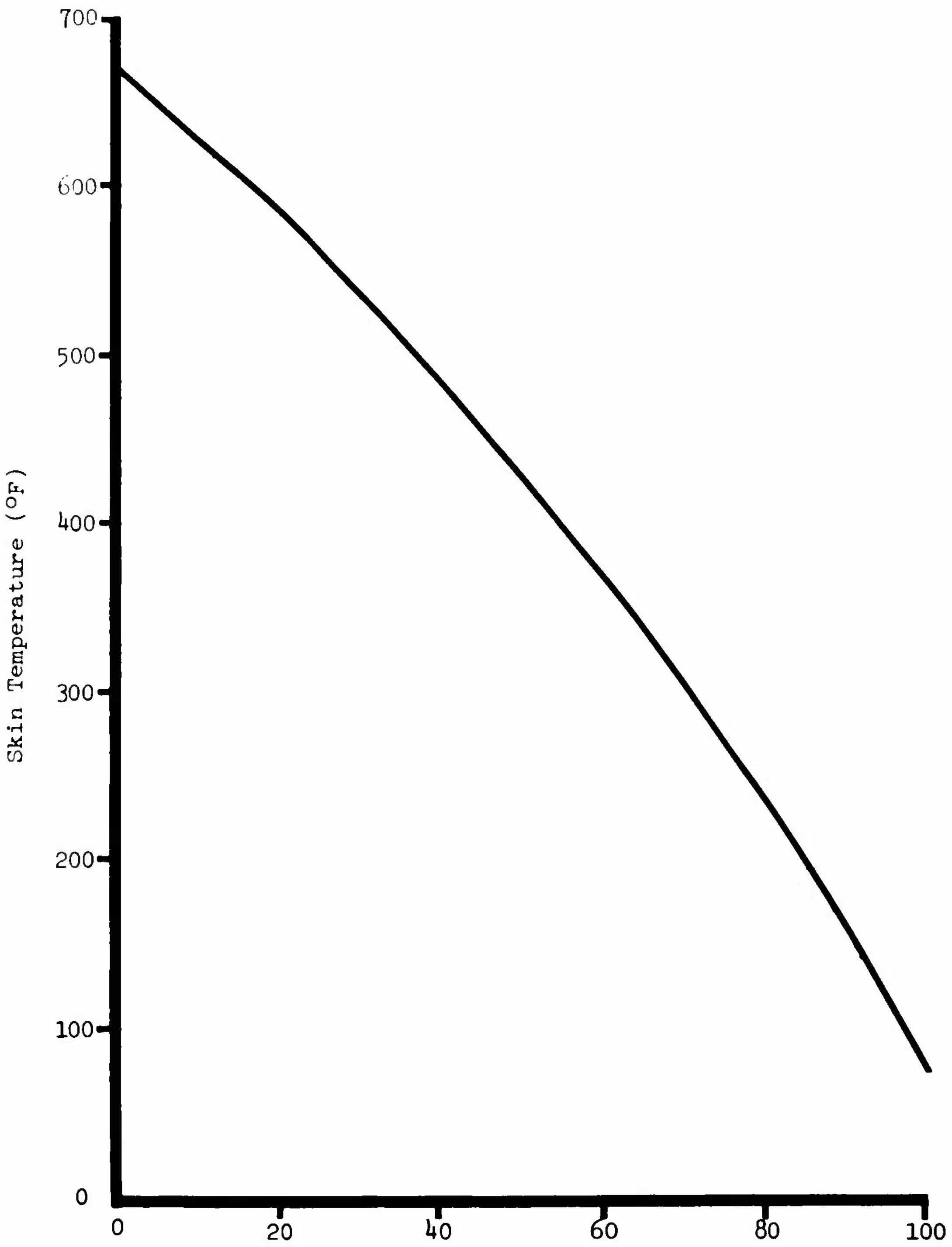


Figure 5. Skin Temperature vs Heat Rejected Through Oil Cooler.

TEST PREPARATION

INSTRUMENTATION RESEARCH

Prior to the first in the series of the thermal map tests, a survey was made of reversible and irreversible temperature indicators to determine their suitability for this test program. The survey included oil submersion tests, calibration tests, and dynamic tests in gearboxes. Protective coatings used to prevent oil soaking of the sensors were also investigated.

Various combinations of sensors and protective covers were tested for degradation when exposed to oil and heat and for ability to be retained on rotating shafts. Table III lists sensors and covers investigated and their applicability for use in this test program. On the basis of these results, Temp-Plate® and Thermopaper® sensors sealed with Kapton® polyimide tape and M-Bond 600 epoxy adhesive were selected for internal gearbox locations where they would be subject to continuous oil exposure.

Thermopaper® sensors with Mylar® tape covers were selected for external locations which would be subject to occasional exposure to lubricant. The methods of sensor application are described in the next section.

Sensor installations were calibrated to assure that the indicators' accuracy was not impaired by the installation methods and/or materials. Sensors and their covers were applied to metal plates using the attaching method which was to be used for internal gearbox locations. The plates were submerged in oil, and the oil was heated. Oil temperature was monitored with an active thermocouple. Sensor indicated temperature versus thermocouple indicated oil temperature was monitored. The difference between measured and indicated temperatures was less than 5°F in all cases. Sensors and their covers were applied to plates using the method to be used for external applications. The plates were placed in an oven. Oven temperature was measured with a thermocouple. Indicated temperature versus air temperature was monitored. All sensors tested indicated within 5°F of their specified temperature.

GEARBOX PREPARATION

The test gearbox was disassembled and temperature sensors were installed prior to each of the four tests. Temperature sensors used and their applications were as follows:

- Thermocouples were used to sense internal stationary component temperatures.

TABLE III. TEMPERATURE SENSOR SYSTEMS INVESTIGATED

Sensor	Protective Cover	Comments
Liquid Crystals®, Liquid Crystal Industries Inc.	None	Washes off in oil mist. Is not generally compatible with any known protective covers.
Tempilaq®, Tempil Div. Big Three Industries Inc.	None	Washes off in oil mist.
	M-Bond 600 Micro-Measurements Div. Wismay Intertechnology Inc.	Tempilaq® reacts with the cover.
	Mylar® tape #850 3M Corp.	Questionable seal against oil.
Detecto Temp®, W. H. Brady Co.	Mylar® tape	Requires 1/8 in. border minimum; is thus unsuitable for most internal applications which require small surface contact.
Thermopaper®, Paper Thermometer Co.	None	Sensor reacts with oil.
	Mylar® tape	Tape eventually allows oil soak.
	M-Bond 600	Sensor reacts with M-Bond 600.
	Kapton® polyimide tape CHR Co. M-Bond 600 covering tape	Works well when one layer of tape adhesive side face up is used between sensor and tape face down.
Temp-Plate® William Wahl Corp.	Kapton® polyimide tape M-Bond 600 covering tape	Works well.

- Temperature sensing tape (Thermopaper®) was used to measure external skin temp.
- Temperature sensing tapes (Thermopaper®) and labels (Temp-Plate®) were used to measure internal rotating component temperatures.

Active thermocouples were installed at designated gearbox locations using standard techniques, i.e., tapping holes in the housing, using lug type thermocouples on existing studs, etc.

Temperature-sensitive tape was applied to external housing locations. The temperature-sensing tape was then covered with a clear tape to protect against oil contamination and oil mist, which could possibly result in inaccurate readings if it came in contact with the temperature-sensitive tape. An external temperature-indicating tape installation is shown in Figure 6.

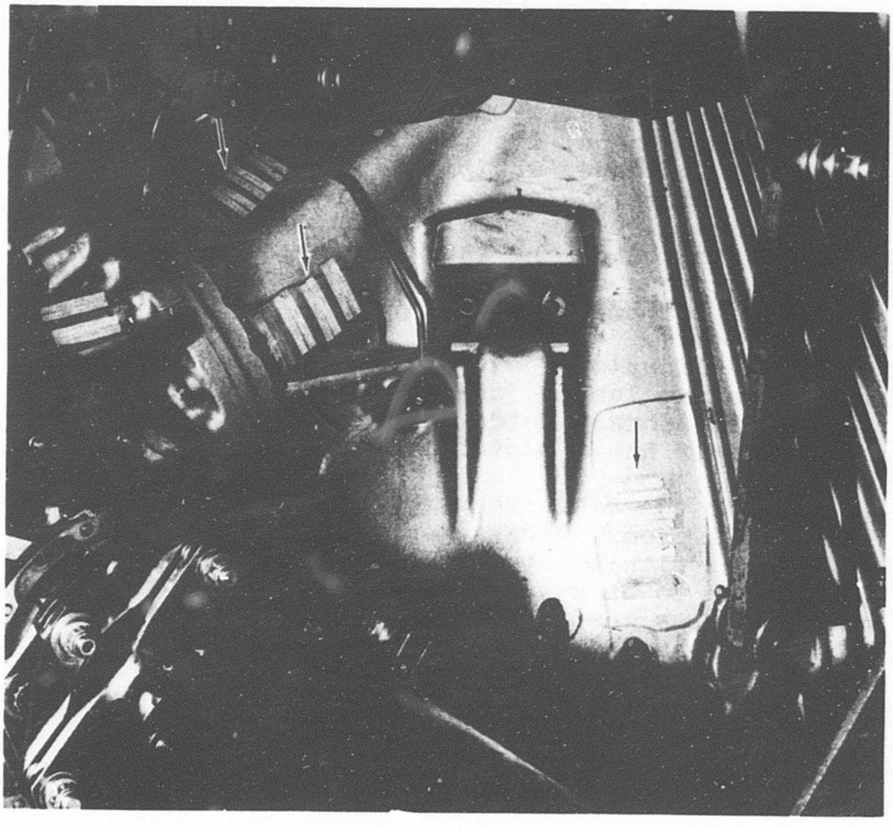


Figure 6. External Temperature Sensing Tape Installations.

The method of applying temperature-sensitive tape and/or labels to rotating components continuously exposed to oil is a multi-step procedure. The steps used are as follows:

1. The areas to which the sensors were applied were cleaned with emery paper down to smooth bare metal. For best retention, the sensor locations chosen were as flat as possible with a maximum area for protective coatings to be applied over the sensors. The areas were washed in methyl ethyl keytone (MEK) prior to sensor application. Care was taken to assure that no metallic particle/solvent solution penetrated any bearings which may have been nearby.

2. The temperature indicators were applied to the center of the prepared area using the adhesive on the back of the indicator.

3. To protect the temperature sensors from becoming oil soaked, which could result in erroneous readings, a Kapton® polyimide tape with a silcone adhesive on one side manufactured by The Connecticut Hard Rubber Co. was used as a cover for the sensors. For applications using Thermopaper® temperature indicating tape, two layers of polyimide tape were used. One layer was placed adhesive side up over the sensor; then a second, larger layer was placed adhesive side down over the installation. This was necessitated by the fact that tests indicated that the Thermopaper® was affected by the adhesive used on the polyimide tape.

   For applications using Temp-Plate® temperature indicating labels, only one layer of polyimide tape, applied adhesive side down, was used, as this type indicator has a protective coating over it already.

4. Because the adhesive used on the polyimide tape is not oil proof, each sensor installation was then covered with an epoxy adhesive which was demonstrated by test to be satisfactorily oil resistant. The parts thus instrumented were then placed in a heated chamber at 125°F for 6 hours to cure the epoxy.

   Typical installations are shown schematically and photographically in Figures 7 and 8.

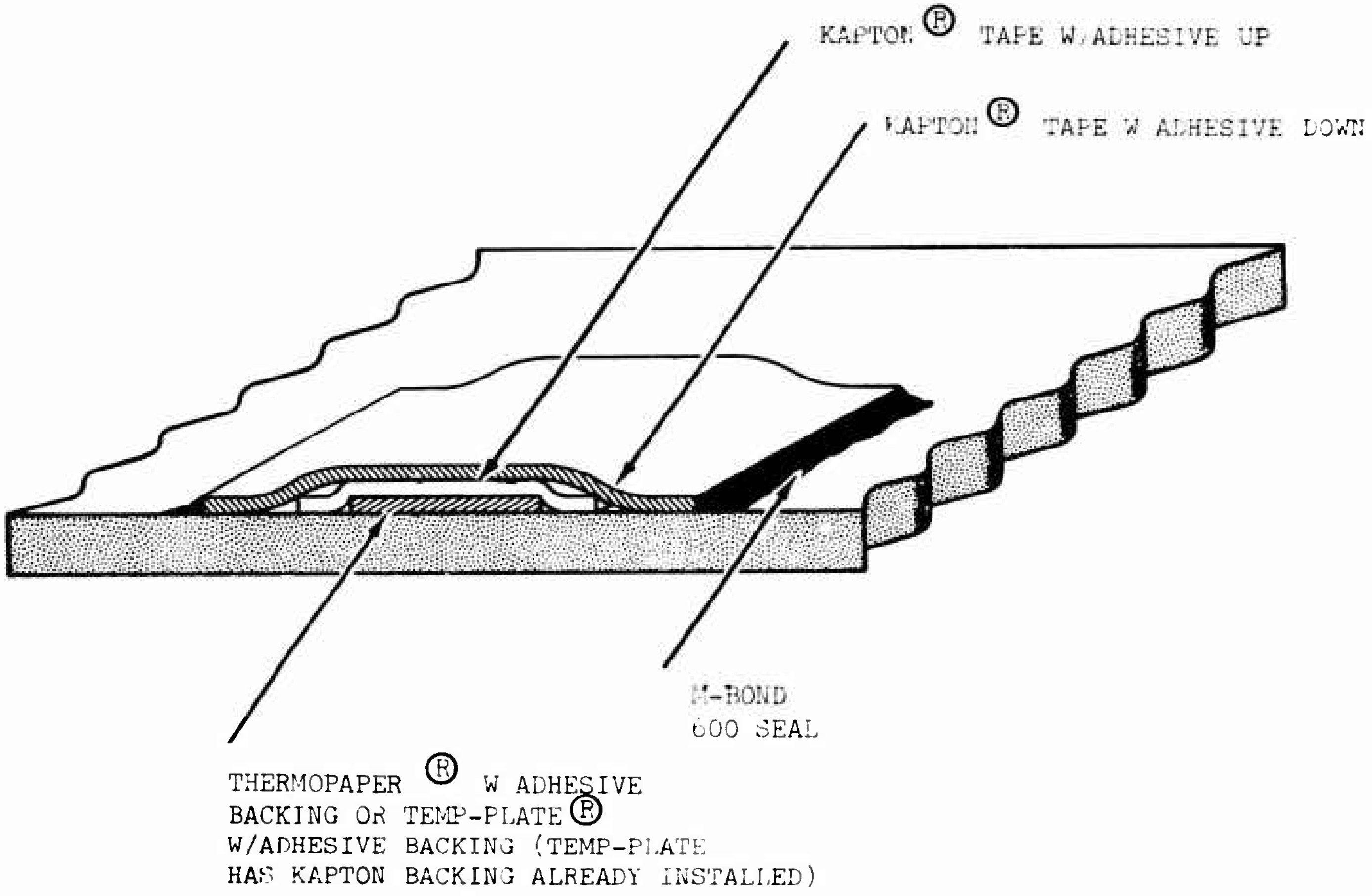


Figure 7. Schematic, Internal Temperature Sensor Installation.

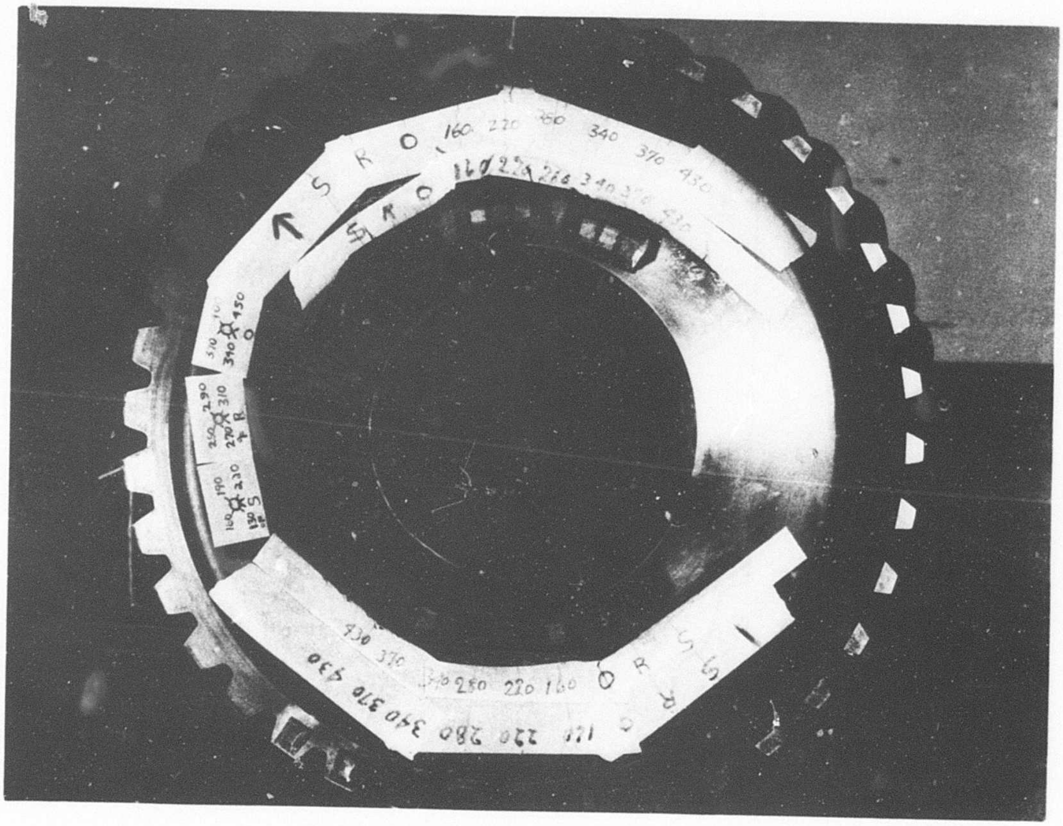


Figure 8. Internal Temperature Sensor Installation.

The locations instrumented for each test are shown in Figure 9. The locations monitored included the following:

- All input shaft bearings
- All main rotor shaft bearings
- Planet roller bearings from each planetary stage
- First-stage input spiral bevel gear set
- Second-stage input spiral bevel gear set
- First-stage and second-stage input gear shafts
- 22 housing locations near bearings, stationary gears, and any other location of special interest
- Oil-in, oil-out, and sump temperatures
- First-stage and second-stage ring gear
- Tail takeoff spiral bevel gear bearings
- Planet gears from the first-stage and second-stage planetary assemblies

Locations monitored and sensor types used for each application are given in Table IV.

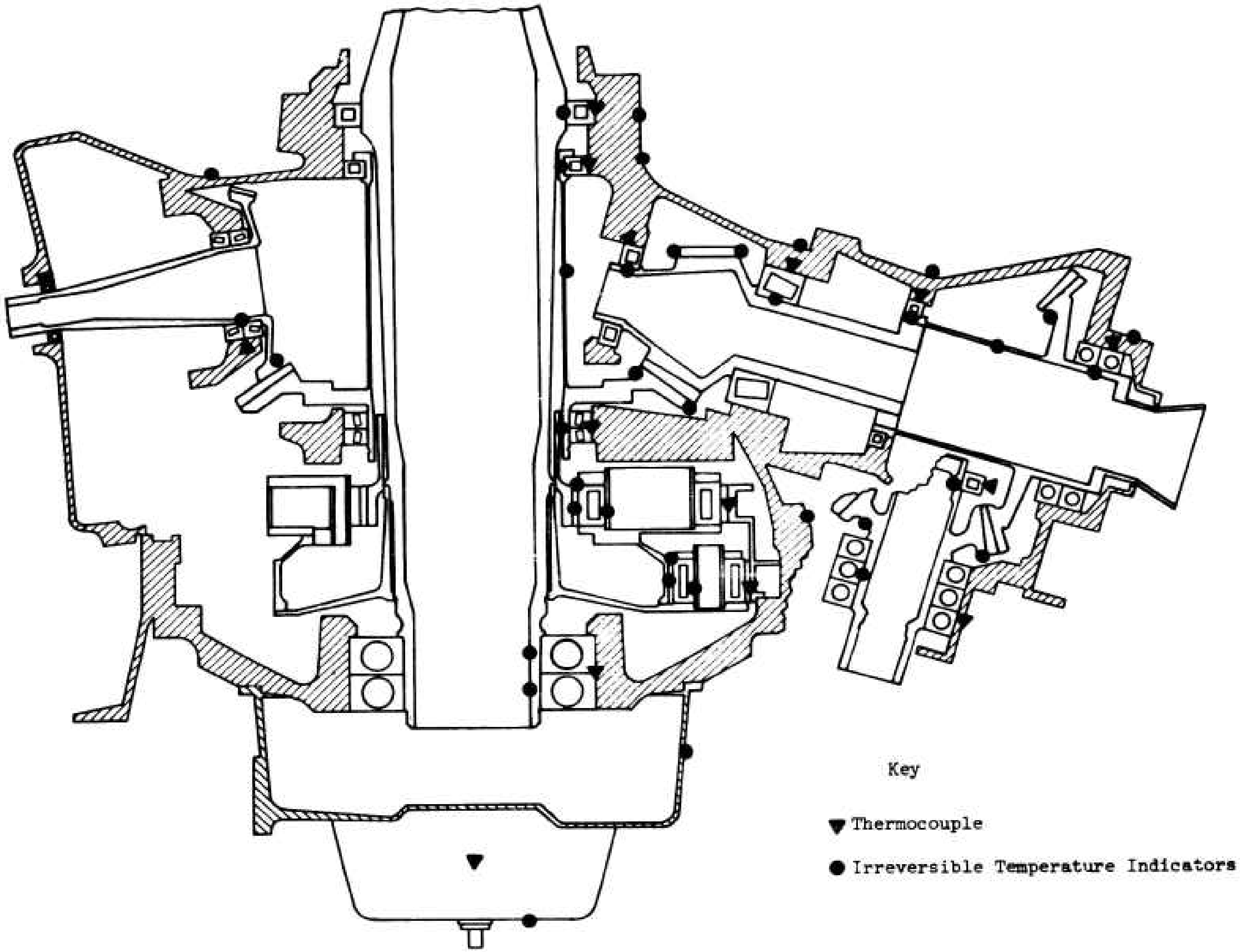


Figure 9. Temperature Sensor Locations.

TABLE IV. TEMPERATURE SENSOR LOCATIONS

Component	Location	Sensor Type*	Range (°F)		
			Test 1	Test 2	T
1st Input Pinion	Stack Brg Inner Race	Tapes & Labels	130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400, 450	180, 200, 210, 230, 250, 260, 270, 280, 290, 300, 310, 330, 360	250, 340,
	Stack Brg Outer Race (both inputs)	T.C.	0-650	0-650	0-6
	Housing, Stack Brg Area (both inputs)	Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 320,
	Roller Brg Inner Race	Tapes & Labels	130, 160, 190, 210, 250, 270, 290, 310	130, 160, 190, 210, 250, 270, 290, 310, 340, 370	250, 340,
	Roller Brg Outer Race and Housing (both inputs)	Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190 210, 230, 250, 300	210, 320,
	Gear Teeth	Tapes & Labels	160, 190, 220, 250, 270, 290, 310, 340 370, 400	210, 230, 240, 250, 270, 290, 300, 330, 330, 350, 370, 380	310, 370,
	Gear Web	Tapes & Labels 340, 370, 400, 450	130, 160, 190, 220, 250, 270, 290, 310,	180, 200, 230, 250 270, 290, 310, 330,	250, 340,
1st Input Gear	Duplex Brg Inner Race	Tape	130, 160, 190, 220 250, 280, 310, 340 370	180, 190, 210, 230 240, 250, 260, 270,	250, 340,
	Duplex Brg Outer Race (both inputs)	T.C.	0-650	0-650	0-6
	Housing, Duplex Brg Area (both inputs)	Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190 210, 230, 250, 300	210, 320,
	Gear Teeth	Tapes & Labels	130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400	230, 250, 270, 280, 290, 310, 330, 340	290, 370
	Gear Shaft	Tapes & Labels	130, 160, 190, 220	250, 270, 290, 310	250, 340,
	Roller Brg Inner Race	Tapes & Labels	130, 160, 190, 220, 250, 270, 280, 290, 310, 340, 370, 400	160, 200, 230, 250, 260, 270, 290, 310 320	160, 260, 320

TABLE IV. TEMPERATURE SENSOR LOCATIONS

	Sensor Type*	Range (°F)			
		Test 1	Test 2	Test 3	Test 4
Race	Tapes & Labels	130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400, 450	180, 200, 210, 230, 250, 260, 270, 280, 290, 300, 310, 330, 360	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310, 340, 370, 400, 450
Race	T.C.	0-650	0-650	0-650	0-650
Brg Area	Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 350, 370
r Race	Tapes & Labels	130, 160, 190, 210, 250, 270, 290, 310	130, 160, 190, 210, 250, 270, 290, 310, 340, 370	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310 340, 370, 400, 450
r Race th inputs)	Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 350 370
	Tapes & Labels	160, 190, 220, 250, 270, 290, 310, 340 370, 400	210, 230, 240, 250, 270, 290, 300, 330, 330, 350, 370, 330	310, 320, 340, 350, 370, 400, 450	250, 270, 290, 310, 340, 370, 400, 450
	Tapes & Labels 340, ·70, 400, 450	130, 160, 190, 220, 250, 270, 290, 310,	180, 200, 230, 250 270, 290, 310, 330,	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310, 340, 370, 400, 450
r Race	Tape	130, 160, 190, 220 250, 280, 310, 340 370	180, 190, 210, 230 240, 250, 260, 270,	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310, 340, 370, 400, 450
r Race	T.C.	0-650	0-650	0-650	0-650
rg Area	Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 350, 370
	Tapes & Labels	130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400	230, 250, 270, 280, 290, 310, 330, 340	290, 310, 330, 350, 370	250, 270, 290, 310, 340, 370, 400, 450
	Tapes & Labels	130, 160, 190, 220	250, 270, 290, 310	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310 340, 370, 400, 450
Race	Tapes & Labels	130, 160, 190, 220, 250, 270, 280, 290, 310, 340, 370, 400	160, 200, 230, 250, 260, 270, 290, 310 320	160, 200, 230, 250, 260, 270, 290, 310, 320	250, 270, 290, 310, 340, 370, 400, 450

TABLE IV. TEMPERATURE SENSOR

Component	Location	Sensor Type*	Test I
1st Input Pinion	Stack Brg Inner Race	Tapes & Labels	130, 160, 190, 250, 270, 290, 340, 370, 400,
	Stack Brg Outer Race (both inputs)	T.C.	0-650
	Housing, Stack Brg Area (both inputs)	Tape (external)	130, 150, 170, 210, 230, 250,
	Roller Brg Inner Race	Tapes & Labels	130, 160, 190, 250, 270, 290,
	Roller Brg Outer Race and Housing (both inputs)	Tape (external)	130, 150, 170, 210, 230, 250,
	Gear Teeth	Tapes & Labels	160, 190, 220, 270, 290, 310, 370, 400
	Gear Web	Tapes & Labels 340, 370, 400, 450	130, 160, 190, 250, 270, 290,
1st Input Gear	Duplex Brg Inner Race	Tape	130, 160, 190, 250, 280, 310, 370
	Duplex Brg Outer Race (both inputs)	T.C.	0-650
	Housing,Duplex Brg Area (both inputs)	Tape (external)	130, 150, 170, 210, 230, 250,
	Gear Teeth	Tapes & Labels	130, 160, 190, 250, 270, 290, 340, 370, 400
	Gear Shaft	Tapes & Labels	130, 160, 190,
	Roller Brg Inner Race	Tapes & Labels	130, 160, 190, 250, 270, 280, 310, 340, 370,

TEMPERATURE SENSOR LOCATIONS

Range (°F)			
Test 1	Test 2	Test 3	Test 4
130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400, 450	180, 200, 210, 230, 250, 260, 270, 280, 290, 300, 310, 330, 360	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 31 340, 370, 400, 45
0-650	0-650	0-650	0-650
130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 35 370
130, 160, 190, 210, 250, 270, 290, 310	130, 160, 190, 210, 250, 270, 290, 310, 340, 370	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 31 340, 370, 400, 45
130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 35 370
160, 190, 220, 250, 270, 290, 310, 340 370, 400	210, 230, 240, 250, 270, 290, 300, 330, 330, 350, 370, 380	310, 320, 340, 350, 370, 400, 450	250, 270, 290, 31 340, 370, 400, 45
130, 160, 190, 220, 250, 270, 290, 310,	180, 200, 230, 250 270, 290, 310, 330,	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 31 340, 370, 400, 45
130, 160, 190, 220 250, 280, 310, 340 370	180, 190, 210, 230 240, 250, 260, 270,	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 31 340, 370, 400, 45
0-650	0-650	0-650	0-650
130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 35 370
130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400	230, 250, 270, 280, 290, 310, 330, 340	290, 310, 330, 350, 370	250, 270, 290, 31 340, 370, 400, 45
130, 160, 190, 220	250, 270, 290, 310	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 31 340, 370, 400, 45
130, 160, 190, 220, 250, 270, 280, 290, 310, 340, 370, 400	160, 200, 230, 250, 260, 270, 290, 310 320	160, 200, 230, 250, 260, 270, 290, 310, 320	250, 270, 290, 31 340, 370, 400, 45

TABLE IV. Continued

Component	Location	Sensor Type*	Range (°F)		
			Test 1	Test 2	Te
	Roller Brg Outer Race	T.C.	0-650	0-650	0-65
	Housing, Roller Brg Area	Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 320,
2nd Input Pinion	Timken Brg Inner Race	Tapes & Labels	130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400	Indicators from Test #1 used	250, 340,
	Timken Brg Outer Race (both inputs)	T.C.	0-650	0-650	0-6
	Housing, Timken Brg Area	Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 320,
	Gear Teeth	Tapes & Labels	130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400, 435. 450	210, 230, 240, 260, 270, 290, 300, 320, 330, 350, 370, 380	130, 250, 340,
	Roller Brg Inner Race	Tapes & Labels	130, 160, 190, 220, 250, 270, 280, 290, 310, 340	180, 210, 240, 250, 270, 290, 300, 310 330, 360	250, 340,
	Roller Brg Outer Race	T.C.	0-650	0-650	0-6
Main Bevel & Outer Shaft Assy	Roller Brg Inner Race	Tapes & Labels	130, 160, 190, 220, 250, 280	130, 160, 190, 220, 250, 290	130, 250,
	Roller Brg Outer Race	T.C.	0-650	0-650	0-6
	Housing, Roller Brg Area	Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 320,
	Shaft, Mid-Length	Tapes & Labels	130, 160, 190, 220, 250, 280	130, 160, 190, 220 250, 280	130, 250,
	Timken Brg Inner Race	Tapes & Labels	130, 160, 190, 220, 250, 280, 310, 340	130, 160, 190, 220, 250, 280, 310, 340	130, 250, 340,
	Timken Brg Outer Race	T.C.	0-650	0-650	0-6
	Gear Teeth	Tapes & Labels	130, 160, 190, 220, 250, 280, 310, 340, 370	130, 160, 190, 220, 250, 280, 310, 340, 370	290, 370

TABLE IV. Continued

ion	Sensor Type*	Range (°F) Test 1	Test 2	Test 3	Test 4
Outer Race	T.C.	0-650	0-650	0-650	0-650
ller Brg Area	Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 350 370
Inner Race	Tapes & Labels	130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400	Indicators from Test #1 used	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310 340, 370, 400, 450
Outer Race uts)	T.C.	0-650	0-650	0-650	0-650
mken Brg Area	Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 350 370
	Tapes & Labels	130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400, 435, 450	210, 230, 240, 260, 270, 290, 300, 320, 330, 350, 370, 380	130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310, 340, 370, 400, 450
Inner Race	Tapes & Labels	130, 160, 190, 220, 250, 270, 280, 290, 310, 340	180, 210, 240, 250, 270, 290, 300, 310 330, 360	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310, 340, 370, 400, 450
Outer Race	T.C.	0-650	0-650	0-650	0-650
Inner Race	Tapes & Labels	130, 160, 190, 220, 250, 280	130, 160, 190, 220, 250, 280	130, 160, 190, 220, 250, 280	250, 270, 290, 310, 340, 370, 400, 450
Outer Race	T.C.	0-650	0-650	0-650	0-650
ller Brg Area	Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 350, 370
Length	Tapes & Labels	130, 160, 190, 220, 250, 280	130, 160, 190, 220 250, 280	130, 160, 190, 220, 250, 280	Indicators from Test #1 used
Inner Race	Tapes & Labels	130, 160, 190, 220, 250, 280, 310, 340	130, 160, 190, 220, 250, 280, 310, 340	130, 160, 190, 220, 250, 280, 310, 320 340, 360	250, 270, 290, 310, 340, 370, 400, 450
uter Race	T.C.	0-650	0-650	0-650	0-650
	Tapes & Labels	130, 160, 190, 220, 250, 280, 310, 340, 370	130, 160, 190, 220, 250, 280, 310, 340, 370	290, 310, 330, 350, 370	250, 270, 290, 310, 340, 370, 400, 450

TABLE IV. Continued

Component	Location	Sensor Type*	Test 1
	Roller Brg Outer Race	T.C.	0-650
	Housing, Roller Brg Area	Tape (external)	130, 150, 170 210, 230, 250
2nd Input Pinion	Timken Brg Inner Race	Tapes & Labels	130, 160, 190 250, 270, 290 340, 370, 400
	Timken Brg Outer Race (both inputs)	T.C.	0-650
	Housing, Timken Brg Area	Tape (external)	130, 150, 170 210, 230, 250
	Gear Teeth	Tapes & Labels	130, 160, 190 250, 270, 290 340, 370, 400 450
	Roller Brg Inner Race	Tapes & Labels	130, 160, 190 250, 270, 280 310, 340
	Roller Brg Outer Race	T.C.	0-650
Main Bevel & Outer Shaft Assy	Roller Brg Inner Race	Tapes & Labels	130, 160, 190 250, 280
	Roller Brg Outer Race	T.C.	0-650
	Housing, Roller Brg Area	Tape (external)	130, 150, 170 210, 230, 250
	Shaft, Mid-Length	Tapes & Labels	130, 160, 190 250, 280
	Timken Brg Inner Race	Tapes & Labels	130, 160, 190, 250, 280, 310,
	Timken Brg Outer Race	T.C.	0-650
	Gear Teeth	Tapes & Labels	130, 160, 190 250, 280, 310 370

IV. Continued

Range (°F)			
Test 1	Test 2	Test 3	Test 4
0-650	0-650	0-650	0-650
130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 350 370
130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400	Indicators from Test #1 used	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310 340, 370, 400, 450
0-650	0-650	0-650	0-650
130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 350 370
130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400, 435, 450	210, 230, 240, 260, 270, 290, 300, 320, 330, 350, 370, 380	130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310 340, 370, 400, 450
130, 160, 190, 220, 250, 270, 280, 290, 310, 340	180, 210, 240, 250, 270, 290, 300, 310 330, 360	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310 340, 370, 400, 450
0-650	0-650	0-650	0-650
130, 160, 190, 220, 250, 280	130, 160, 190, 220, 250, 280	130, 160, 190, 220, 250, 280	250, 270, 290, 310, 340, 370, 400, 450
0-650	0-650	0-650	0-650
130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 350, 370
130, 160, 190, 220, 250, 280	130, 160, 190, 220 250, 280	130, 160, 190, 220, 250, 280	Indicators from Test #1 used
130, 160, 190, 220, 250, 280, 310, 340	130, 160, 190, 220, 250, 280, 310, 340	130, 160, 190, 220, 250, 280, 310, 320 340, 360	250, 270, 290, 310, 340, 370, 400, 450
0-650	0-650	0-650	0-650
130, 160, 190, 220, 250, 280, 310, 340, 370	130, 160, 190, 220, 250, 280, 310, 340, 370	290, 310, 330, 350, 370	250, 270, 290, 310 340, 370, 400, 450

TABLE IV. Continued

Component	Location	Sensor Type*	Range (°F) Test 1	 Test 2	 Tes
	1st Stage Planetary Sun Gear	Tapes & Labels	130, 160, 190, 220, 250, 280, 310, 340, 370	130, 160, 190, 220, 250, 280, 310, 340, 370	260, 28 340, 36
Ring Gear	1st Stage Gear Teeth	T.C.	0-650	0-650	0-650
	2nd Stage Gear Teeth	T.C.	0-650	0-650	0-650
	Housing, Ring Gear Area	Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 24 320, 34
1st Planetary Assy	Pinion Gear Teeth (2 gears)	Tapes	130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400, 450	180, 190, 210, 220, 240, 250, 270, 290, 300, 310, 330, 350, 400	210, 24 290, 31 400, 45
	Pinion Roller Brg (2 Brgs)	Tapes & Labels	130, 160, 190, 220, 250, 270, 290, 310, 340, 370	130, 190, 210, 220, 240, 250, 270, 290, 310, 330, 350, 400	190, 22 290, 31 370
	2nd Stage Planetary Sun Gear	Tapes & Labels	130, 160, 190, 220, 250, 290, 310, 340, 370, 400	130, 160, 190, 220, 250, 270, 290, 310	250, 27 340, 37
2nd Planetary Assy	Pinion Gear Teeth (2 gears)	Tapes & Labels	130, 160, 190, 220, 250, 270, 290, 310, 340, 370	130, 160, 190, 220, 250, 270, 290, 310	210, 24 290, 31 400, 45
	Pinion Roller Brg (2 Brgs)	Tapes & Labels	130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400, 450	130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400, 450	250, 27 320, 34 400, 45
Main Rotor Shaft	Roller Brg Inner Race	Tapes & Labels	130, 160, 190, 220, 250, 280, 310, 340, 370	130, 160, 190, 220, 250, 280, 310, 340, 370	130, 16 250, 27
	Roller Brg Outer Race	T.C.	0-650	0-650	0-650
	Housing, Roller Brg Area	Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 24 320, 34
	Duplex Brg Inner Race	Tapes & Labels	130, 160, 190, 220, 250, 230, 310, 340, 370, 400	130, 160, 190, 220, 250, 230, 310, 340, 370, 400	130, 16 250, 29 370, 40
	Duplex Brg Outer Race	T.C.	0-650	0-650	0-650

TABLE IV. Continued

	Sensor Type*	Range (°F) Test 1	Test 2	Test 3	Test 4
un Gear	Tapes & Labels	130, 160, 190, 220, 250, 280, 310, 340, 370	130, 160, 190, 220, 250, 280, 310, 340, 370	260, 280, 310, 320, 340, 360	250, 270, 290, 310, 340, 370, 400, 450
	T.C.	0-650	0-650	0-650	0-650
	T.C.	0-650	0-650	0-650	0-650
ea	Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 350 370
gears)	Tapes	130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400, 450	180, 190, 210, 220, 240, 250, 270, 290, 300, 310, 330, 350, 400	210, 240, 250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310, 340, 370, 400, 450
Brgs)	Tapes & Labels	130, 160, 190, 220, 250, 270, 290, 310, 340, 370	180, 190, 210, 220, 240, 250, 270, 290, 310, 330, 350, 400	190, 220, 250, 270, 290, 310, 320, 350, 370	250, 270, 290, 310 340, 370, 400, 450,
un Gear	Tapes & Labels	130, 160, 190, 220, 250, 280, 310, 340, 370, 400	130, 160, 190, 220, 250, 270, 290, 310	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310, 340, 370, 400, 450
gears)	Tapes & Labels	130, 160, 190, 220, 250, 270, 290, 310, 340, 370	130, 160, 190, 220, 250, 270, 290, 310	210, 240, 250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310, 340, 370, 400, 450,
rgs)	Tapes & Labels	130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400, 450	130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310, 320, 340, 360, 370, 400, 450	250, 270, 290, 310, 340, 370, 400, 450
	Tapes & Labels	130, 160, 190, 220, 250, 280, 310, 340, 370	130, 160, 190, 220, 250, 280, 310, 340, 370	130, 160, 190, 220, 250, 270, 290, 310	130, 160, 190, 220, 250, 270, 290, 310 340, 370, 400, 450
	T.C.	0-650	0-650	0-650	0-650
ea	Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 350, 370
	Tapes & Labels	130, 160, 190, 220, 250, 230, 310, 340, 370, 400	130, 160, 190, 220, 250, 230, 310, 340, 370, 400	130, 160, 190, 220, 250, 280, 310, 340, 370, 400	250, 270, 290, 310, 340, 370, 400, 450
	T.C.	0-650	0-650	0-650	0-650

A

TABLE IV. Cont

Component	Location	Sensor Type*	Test 1
	1st Stage Planetary Sun Gear	Tapes & Labels	130, 160, 250, 280, 370
Ring Gear	1st Stage Gear Teeth	T.C.	0-650
	2nd Stage Gear Teeth	T.C.	0-650
	Housing, Ring Gear Area	Tape (external)	130, 150, 210, 230,
1st Planetary Assy	Pinion Gear Teeth (2 gears)	Tapes	130, 160, 250, 270, 340, 370,
	Pinion Roller Brg (2 Brgs)	Tapes & Labels	130, 160, 250, 270, 340, 370
	2nd Stage Planetary Sun Gear	Tapes & Labels	130, 160, 250, 280, 370, 400
2nd Planetary Assy	Pinion Gear Teeth (2 gears)	Tapes & Labels	130, 160, 250, 270, 340, 370
	Pinion Roller Brg (2 Brgs)	Tapes & Labels	130, 160, 250, 270, 340, 370,
Main Rotor Shaft	Roller Brg Inner Race	Tapes & Labels	130, 160, 250, 280, 370
	Roller Brg Outer Race	T.C.	0-650
	Housing, Roller Brg Area	Tape (external)	130, 150, 210, 230,
	Duplex Brg Inner Race	Tapes & Labels	130, 160, 250, 280, 370, 400
	Duplex Brg Outer Race	T.C.	0-650

B

LE IV. Continued

Range (°F)			
Test 1	Test 2	Test 3	Test 4
130, 160, 190, 220, 250, 280, 310, 340, 370	130, 160, 190, 220, 250, 280, 310, 340, 370	260, 280, 310, 320, 340, 360	250, 270, 290, 310 340, 370, 400, 450
0-650	0-650	0-650	0-650
0-650	0-650	0-650	0-650
130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 350 370
130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400, 450	180, 190, 210, 220, 240, 250, 270, 290, 300, 310, 330, 350, 400	210, 240, 250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310 340, 370, 400, 450
130, 160, 190, 220, 250, 270, 290, 310, 340, 370	180, 190, 210, 220, 240, 250, 270, 290, 310, 330, 350, 400	190, 220, 250, 270, 290, 310, 320, 350, 370	250, 270, 290, 310 340, 370, 400, 450
130, 160, 190, 220, 250, 280, 310, 340, 370, 400	130, 160, 190, 220, 250, 270, 290, 310	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310 340, 370, 400, 450
130, 160, 190, 220, 250, 270, 290, 310, 340, 370	130, 160, 190, 220, 250, 270, 290, 310	210, 240, 250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310 340, 370, 400, 450
130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400, 450	130, 160, 190, 220, 250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310, 320, 340, 360, 370, 400, 450	250, 270, 290, 310 340, 370, 400, 450
130, 160, 190, 220, 250, 280, 310, 340, 370	130, 160, 190, 220, 250, 280, 310, 340, 370	130, 160, 190, 220, 250, 270, 290, 310	130, 160, 190, 220 250, 270, 290, 310 340, 370, 400, 450
0-650	0-650	0-650	0-650
130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 350 370
130, 160, 190, 220, 250, 280, 310, 340, 370, 400	130, 160, 190, 220, 250, 280, 310, 340, 370, 400	130, 160, 190, 220, 250, 280, 310, 340, 370, 400	250, 270, 290, 310 340, 370, 400, 450
0-650	0-650	0-650	0-650

TABLE IV. Continued

Component	Location	Sensor Type*	Range (°F)		
			Test 1	Test 2	Test 3
Sump Cover	Side	Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 320, 340
	Bottom	Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 320, 340
Tail Takeoff Bevel Gear	Gear Teeth	Tape	130, 160, 190, 220, 250, 270, 280, 290, 310, 340, 370, 400, 430, 450	130, 160, 190, 220, 250, 270, 280, 290, 310, 340, 370, 400, 430, 450	250, 270, 340, 370,
	Timken Brg Inner Race	Tapes & Labels	130, 160, 190, 220, 250, 270, 280, 290 310, 340, 370, 400, 430	130, 160, 190, 220, 250, 270, 280, 290, 310, 340, 370, 400, 430	250, 270, 340, 370,
	Timken Brg Outer Race	T.C.	0-650	0-650	0-650
	Housing, Timken Brg Area	Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 320, 340
	Roller Brg Outer Race	T.C.	0-650	0-650	0-650
Oil-in	Sump	T.C.	0-650	0-650	0-650
Oil-out	Oil-in Line	T.C.	0-650	0-650	0-650

*"Tape" denotes Thermopaper ® temperature indicators manufactured by Paper Thermometer Co. Inc.

"Label" denotes Temp-Plate ® part number 140 temperature indicators manufactured by William Wahl Corp.

"T.C." denotes iron-constantan thermocouples.

TABLE IV. Continued

Sensor Type*	Range (°F)			
	Test 1	Test 2	Test 3	Test 4
Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 350 370
Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 350, 370
Tape	130, 160, 190, 220, 250, 270, 280, 290, 310, 340, 370, 400, 430, 450	130, 160, 190, 220, 250, 270, 280, 290, 310, 340, 370, 400, 430, 450	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310, 340, 370, 400, 450
Tapes & Labels	130, 160, 190, 220, 250, 270, 280, 290 310, 340, 370, 400, 430	130, 160, 190, 220, 250, 270, 280, 290, 310, 340, 370, 400, 430	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310 340, 370, 400, 450
T.C.	0-650	0-650	0-650	0-650
Tape (external)	130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 270, 290 320, 340	280, 310, 330, 350, 370
T.C.	0-650	0-650	0-650	0-650
T.C.	0-650	0-650	0-650	0-650
T.C.	0-650	0-650	0-650	0-650

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TABLE IV. Continue

Component	Location	Sensor Type*	Test 1
Sump Cover	Side	Tape (external)	130, 150, 170, 210, 230, 250,
	Bottom	Tape (external)	130, 150, 170, 210, 230, 250,
Tail Takeoff Bevel Gear	Gear Teeth	Tape	130, 160, 190 250, 270, 280 310, 340, 370 430, 450
	Timken Brg Inner Race	Tapes & Labels	130, 160, 190 250, 270, 280 310, 340, 370 430
	Timken Brg Outer Race	T.C.	0-650
	Housing, Timken Brg Area	Tape (external)	130, 150, 170 210, 230, 250
	Roller Brg Outer Race	T.C.	0-650
Oil-in	Sump	T.C.	0-650
Oil-out	Oil-in Line	T.C.	0-650

*"Tape" denotes Thermopaper® temperature indicators manufactured by Paper Thermometer Co. Inc.

"Label" denotes Temp-Plate® part number 440 temperature indicators manufactured by William Wahl Corp.

"T.C." denotes iron-constantan thermocouples.

LE IV. Continued

Range (°F)			
Test 1	Test 2	Test 3	Test 4
130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 350 370
130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 270, 290, 320, 340	280, 310, 330, 350, 370
130, 160, 190, 220, 250, 270, 280, 290, 310, 340, 370, 400, 430, 450	130, 160, 190, 220, 250, 270, 280, 290, 310, 340, 370, 400, 430, 450	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310, 340, 370, 400, 450
130, 160, 190, 220, 250, 270, 280, 290 310, 340, 370, 400, 430	130, 160, 190, 220, 250, 270, 280, 290, 310, 340, 370, 400, 430	250, 270, 290, 310, 340, 370, 400, 450	250, 270, 290, 310 340, 370, 400, 450
0-650	0-650	0-650	0-650
130, 150, 170, 190, 210, 230, 250, 300	130, 150, 170, 190, 210, 230, 250, 300	210, 240, 270, 290 320, 340	280, 310, 330, 350, 370
0-650	0-650	0-650	0-650
0-650	0-650	0-650	0-650
0-650	0-650	0-650	0-650

Three holes were drilled in the gearbox housing prior to the third test run to allow insertion of a handheld probe to measure gear-tooth temperatures after test shutdown. The locations where such measurements were made were as follows:

- Left-hand first-stage input pinion
- Left-hand first-stage input gear (no hole required for this location, as an inspection port in the housing allowed access to this gear)
- Left-hand second-stage input pinion
- Main bevel gear

Thermal expansion measurement instrumentation was attached to the test gearbox and test stand prior to each test run. The transducers used for this measurement were linear voltage differential transformers (LVDT's) whose voltage output varies linearly with the displacement of the transformer inner coil with respect to the transformer outer coil. The LVDT inner shaft and coil were bonded to the test gearbox skin. The LVDT outer coil was fixed to ground by a bracket. As the gearbox housing expanded, the transformer inner coil moved relative to the outer coil, and a change in transducer output voltage occurred. Thermal expansion measurements were made immediately upon shutdown and as the test gearbox cooled. This procedure was necessary due to the instrumentation's sensitivity to stand vibration encountered during operation. A typical test installation is shown in Figure 10. The test gearbox with LVDT's and bracketry is shown in Figure 11. Locations for LVDT installations are shown in Figure 12. Due to the vibration problems encountered with the LVDT's, a trammel bar was also used during tests 3 and 4 to measure thermal growth.

The oil used in all tests was MIL-L-7808G manufactured by Stauffer Chemical Co.

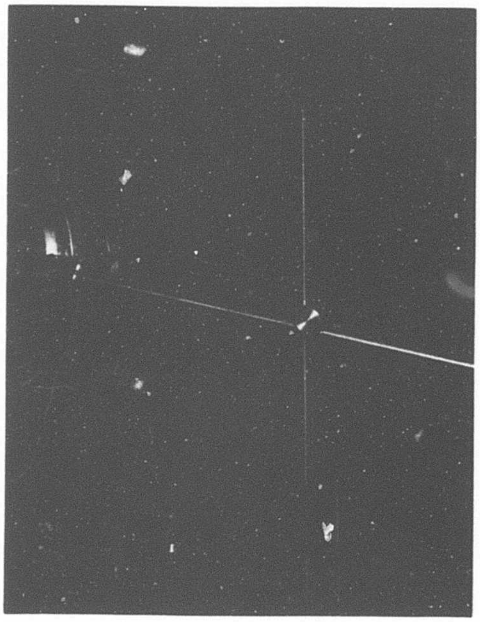

Figure 10. LVDT Installation (Typical).

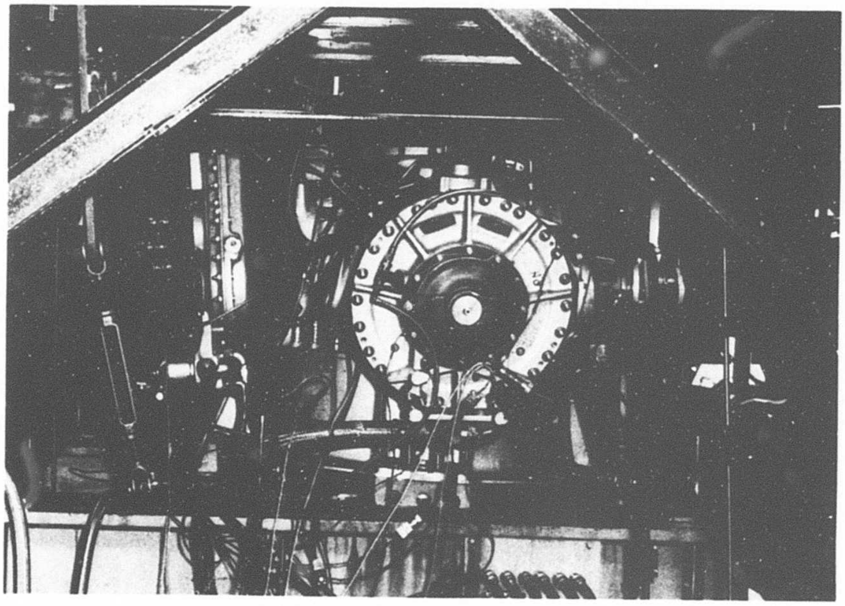

Figure 11. Gearbox in Test Stand With LVDT's Installed.

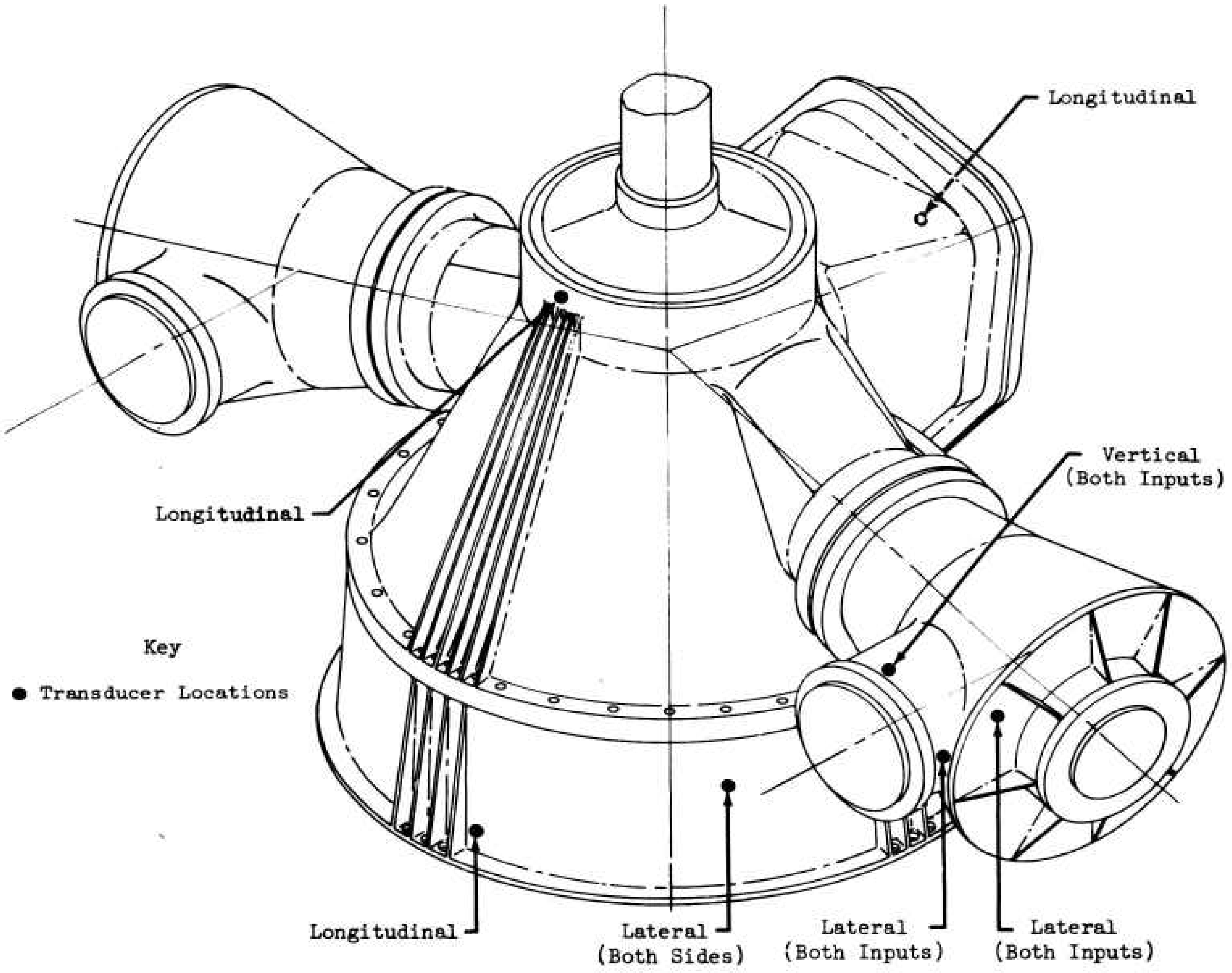

Figure 12. LVDT Displacement Transducer Locations.

DESCRIPTION OF FACILITIES

All testing performed under this contract was accomplished in the Government-owned/Sikorsky-built CH-54A/B main transmission test facility located in the contractor's plant in Stratford, Connecticut. The facility is illustrated schematically in Figure 13 and shown in Figures 14 and 15.

The facility is designed on the regenerative principle. Input and output shafts of the gearbox under test are coupled together through shafting and commercial gearboxes, forming closed mechanical loops, each of which may be torqued to equivalent flight loads. Torques in the individual loops are independent of speed and may be dynamically applied, maintained, changed or released.

As shown in Figure 13, the inputs of the test gearbox are connected to the input facility gearbox, which in turn is connected to the upper facility gearbox and the tail facility gearbox. The torque loop for main shaft power is completed by connecting the upper facility gearbox to the test gearbox through a coupling and thrust cylinder arrangement which permits the application of thrust to the test gearbox main rotor shaft. The tail loop is closed by connecting tail facility gearbox to the tail takeoff coupling of the test gearbox.

Both the input and tail facility gearboxes are equipped with helical gears which can be adjusted hydraulically to increase windup (torque) in the mechanical loop. This torque is then transmitted throughout the mechanical loop. Input and tail torques are independently controllable.

Power to drive the facility is provided by an 800-horsepower synchronous motor which drives through an eddy-current clutch into the input facility gearbox. The facility speed is independently controllable through the clutch from 0 to 103% (9270 rpm) of normal speed.

The facility controls shown in Figure 15 are located adjacent to the test cell. All instrumentation used to monitor the test gear and the facility components is located at this station.

In place of the oil-to-air heat exchanger used on the aircraft, the facility is equipped with an oil-to-water heat exchanger. The oil temperature into the test gearbox is controlled by varying the flow rate of cooling water through the heat exchanger. Water flow rate is regulated from the test stand control panel during facility operation.

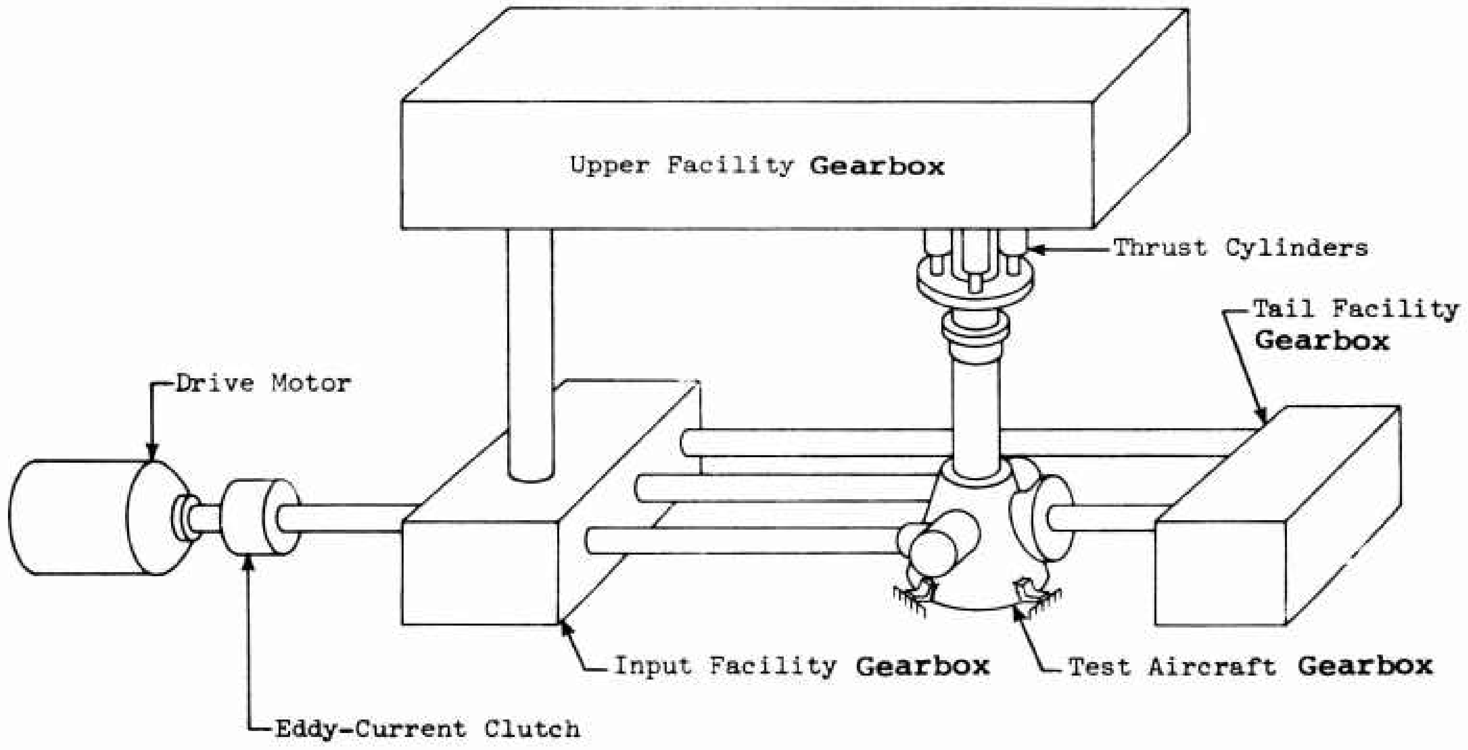

Figure 13. CH-54 Main Transmission Regenerative Test Stand Schematic.

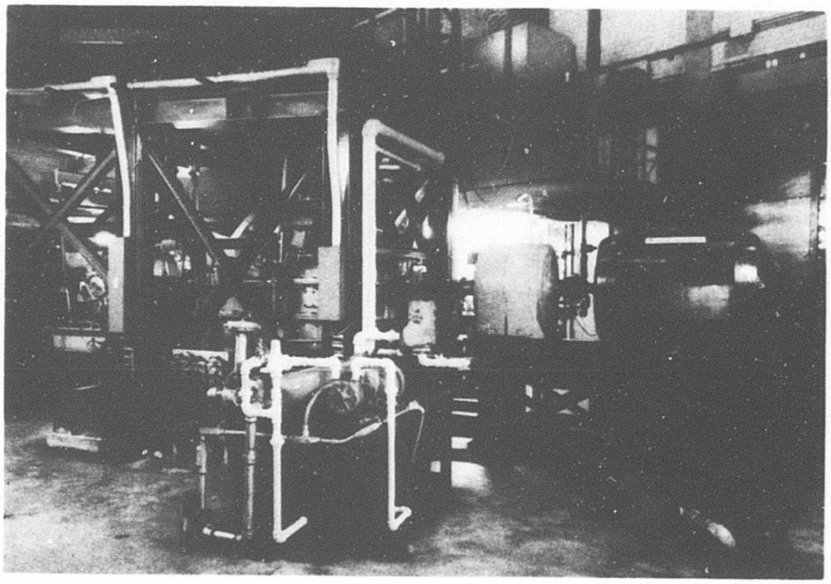

Figure 14. CH-54 Main Transmission Test Stand.

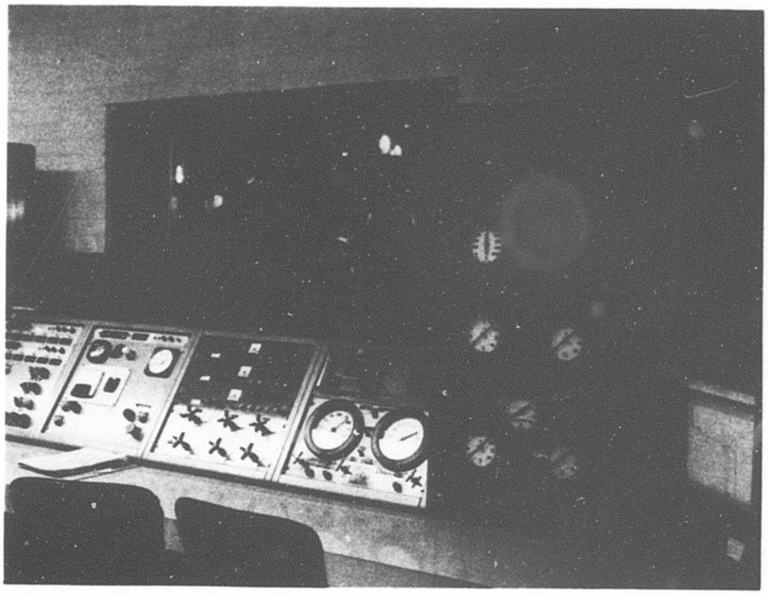

Figure 15. CH-54 Main Transmission Test Stand Control Panel.

TEST PROCEDURE

TEST 1 - BASELINE CONDITION

For the baseline test and each subsequent test, the test gearbox was installed in the test facility and the active thermocouples were connected to the facility instrumentation. The LVDT's were mounted in place and nulled.

The gearbox was run at 1000 hp/input and 2000 hp/input for 10 minutes at each power to demonstrate satisfactory gearbox operation. The baseline run at 3300 hp/input, 600 hp tail takeoff power was then performed with a stabilized oil-in temperature of 160 ± 7°F until temperature stabilization. No forced air cooling was used during this or any subsequent testing.

The gearbox was then run 10 minutes at reduced power (1000 hp/input) and full cooler flow to reduce gearbox component temperatures below those of the stabilized test condition at the completion of this and all subsequent test runs. This was done to prevent areas which were local "hot spots", and used oil flow as a primary heat rejection path, from unduly heating surrounding areas when the oil flow was stopped at shutdown and conduction became the primary mode of heat rejection. Such conduction could result in erroneously high temperature readings on irreversible tapes and labels in surrounding areas if such precautions were not taken.

Thermal growth measurement on this test was unsatisfactory due to instrumentation calibration and vibration problems encountered with the LVDT's and the mounting brackets.

At the completion of the baseline test and each subsequent test, the gearbox was removed from the facility and disassembled for inspection of the temperature sensors and for general gearbox condition. Upon completion of each inspection, the gearbox was instrumented for the next test in the series, reassembled, and reinstalled in the test facility.

TEST 2

The gearbox was warmed up and checked for proper operation and then test run at 3300 hp/input, 600 hp tail takeoff power with a stabilized oil-out temperature of 275° ±20°F until temperature stabilization.

Temperatures were monitored as before using thermocouples, internal irreversible temperature indicating tapes and labels, and external irreversible temperature indicating tapes. Thermal expansion was measured using the LVDT sensors.

TEST 3

The test gearbox was warmed up and checked for proper operation and then test run at 3300 hp/input, 600 hp tail takeoff power with a stabilized oil-out temperature of 325 ± 10°F. Gearbox instrumentation was the same as for previous tests with one addition: a trammel and scale were used as a backup system for the LVDT's, to measure thermal expansion of the test gearbox.

Immediately upon test shutdown, caps were removed from the left-hand first-stage input gear inspection port and three access holes drilled for this test. A handheld pyrometer was inserted and gear tooth temperatures were monitored for the following gears:

- Left-hand first-stage input pinion
- Left-hand first-stage input gear
- Left-hand second-stage input pinion
- Main bevel gear

Care was taken to assure that temperatures were measured in the middle of the load-bearing area of the face of each gear tooth monitored.

The LVDT's measuring thermal expansion were monitored as the gearbox cooled, and the trammel bar and scale were used to verify accuracy. Trammel bar measurements were taken on the gearbox immediately upon shutdown, and temperatures were recorded with thermocouples. This was repeated when the gearbox had cooled to ambient temperatures.

TEST 4

The gearbox was warmed up and checked for proper operation. The baseline condition was duplicated to permit an infrared study of the gearbox at this condition. This Sikorsky-funded infrared study was performed in addition to the requirements of the subject contract. The purpose of the study was to measure the infrared signature of the test gearbox to provide more insight into the housing temperatures. The study was performed at baseline and the test 4 elevated temperature. The infrared monitoring system, an AGA Thermovision®, is described in the appendix.

The fourth test run was performed at 3300 hp/input, 600 hp tail takeoff power with a stabilized oil-out temperature of 365 ±10° F.

Immediately upon completion of the test run, the temperatures of the input pinions (first and second stage), the first stage bevel gear, and the main bevel gear were measured with the handheld sensor. Thermal expansion data was also obtained with the LVDT's and the trammel bar. When the gearbox had cooled to ambient temperature, all thermal expansion measurements were repeated.

TEST RESULTS

In all temperature data presented in this section, the following criteria were used:

1. For all data obtained from thermocouples, the maximum temperature recorded at each location is presented. This is done to obtain readings for precisely the same test condition as those readings obtained from irreversible temperature indicators. Irreversible indicators react to their specified temperature virtually instantaneously and thus will indicate a maximum rather than the mean temperature encountered.

2. Temperature data obtained from irreversible temperature indicators is presented as the mean of the maximum temperature encountered and the minimum temperature not encountered at that location. Since the temperature difference between indicators varied between 10° and 30°F, the accuracy of the readings is within 3% absolute.

TEST 1

The run-in periods of 10 minutes each at 1000 hp/input, 100 hp tail takeoff power, 100% speed and 2000 hp/input, 350 hp tail takeoff power, 100% speed were successfully accomplished. The run-in period was interrupted twice to clean the test gearbox oil line strainer of thermal indicators and polyimide covers which were caught in it and reducing oil flow. Oil pressures, oil flow, and all monitored temperatures were in the acceptable range after the second cleaning of the strainer.

The thermal map baseline run at 3300 hp per input, 600 hp tail takeoff power, 100% speed was then performed. The stabilized oil-in temperature was 160°F. Other stabilized data is shown in Table V. The inspection performed at the completion of the test run showed all components to be in satisfactory condition. Inspection revealed that a sufficient number of internal irreversible temperature indicators had been retained to yield thermal readings at over 80% of the assigned internal locations. External irreversible tape and thermocouple readings were satisfactorily obtained. All gearbox components were in good condition at the test completion.

Thermal data obtained from Test 1 is shown in Figures 16 and 17. Figures 18 through 23 are photographs of selected gearbox locations showing sensor condition at test completion.

Thermal expansion measurements made were unsatisfactory due to calibration and vibration problems with the LVDT sensors and their brackets.

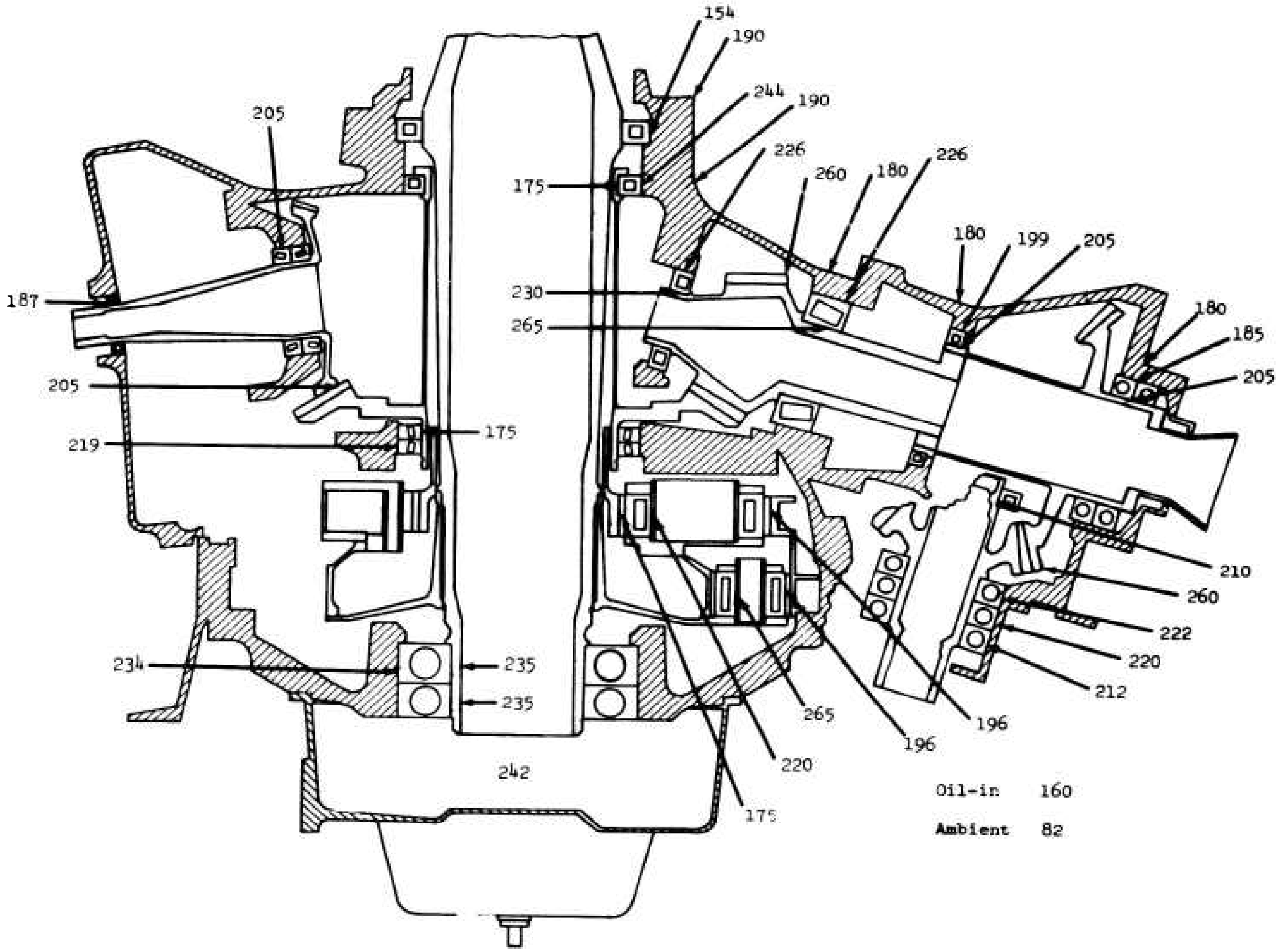

Figure 16. Thermal Map, Internal, Test 1.

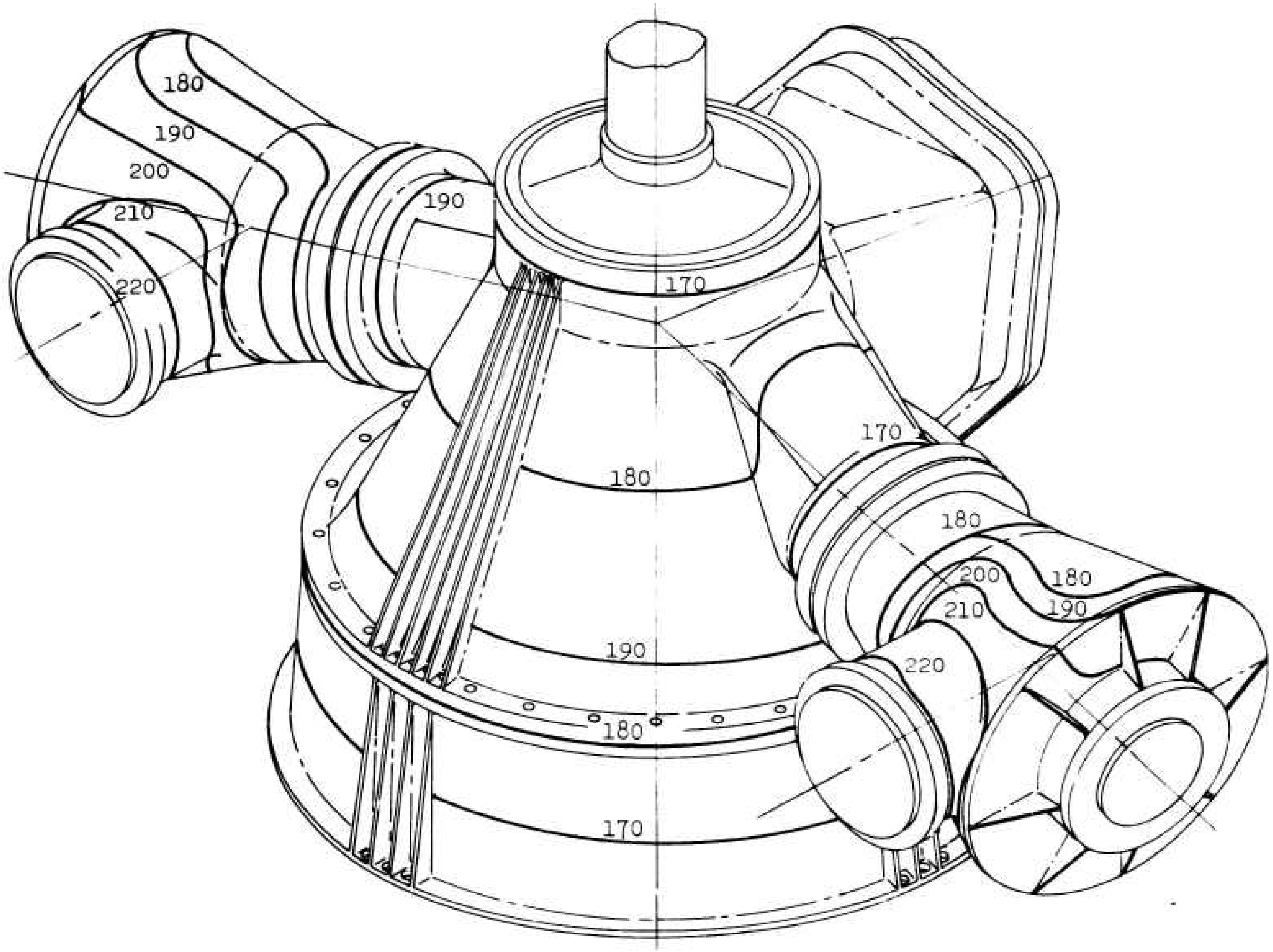

Figure 17. Thermal Map, External, Test 1.

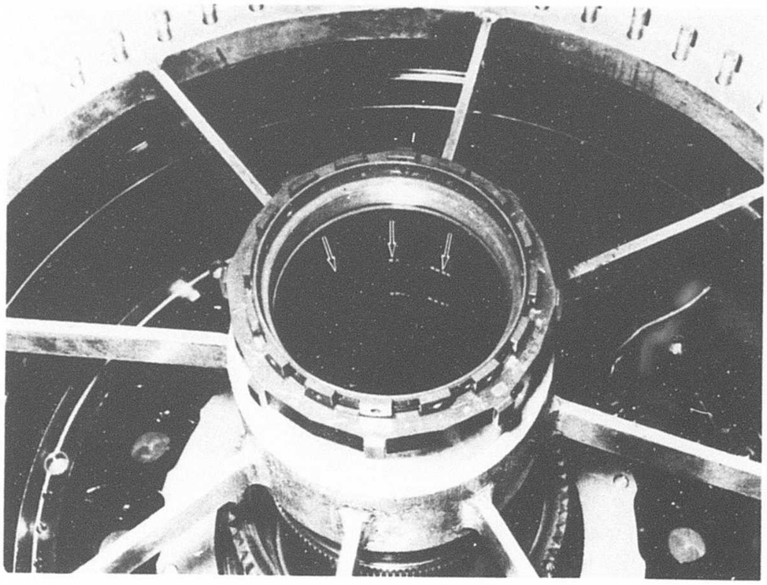

Figure 18. Main Rotor Shaft Roller Bearing Inner Race Temperature Indicators.

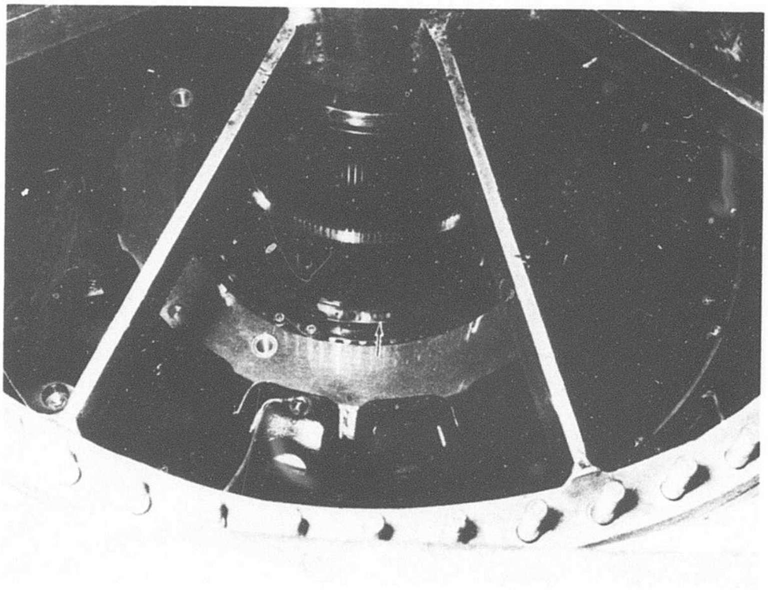

Figure 19. Main Bevel Gear Timken Bearing Inner Race Temperature Indicators.

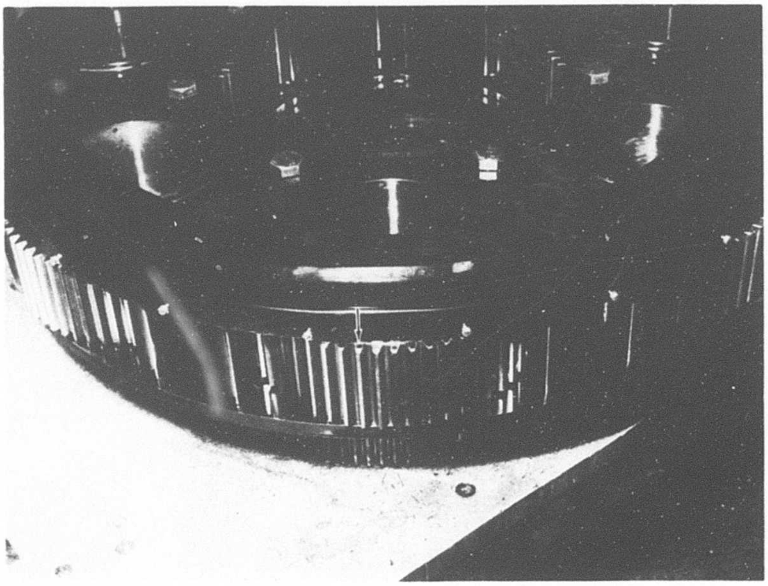

Figure 20. First-Stage Planetary Pinion Gear Tooth Temperature Indicators.

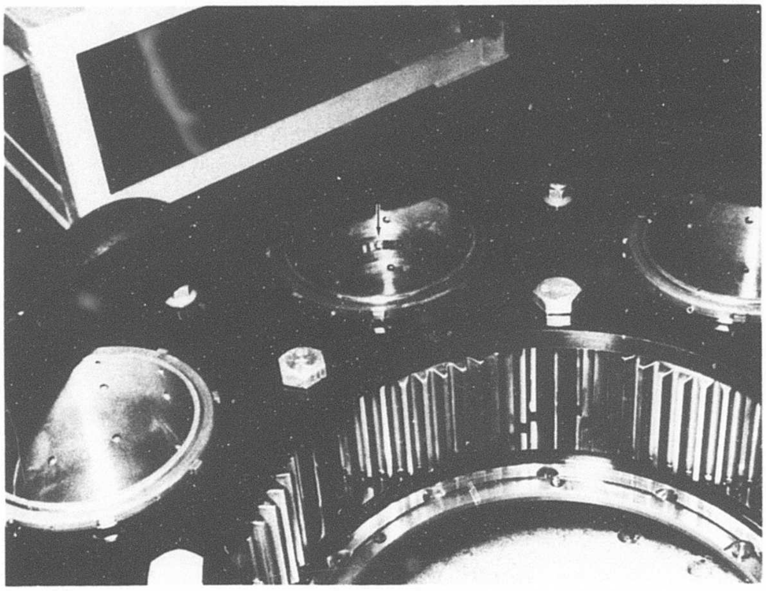

Figure 21. First-Stage Planetary Pinion Roller Bearing Inner Race Temperature Indicators.

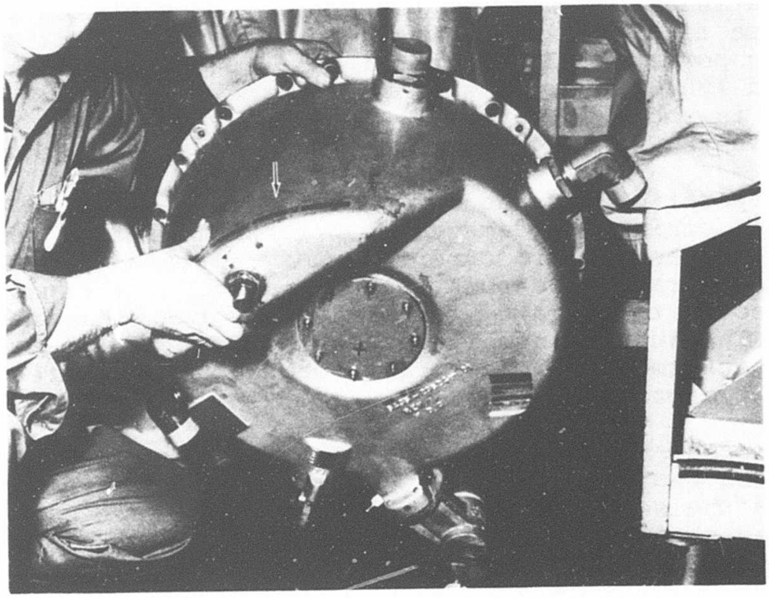

Figure 22. Sump With Bottom Temperature Indicators.

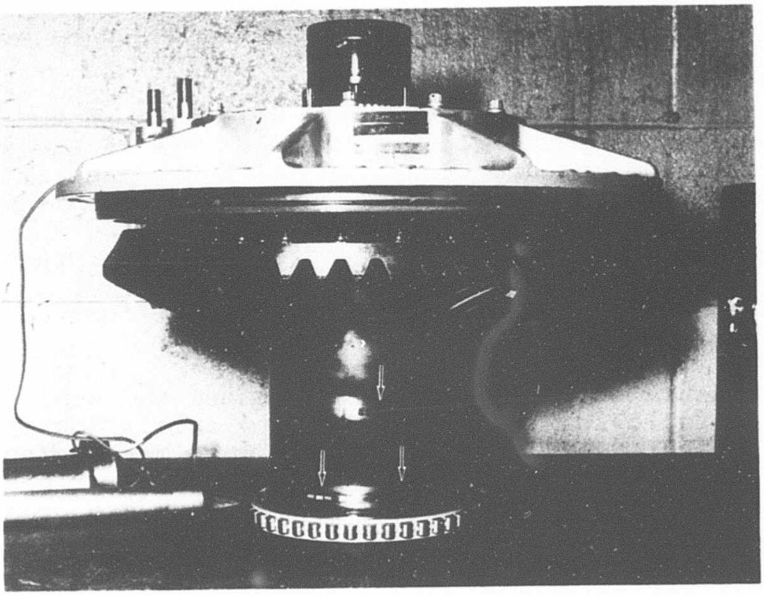

Figure 23. First-Stage Gear With Temperature Indicators.

INCREASED TEMPERATURE TESTS

After a satisfactory warm-up and run-in, each of the increased temperature test conditions was conducted at the maximum rated continuous power of 3300 hp per input, 600 hp tail takeoff power, and 100% speed. A summary of each stabilized test condition is shown in Table V. Internal and housing thermal maps for Tests 2 through 4 are shown in Figures 24 through 29.

During preparation for the second test, the left-hand first-stage input pinion was damaged when the temperature control unit of the oven used to cure the epoxy coating over the internal temperature sensors malfunctioned. The pinion had been subjected to elevated temperatures for a sustained period of time. The input assembly was replaced. The replacement assembly performed satisfactorily throughout the three increased temperature tests.

During the post-test inspection following the second test, it was observed that four thrust washers and four planetary pinions in the second-stage planetary system were scored. It is believed that decreased clearance between the planetary pinion and thrust washer caused by the material used to cover the temperature indicators on the pinions accidently getting between the pinion and the thrust washer contributed to the scoring as an abrasive between the washer and gear. The epoxy material acts as an abrasive on the surface of the thrust washer, which is lead-plated bronze material, and leads to rapid deterioration. The planetary assembly was reassembled with the damaged thrust washers replaced. The damaged pinions were ground slightly to blend the scoring.

Difficulties were experienced during all tests in measuring thermal expansion of the housing using LVDT's as the sensors. Test stand vibrations and bracketry stiffness made it difficult to interpret data from the first two tests or resulted in a loosening of the bond between the gearbox housing and the LVDT probe and a subsequent loss of measurement. The brackets were modified and eased the problem to some degree, but an additional method of measurement was sought to obtain more accurate data.

A direct measurement system using a trammel and scale was implemented following the second test to obtain housing thermal expansion measurements. Locations for such measurements are shown in Figure 30. Results for thermal expansion measurements obtained with both the LVDT's and trammel bar are presented in Table VI. The mean of the measured housing thermal expansion coefficient values is 16.8×10^{-6} $({}^{\circ}F)^{-1}$. This value is within 5% of the handbook* value of 16.0×10^{-6} $({}^{\circ}F)^{-1}$.

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*Marks, Lionel S., MECHANICAL ENGINEERS' HANDBOOK, New York, McGraw-Hill Book Co. Inc., 1951, p. 609.

TABLE V. STABILIZED OPERATING PARAMETERS

Parameters		Test 1	Test 2	Test 3	Test 4
Left-Hand Input Power	(hp)	3300	3300	3300	3300
Right-Hand Input Power	(hp)	3300	3300	3300	3300
Tail Takeoff Power	(hp)	600	600	600	600
Speed	(%)	100	100	100	100
Oil-In Temp	(°F)	160	180	250	300
Oil-Out Temp	(°F)	242	280	325	372
Oil Pressure, Pump	(psi)	62	61	66	69
Oil Pressure, Last Jet	(psi)	47	47	50	53
Oil Flow	(gpm)	19.9	19.8	19.5	20.6

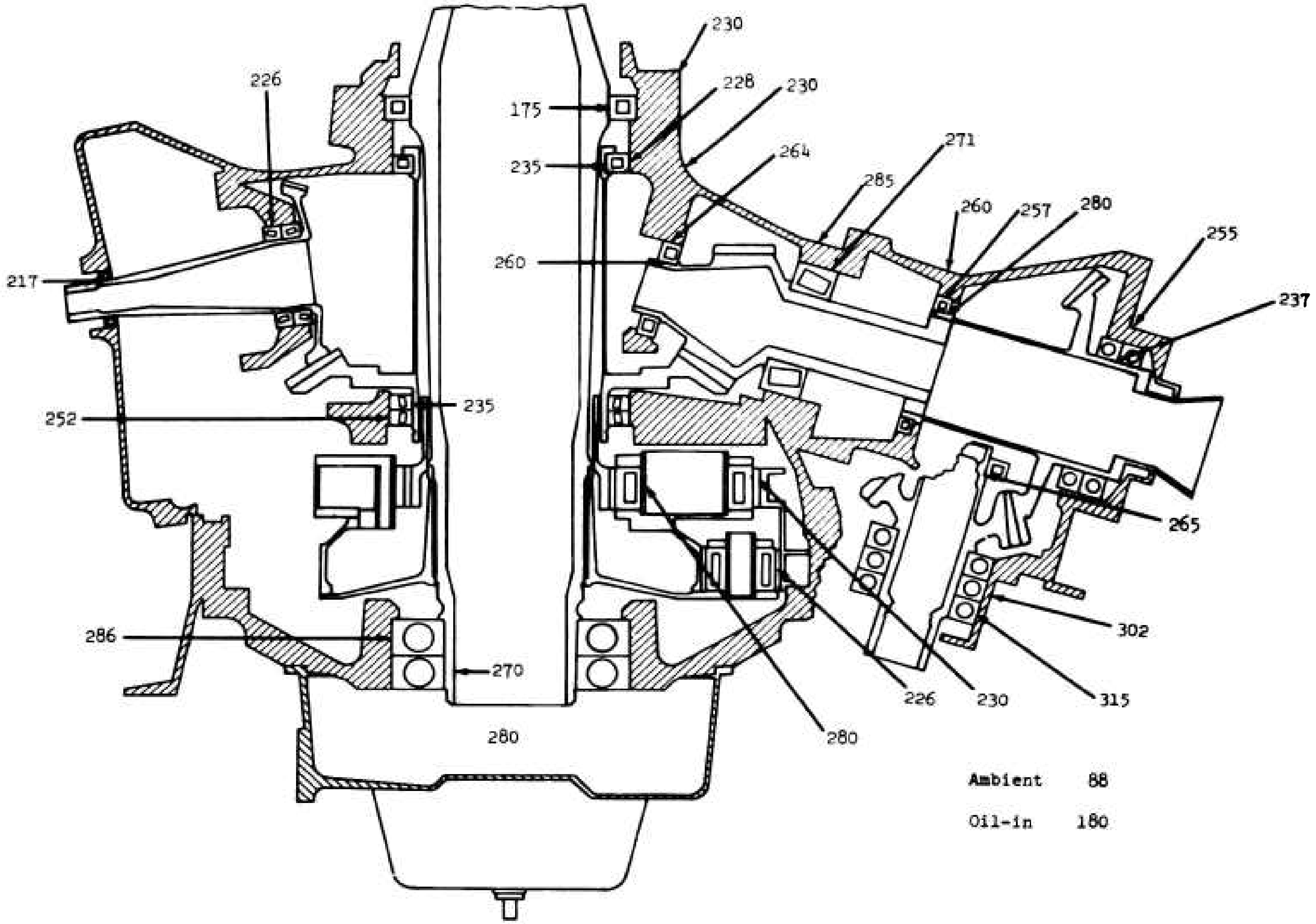


Figure 24. Thermal Map, Internal, Test 2.

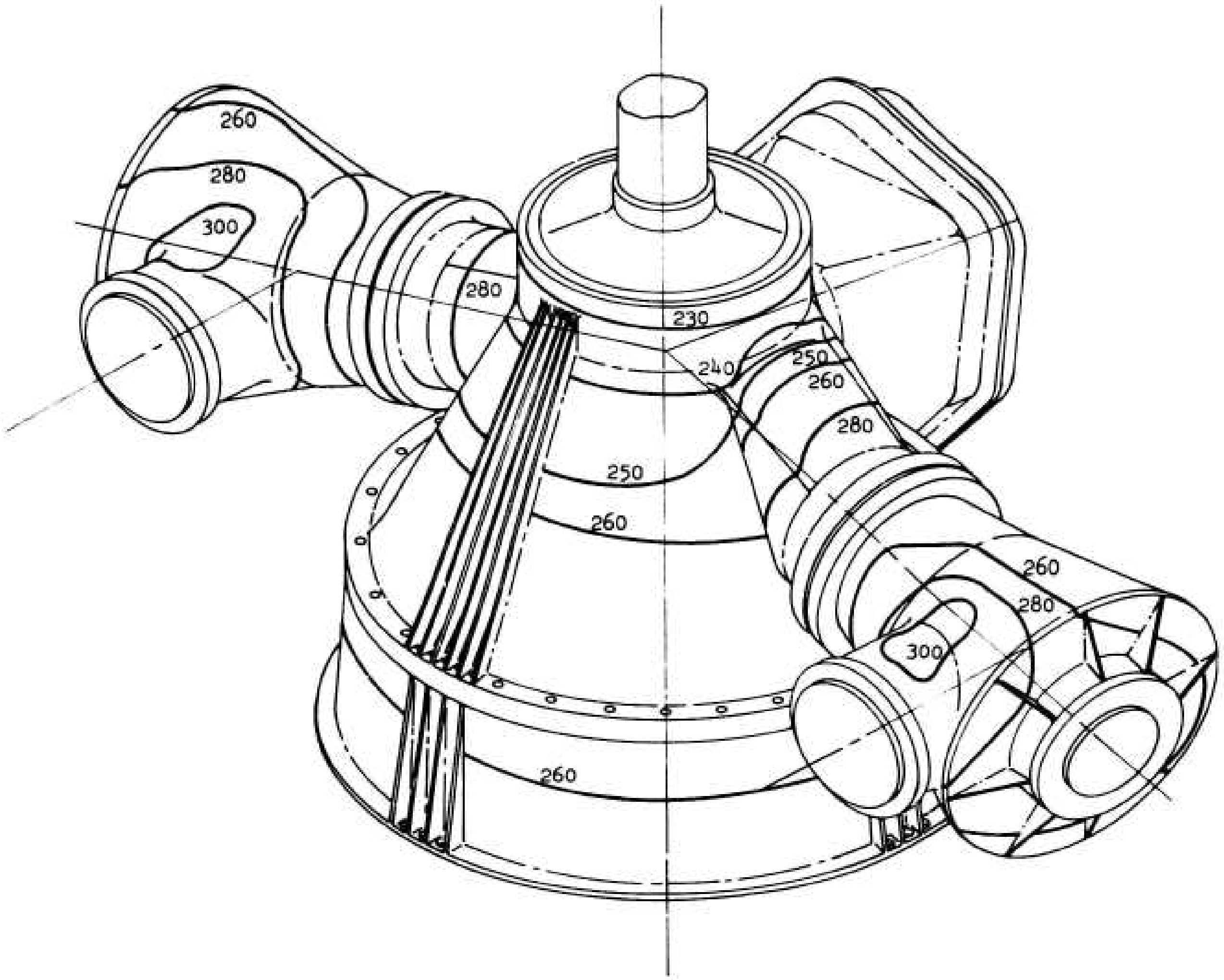


Figure 25. Thermal Map, External, Test 2.

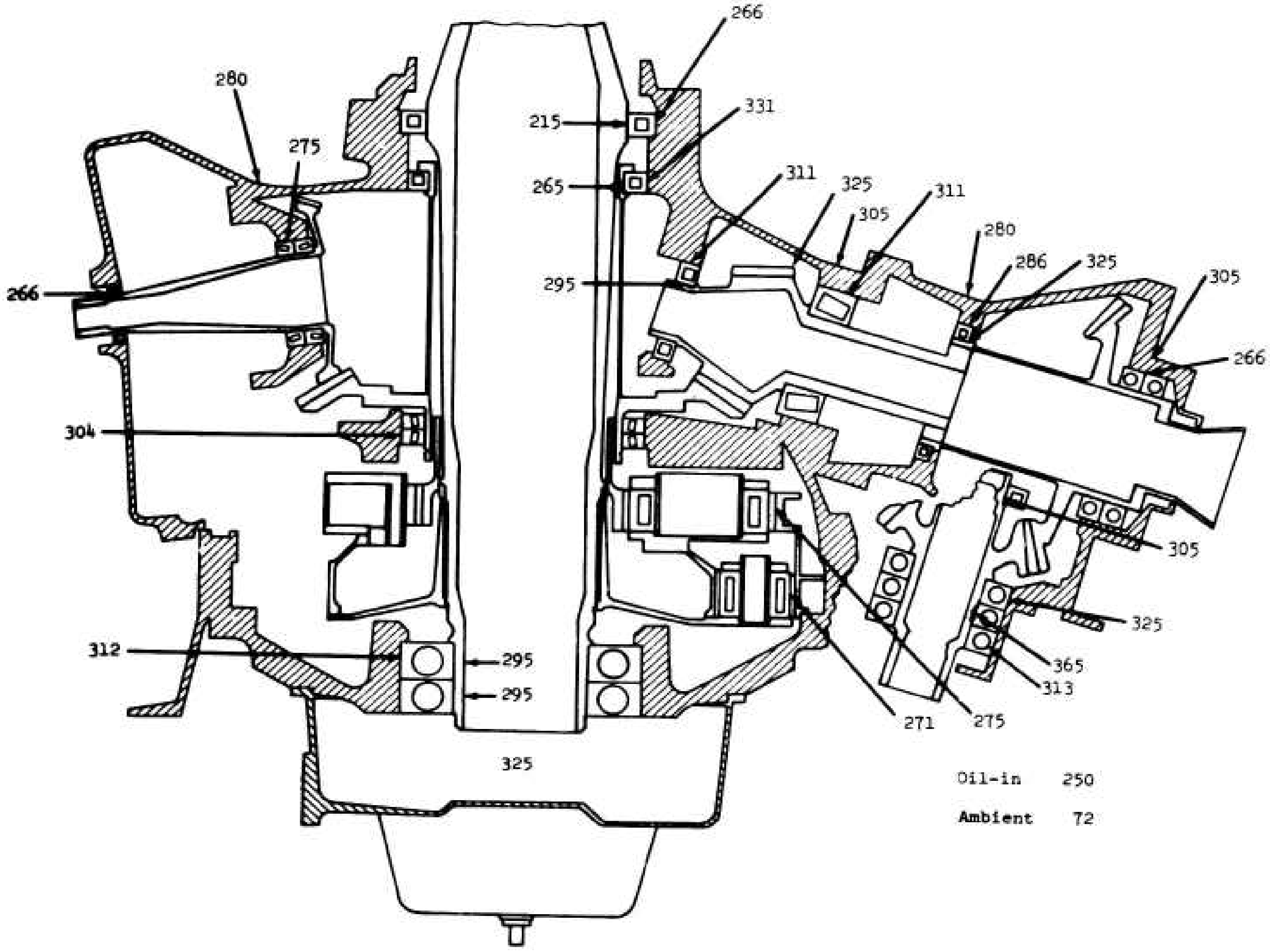


Figure 26. Thermal Map, Internal, Test 3.

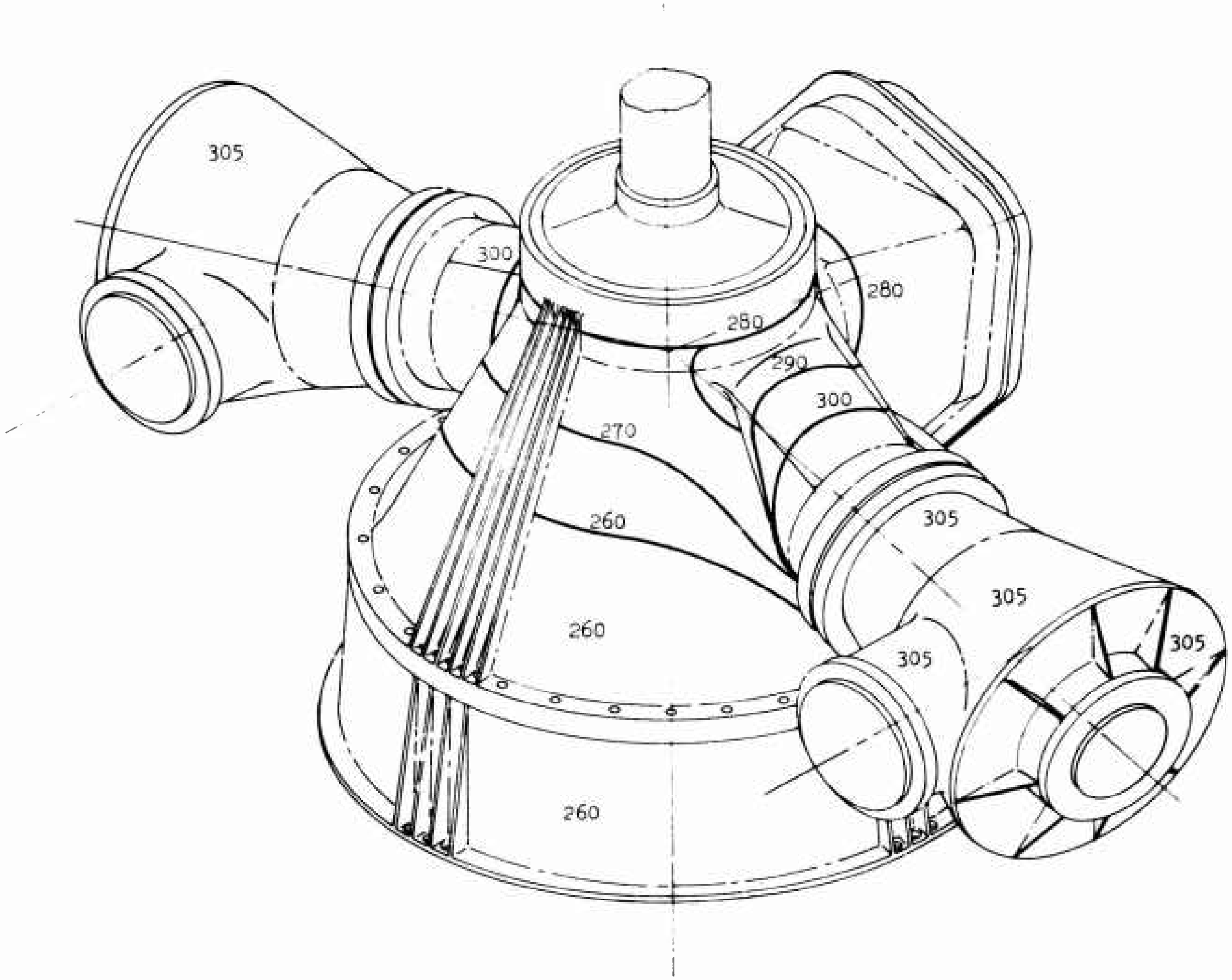
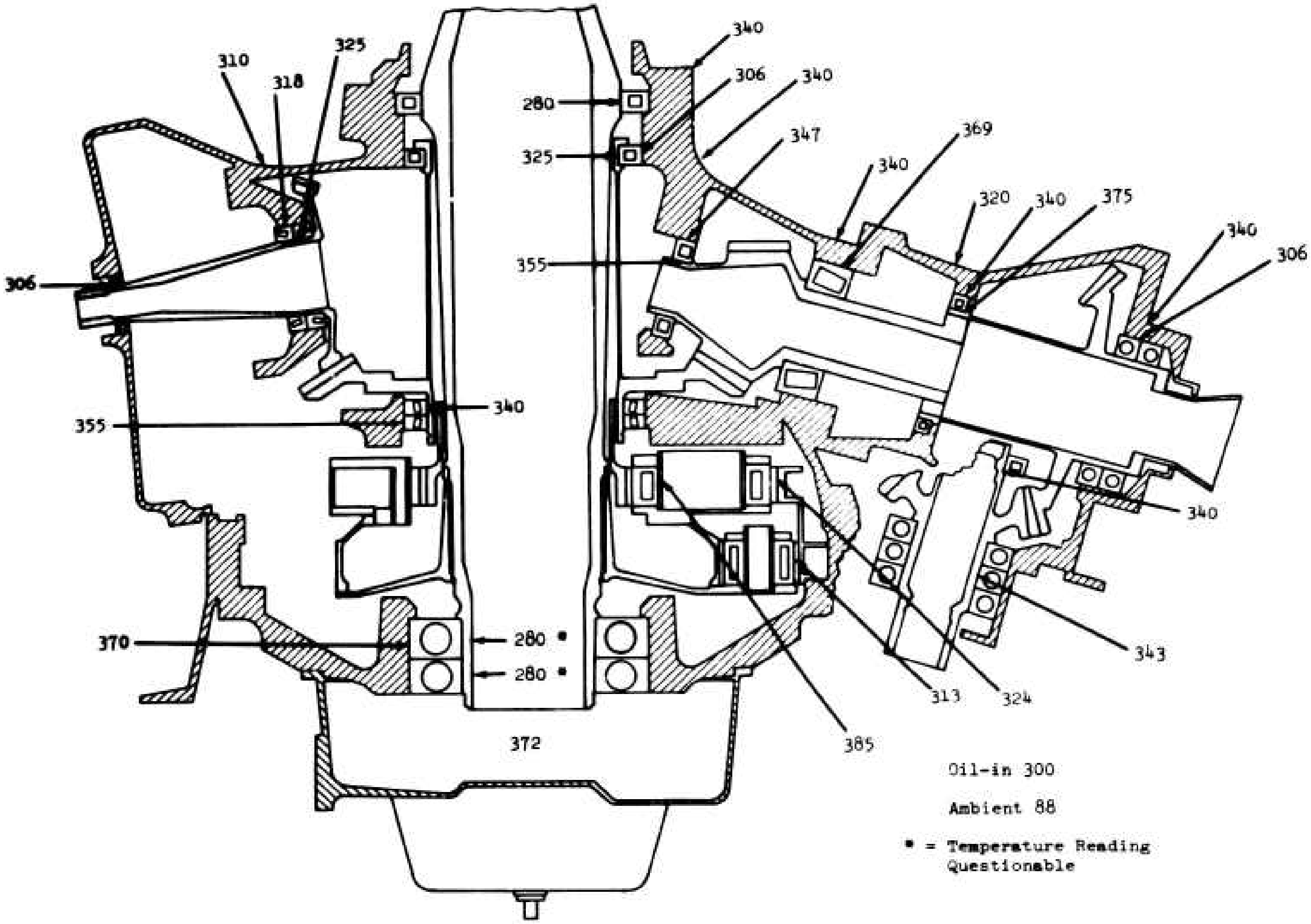


Figure 27. Thermal Map, External, Test 3.



Oil-in 300

Ambient 88

* = Temperature Reading Questionable

Figure 28. Thermal Map, Internal, Test 4.

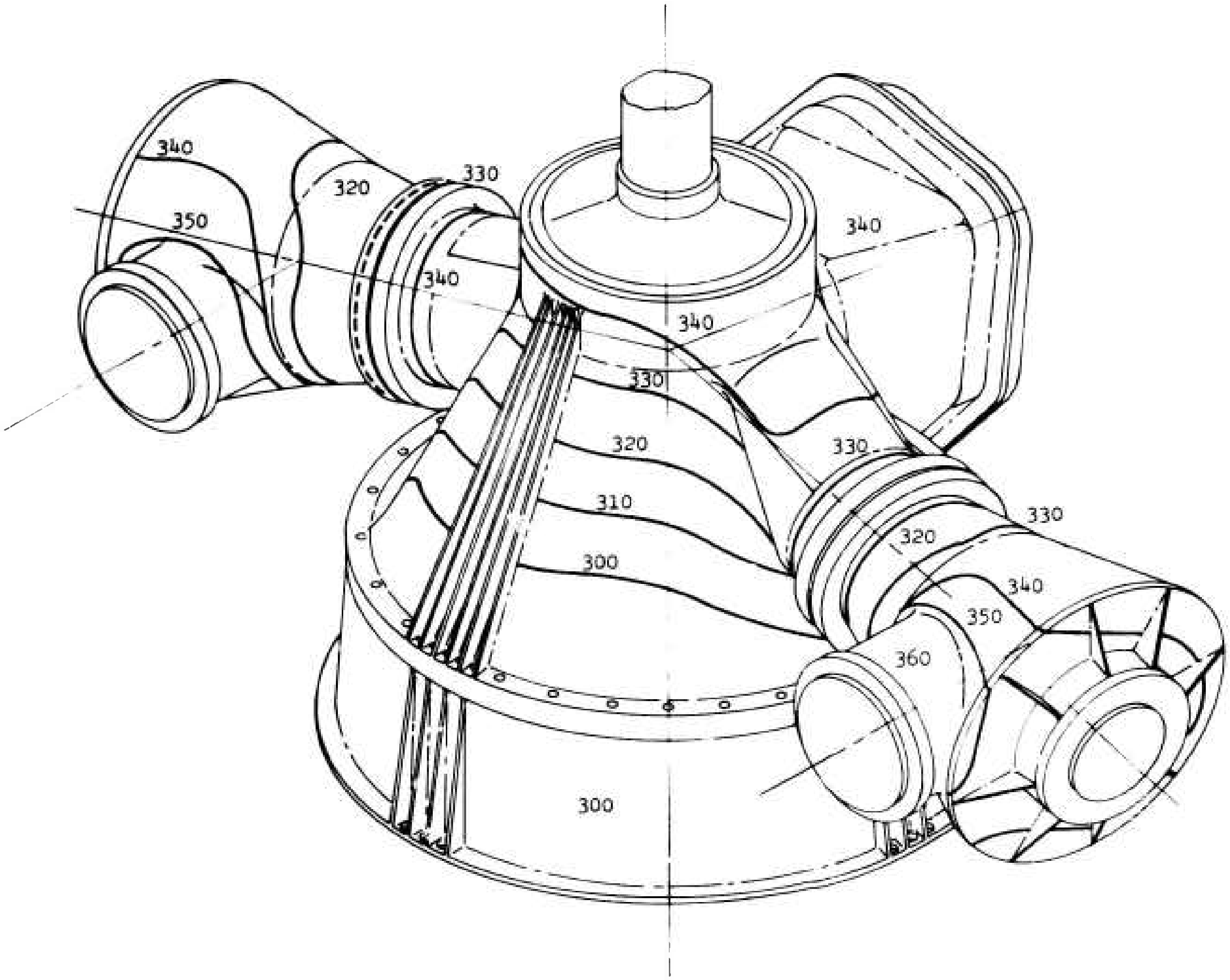


Figure 29. Thermal Map, External, Test 4.

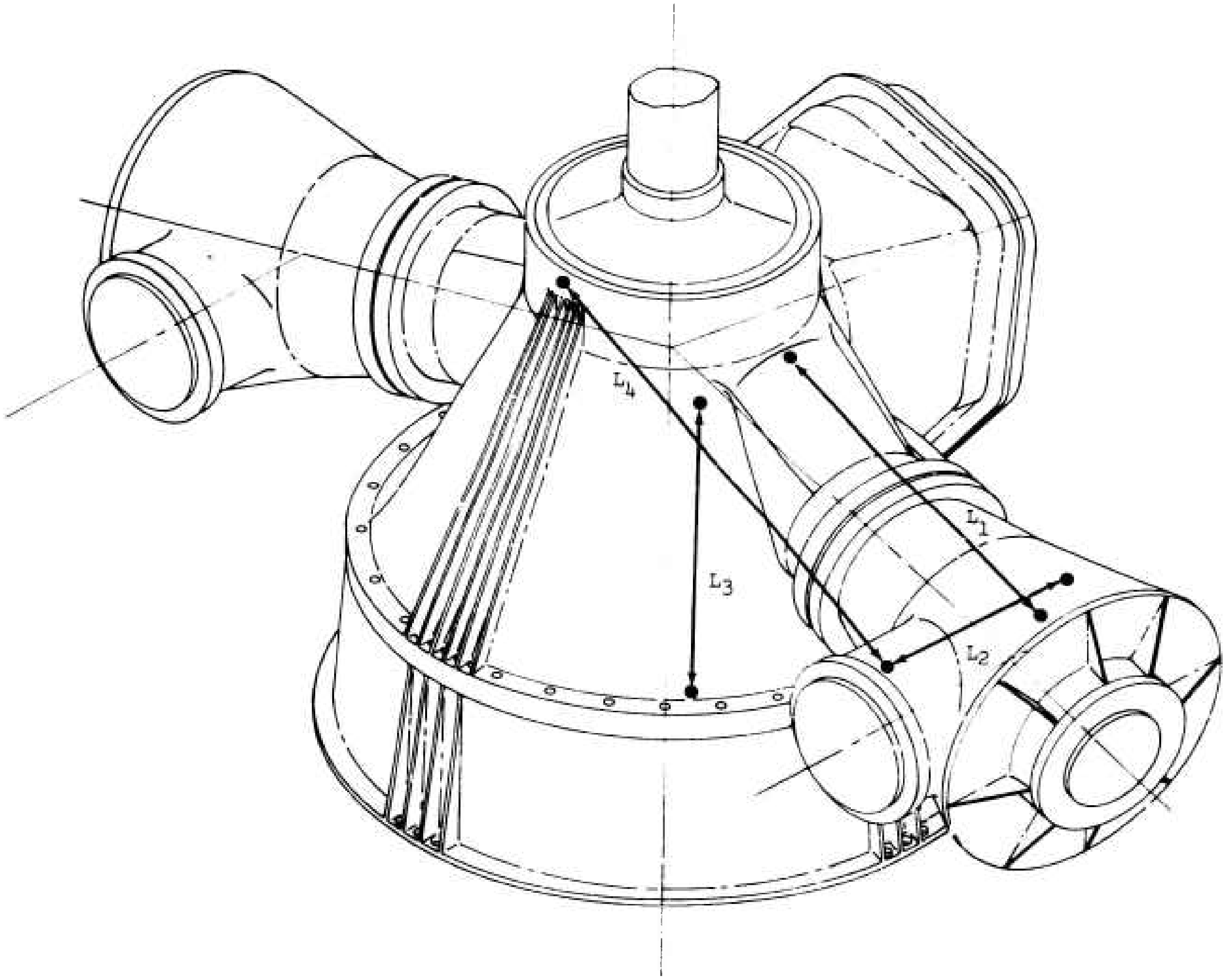


Figure 30. Trammel Measurement Locations.

TABLE VI. THERMAL EXPANSION MEASUREMENTS AND DATA REDUCTIONS

Parameter	L_o	L	$L-L_o$	T	T_o	ΔT	$\alpha = \frac{L-L_o}{L\,\Delta T}$
Test 3							
Input Section, Lateral	25.337	25.405	.068	212	60	162	16.6×10^{-6}
Input Section, Longitudinal	18.202	18.268	.064	276	60	162	16.8×10^{-6}
Main Housing, Vertical	24.375	24.450	.075	212	60	162	19.0×10^{-6}
Nominal Input Centerlines 1/2 Width, Lateral	26.649	26.722	.073	212	60	162	16.9×10^{-6}
Input Width, Lateral	60.375	60.538	.163	212	60	162	16.6×10^{-6}
Main Housing, Lateral	46.879	47.013	.134	212	60	162	17.7×10^{-6}
Test 4							
Input Section, Lateral	25.340	25.396	.056	200	65	135	16.4×10^{-6}
Input Section, Longitudinal	18.195	18.245	.050	200	65	135	20.4×10^{-6}
Main Housing, Vertical	24.380	24.440	.060	200	65	135	18.2×10^{-6}
First-Stage Input Pinion Housing	26.641	26.693	.052	185	65	120	10.6×10^{-6}
Input Width, Lateral	60.381	60.503	.122	185	65	120	16.8×10^{-6}
Main Housing, Lateral	16.884	46.984	.100	200	65	135	15.8×10^{-6}

Temperatures recorded on the pinion and bevel gears with the handheld probe at the completion of tests 3 and 4 disclosed good correlation with the ΔT between the gears and surrounding bearing temperatures found in the baseline test. The temperature sensors on the pinion and bevel gears were lost during these tests; but based on the probe data, it appears that the gear tooth temperatures reached approximately 330°F at the first-stage and second-stage meshes during test 3 and approximately 380°F on both meshes during test 4.

In order to obtain additional data and to substantiate the temperature data already obtained on the gearbox housing, Sikorsky Aircraft funded an internal research and development program to obtain the use of a Thermovision® measurement system manufactured by AGA Industries to permit an infrared study of the test gearbox housing. The infrared signature of the test gearbox was obtained during the fourth test run. The baseline condition from the initial test in the series was duplicated, and a series of color and black-and-white photos was taken of the Thermovision® cathode ray tube display. Isothermic photos of the baseline condition are shown in Figures 31 through 35. This data agrees well with external tape and thermocouple measurements made during test 1. Further, by providing real-time external housing temperature monitoring, it assured that the housing temperatures obtained by the tape sensors were accurate and were not affected by possible oil contamination or heat soak-back conditions. This real-time monitoring also established the absence of any hot or cold spots between designated tape locations on the housing. Isothermic photographs of the elevated temperatures of test 4 are shown in Figures 36 through 39. Due to a loss of coolant in the infrared sensor, Figures 36 through 39 were actually photographed as the gearbox completed the cooling run. Cooling of the gearbox at this time had been relatively uniform and thus the photographs accurately depict the isotherms as measured by the thermocouples and temperature tapes at the maximum temperatures of test 4.

Inspection of the gearbox components after test 2 disclosed no abnormalities other than the thrust washer problem previously described. The gear patterns on all gears were satisfactory and all bearings were in good condition. After test 3, slight evidence of scoring was detected on both the first-stage and second-stage input pinion and bevel gears. The bearings in the planetary showed slight discoloration due to temperature. At the completion of test 4, the scoring on the inputs was more pronounced but did not result in an unsatisfactory pattern. As in the previous test, the planetary bearings showed more evidence of heat discoloration but rotated freely by hand.

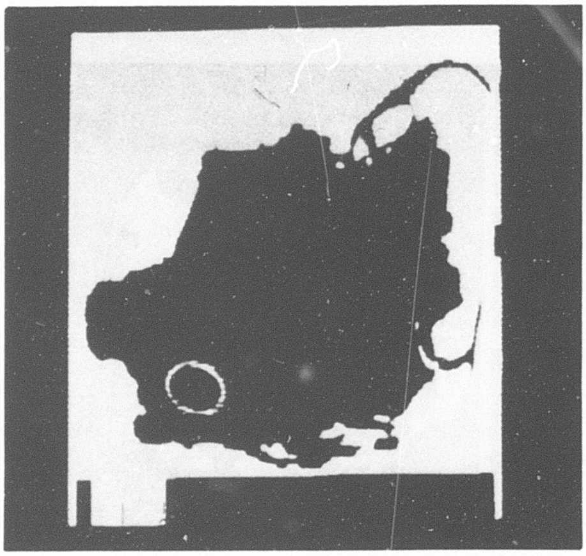


Figure 31. CH-54B Main Gearbox Infrared Photo, Baseline Condition; White Area Indicates Temperatures Less Than 86°F.

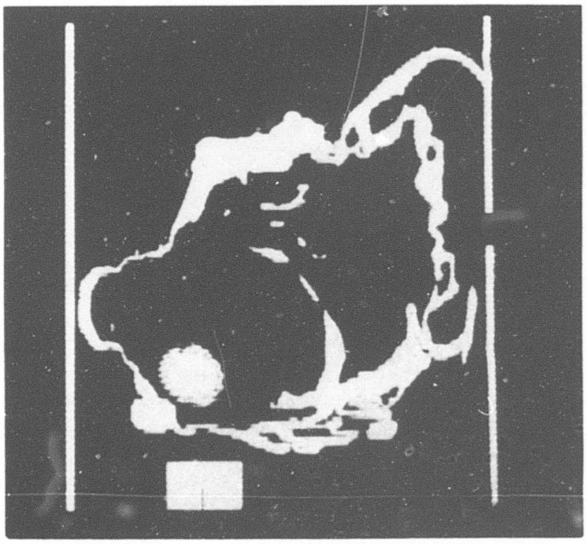


Figure 32. CH-54B Main Gearbox Infrared Photo, Baseline Condition; White Area Indicates Temperatures Between 86° and 140°F.

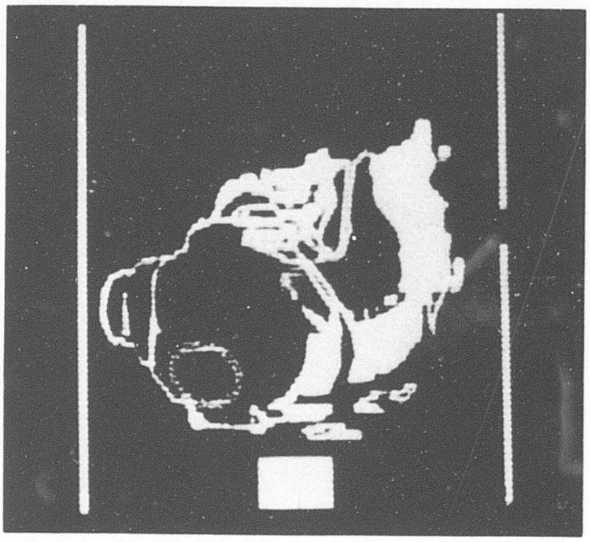


Figure 33. CH-54B Main Gearbox Infrared Photo, Baseline Condition; White Area Indicates Temperatures Between 140° and 167°F.

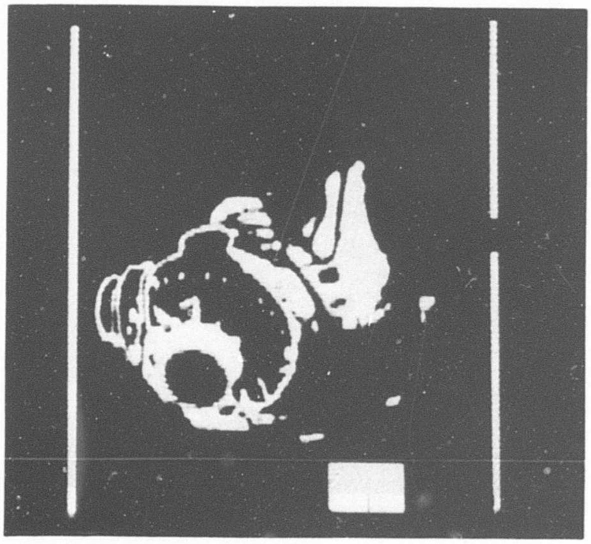


Figure 34. CH-54B Main Gearbox Infrared Photo, Baseline Condition; White Area Indicates Temperatures Between 167°and 194°F.

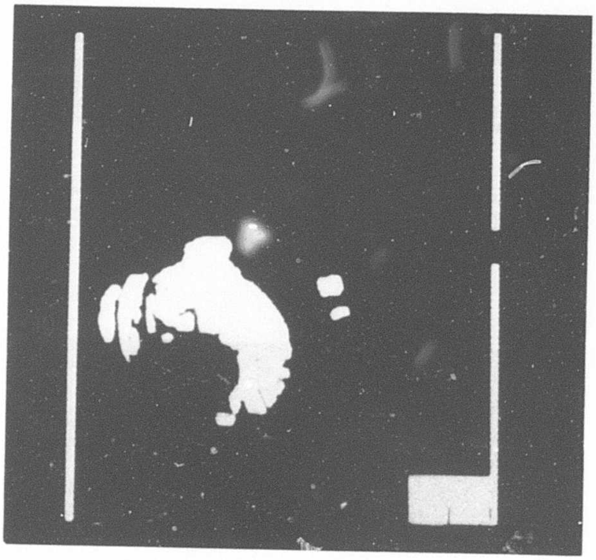


Figure 35. CH-54B Main Gearbox Infrared Photo, Baseline Condition; White Area Indicates Temperatures Between 194° and 212°F.

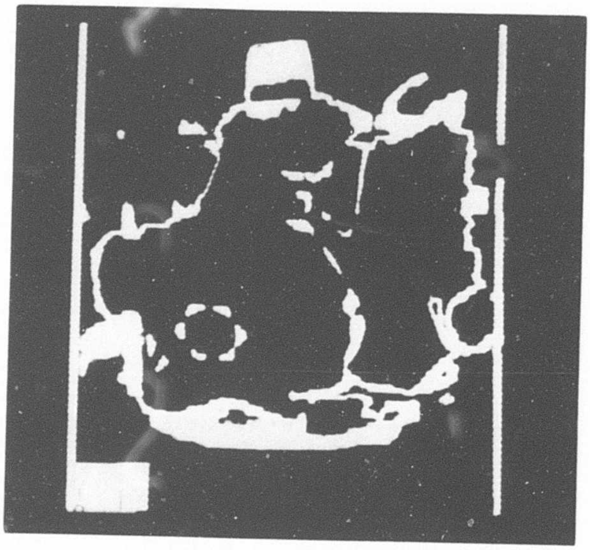


Figure 36. CH-54B Main Gearbox, Elevated Temperature Condition; White Area Indicates Temperatures Less Than 251°F.

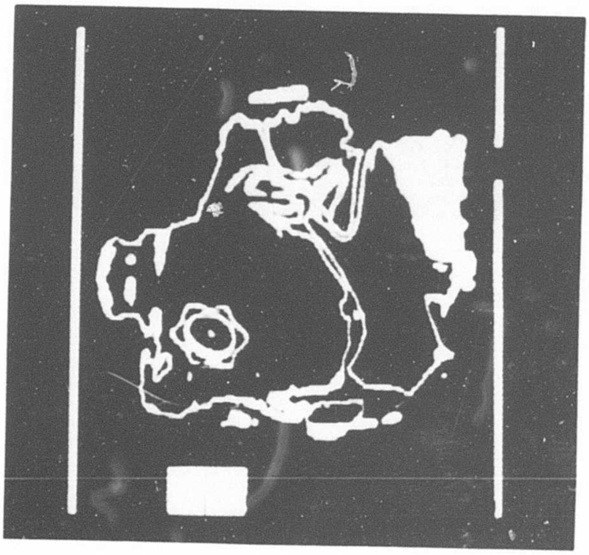


Figure 37. CH-54B Main Gearbox, Elevated Temperature Condition; White Area Indicates Temperatures Between 251°and 307°F.

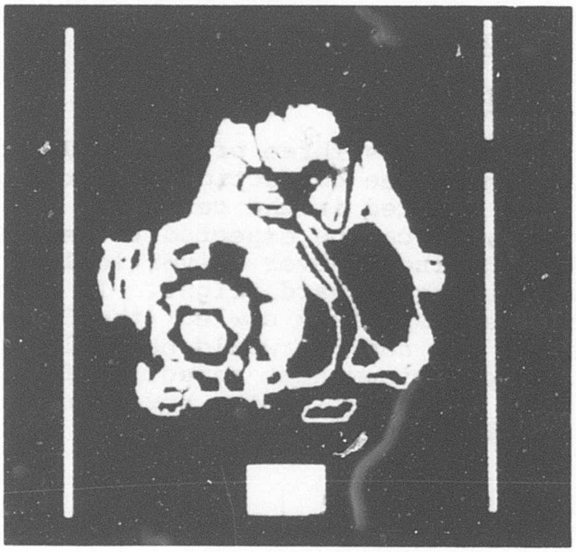


Figure 38. CH-54B Main Gearbox, Elevated Temperature Condition; White Area Indicates Temperatures Between 307°and 341°F.

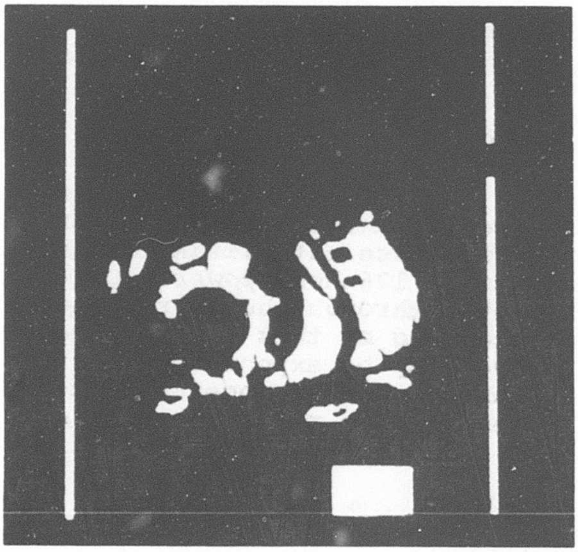


Figure 39. CH-54B Main Gearbox, Elevated Temperature Condition; White Area Indicates Temperatures Between 341°and 367°F.

DISCUSSION OF RESULTS

THERMAL DATA ANALYSIS

The CH-54B main gearbox has three primary modes of heat rejection: oil cooling, free convection, and radiation. Since the main gearbox is located in the center of the "eye" of the main rotor downwash, it can be expected to receive negligible forced air cooling during a hover or vertical ascent and only a slight increase during forward flight. In an application where the gearbox is completely cowled (the CH-54B is not cowled), the forced air cooling would be small even during forward flight. The maximum heat rejection from the gearbox would normally take place during the hover or vertical ascent condition when maximum torque is transmitted through the gearbox.

Heat Rejection

The total heat rejected from the gearbox is

$$Q = FHP = Q_{EX} + Q_C + Q_R \tag{9}$$

where

FHP = total energy dissipated (frictional horsepower)

Q_{EX} = heat rejected through the lubrication heat exchanger (oil cooler)

Q_C = heat convected to the surrounding air

Q_R = heat radiated to the surrounding air

Lubrication System Cooler

From previous tests conducted at Sikorsky Aircraft, the total frictional horsepower in the CH-54B main gearbox under conditions similar to those established during the baseline test in this program is 126 horsepower. Of this total power, 83 percent is rejected through the lubrication system cooler. Based on previous testing of this and other gearboxes, the frictional horsepower may be expected to decrease by approximately 10% as the gearbox operating temperature is raised through a temperature range comparable to those experienced during this test unless lubrication becomes marginal.

Convection and Radiation

The heat convected from a body to the surrounding air is given by

$$Q_c = hA(T - T_A) \tag{10}$$

where h = heat transfer coefficient
A = applicable surface area
T = skin temperature
T_A = temperature of the ambient air

The CH-54B gearbox surface can be divided into three primary zones:

- The main housing cone and rear cover section
- The high-speed input sections
- The gearbox sump

The total heat rejected from the gearbox housing through convection is thus

$$Q_C = Q_{CM} + Q_{CI} + Q_{CS} \quad (11)$$

where Q_{CM} = heat convected through skin of main cone and rear cover section
Q_{CI} = heat convected through skin of input sections
Q_{CS} = heat convected through skin of sump cover

As installed in the aircraft, the gearbox sump is surrounded by other components, and thus the heat it convects to the air can be considered negligible. In the test stand, however, the sump is exposed and must therefore be considered when making heat loss calculations based on test stand data. Previous tests (Reference 1) have shown the effective heat transfer coefficient of the CH-54A main gearbox housing to be

$$h = .108 \qquad \text{Btu/(ft}^2\text{-min-°F)}$$

Since the housing of the CH-54B main gearbox is identical to that of the CH-54A, the same value of h will be used in the calculations of this study.

The affected areas of each housing zone are given in Table VII. When equations (10) and (11) are combined, the resulting expression for gearbox convection is

$$Q_C = hA_M(T_M - T_A) + hA_I(T_I - T_A) + hA_S(T_S - T_A)$$

where T_M, T_I, T_S and T_A are mean temperatures of the main housing surface, input section housing surface, and sump cover surface and ambient air respectively.

TABLE VII. MAIN GEARBOX HOUSING SECTION SURFACE AREAS

Zone	Symbol	Area (ft^2)
Main Cone	M	28.7
Inputs (total)	I	18.4
Sump	S	12.6

The heat radiated by a body is given by

$$Q = A \epsilon \sigma \left(T^4 - T_A^4\right) \tag{13}$$

where A = effective surface area
ϵ = surface emissivity
σ = Stefan-Boltzmann constant
= 2.88×10^{-11} Btu/ (ft^2-min-°F)
T = absolute body temperature
T_A = absolute ambient air temperature

The total heat radiated by the gearbox is thus

$$Q_R = Q_{RM} + Q_{RS} + Q_{RI} \tag{14}$$

where Q_{RM} = heat radiated by main housing section
Q_{RI} = heat radiated by input sections
Q_{RS} = heat radiated by sump cover

The combining of equations (13) and (14) yields the following expression for heat radiated by the gearbox:

$$Q_R = A_M \epsilon \sigma \left(T_M^4 - T_A^4\right) + A_S \epsilon \sigma \left(T_S^4 + T_A^4\right) + A_I \epsilon \sigma \left(T_I^4 - T_A\right) \tag{15}$$

The CH-54B gearbox housings and covers are painted with an olive-drab flat matte lacquer which has an emissivity of 0.60. The gearbox used for this test was painted with a gray lacquer, and the emissivity, as measured by the Thermovision®, was approximately 0.80.

The heat rejected through the oil cooler is given by

$$Q_{EX} = \dot{m} c_p \left(T_o - T_i\right) \tag{16}$$

where $\dot{m}$ = gearbox oil flow
c_p = lube oil specific heat
T_o = oil-out temperature
T_i = oil-in temperature

It is difficult to evaluate Q_{EX} using equation (16), however, because the specific heat and density of the lube oil are not constants but rather functions of many parameters.

The heat rejected through the oil cooler can be found indirectly by rearranging equation (9) as follows:

$$Q_{EX} = FHP - (Q_C + Q_R) \tag{17}$$

Using the calculated values of Q_C and Q_R and the known friction HP, Q_{EX} can be calculated by equation 17. The parameter values for the succeeding equations are summarized in Table VIII.

TABLE VIII. GEARBOX COOLING PERFORMANCE PARAMETERS

Symbol	Parameter	Value
h	Heat transfer coefficient	.108 Btu/(ft^2-min-°F)
σ	Stefan-Boltzmann constant	2.88×10^{-11} Btu/(ft^2-min-°R^4)
ϵ	Gearbox skin emissivity	0.80

The mean skin temperatures used in the convection and radiation calculations were taken from the skin thermal maps, Figures 17, 25, 27 and 29. These mean skin temperatures are summarized in Table IX. When the parameter and variable values from Tables VII, VIII, and IX are substituted into equations (9), (12), (15), and (17), the resulting heat flow values are as shown in Table X. A quantitative comparison of heat flow through each major heat rejection mechanism is shown in Figure 40 as a function of stabilized oil-out temperatures.

Test experience shows that attempting to calculate the heat rejected by the gearbox through the oil cooler using the oil-in and oil-out temperatures, oil flow rate, and manufacturer's data for the specific heat and specific gravity of the lube oil can result in significant errors due to churning of the oil. Churning of the oil introduces air into the oil, which reduces its specific gravity. To determine the effects of this aeration on the oil density, equation (16) may be rewritten as

$$Q_{EX} = q \rho S \underline{c}_p (T_o - T_i)$$

where q = lube oil flow, gpm
ρ = density of water, lb/gal.
S = lube oil specific gravity

This equation may in turn be rearranged to express the specific gravity of the oil as

$$S = \frac{Q_{EX}}{q \rho c_p (T_o - T_i)} \tag{18}$$

TABLE IX. MEAN SKIN TEMPERATURES

Symbol	Location	Temperature (°F)	Temperature (°R)
Test 1			
T_A	Ambient	82	542
T_M	Main Housing Section	180	640
T_I	Input Section	210	670
T_S	Sump Assembly	243	703
Test 2			
T_A	Ambient	88	548
T_M	Main Housing Section	260	720
T_I	Input Section	280	740
T_S	Sump Assembly	280	740
Test 3			
T_A	Ambient	72	[illegible]
T_M	Main Housing Section	260	[illegible]
T_I	Input Section	305	765
T_S	Sump Assembly	300	760
Test 4			
T_A	Ambient	88	548
T_M	Main Housing Section	310	770
T_I	Input Section	345	805
T_S	Sump Assembly	320	780

TABLE X. GEARBOX HEAT FLOW

	Heat Flow		
Heat Path	HP	Btu/min	% Total Dissipated
Test 1			
Main Housing, Convection	7.2	304	5.7
Input Sections, Convection	6.0	254	4.8
Sump Cover, Convection	5.2	219	4.1
Total Convection	18.4	777	14.6
Main Housing, Radiation	1.3	52.5	1.0
Input Sections, Radiation	1.2	47.6	.9
Sump Cover, Radiation	1.0	44.7	.8
Total Radiation	3.5	144.9	2.7
Oil Heat Exchanger	104.1	4420	83.1
Total, Test 1	126	5342	100
Test 2			
Main Housing, Convection	12.6	533	10.3
Input Sections, Convection	9.0	381	7.4
Sump Cover, Convection	6.2	261	5.0
Total Convection	27.7	175	22.7
Main Housing, Radiation	2.7	116	2.2
Input Sections, Radiation	2.1	87	1.7
Sump Cover, Radiation	1.4	60	1.2
Total Radiation	6.2	263	5.1
Oil Heat Exchanger	88.1	3735	72.2
Total, Test 2	122	5173	100
Test 3			
Main Housing, Convection	13.7	583	11.8
Input Sections, Convection	10.9	463	9.3
Sump Cover, Convection	7.3	310	6.2
Total Convection	32.0	1356	27.3
Main Housing, Radiation	2.9	122	2.5
Input Sections, Radiation	2.6	108	2.2
Sump, Radiation	1.7	74	1.5
Total Radiation	7.2	304	6.2
Oil Heat Exchanger	77.8	3301	66.5
Total, Test 3	117	4970	99.0

TABLE X. Continued

Heat Path	Heat Flow		
	HP	Btu/min	% Total Dissipated
Test 4			
Main Housing, Convection	16.2	688	14.4
Input Sections, Convection	12.0	511	10.7
Sump Cover, Convection	7.4	316	6.6
Total Convection	35.7	1515	31.7
Main Housing, Radiation	4.0	169	3.5
Input Sections, Radiation	3.3	136	2.8
Sump Cover, Radiation	1.8	79	1.6
Total Radiation	9.1	384	7.9
Oil Heat Exchanger	68.2	2893	60.4
Total, Test 4	113	4792	100.1

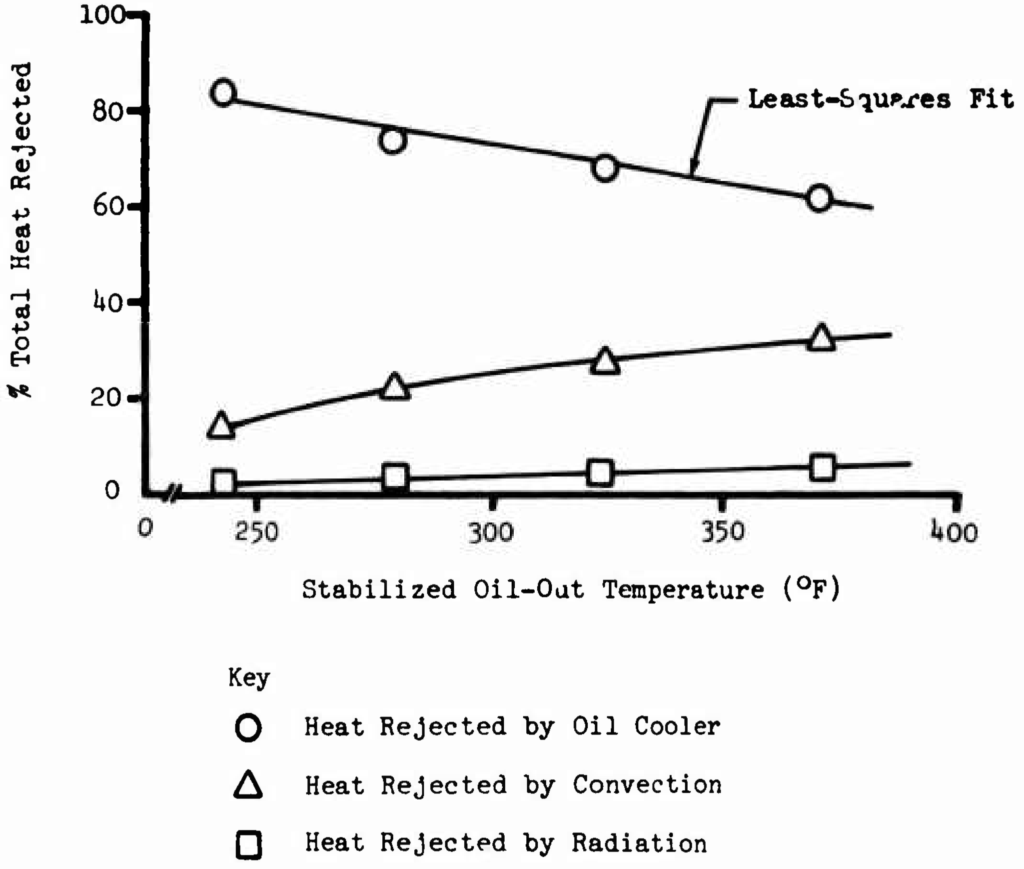


Figure 40. Heat Rejection Mechanisms vs Temperature.

To illustrate the magnitude of variation in specific gravity due to aeration, the manufacturer's data for nonaerated MIL-L-7808G list S as .90. The value for S calculated from test data using equation (18) is .63.

The curve representing heat rejected by the oil cooler in Figure 40 is the result of a linear least-squares fit to the data points. A linear extrapolation of this line yields a projected stabilized oil-out temperature of 739°F for the condition where no heat is rejected by the oil cooler. This projection is an extrapolation of the data and is not intended as a prediction of results for some future test of this type. Before a stabilized temperature in excess of 700°F would be reached, changes would occur in material properties of gearbox components and the lubricant itself, which would make this analysis invalid for such extreme temperatures.

Using Figure 40, a check can now be made of the predicted skin temperature values of Figure 5. For example, at an oil-out temperature of 325°F, the percentage of total heat rejected by the oil cooler is 77.8. From Figure 5 the projected skin temperature at this percentage is 260°F. The mean measured skin temperature is 283°F.

Limiting factors for elevated temperature operation include the following considerations. The strength, hardness, and surface wear characteristics of component materials in general degrade with increased temperature. Designs for gearboxes which will normally operate with temperatures comparable to those encountered in this test program must necessarily reevaluate contemporary material applications and consider alternatives. Probably a greater obstacle to achieving a gearbox capable of operating at such elevated temperatures is the limiting properties of the lubricant used. When operating at temperatures near the flash point of the lubricant, the probability of fire is increased. In addition, deterioration of the lubricant film can result in surface distress in both gears and bearings. Vaporization of the lubricant poses a more severe temperature limitation, however.

Significant oil vaporization can take place at temperatures below the oil flash point. Two direct results of this are:

- The oil film on components may vaporize, resulting in localized loss of lubrication. This would lead to a high wear condition, and the resulting increase in friction could result in a thermally unstable condition.

- A significant reduction in gearbox lubricant level caused by oil vaporization during extended periods of gearbox operation at elevated temperatures could result in unsatisfactory gearbox lubrication.

Currently used MIL-L-7808 and MIL-L-23699 lubricating oils have minimum flash points of 400°F and 475°F, respectively. At 400°F, up to 35 percent of the oil may be lost by evaporation within 6.5 hours using MIL-L-7808 oil. With MIL-L-23699 oil, the figure is 10 percent.

A possible alternative lubricant for high-temperature transmission operation is a polyphenyl ether which may be used at bulk temperatures up to 600°F. However, the use of this class of oil would present other drawbacks. Polyphenyl ethers have rather poor low-temperature properties. For most operation, a diluent would have to be added to the oil each time a cold start is made. In addition, the cost of this type of oil is presently 15 to 20 times more than that of the currently used lubricants.

The good agreement in total frictional power loss between that predicted by analysis and that measured during tests demonstrates that current analytical techniques are adequate in identifying heat sources within helicopter gearboxes. On this basis, substantiated by comparison with the internal thermal maps (Figures 15, 23, 25, and 27), it is believed that Table I accurately describes quantitatively the heat sources within the CH-54B main transmission. A summary of heat rejection paths is shown in Figure 41.

THERMAL EXPANSION DATA ANALYSIS

The thermal expansion data (Table VI) shows very good agreement with the data that would be predicted by using standard analytical techniques and the handbook value for magnesium alloy. On the basis of this agreement and the lack of any complicating mechanisms, it is believed that the deviation between measured and handbook values for the housing coefficient of expansion is more a product of imprecision in length measurement and establishment of an applicable mean skin temperature than a true difference between these coefficients. The main housing section is calculated to expand in the longitudinal direction an amount identical to the measured main housing lateral expansion included in Table VI since both measurements are, in fact, radial expansion measurements.

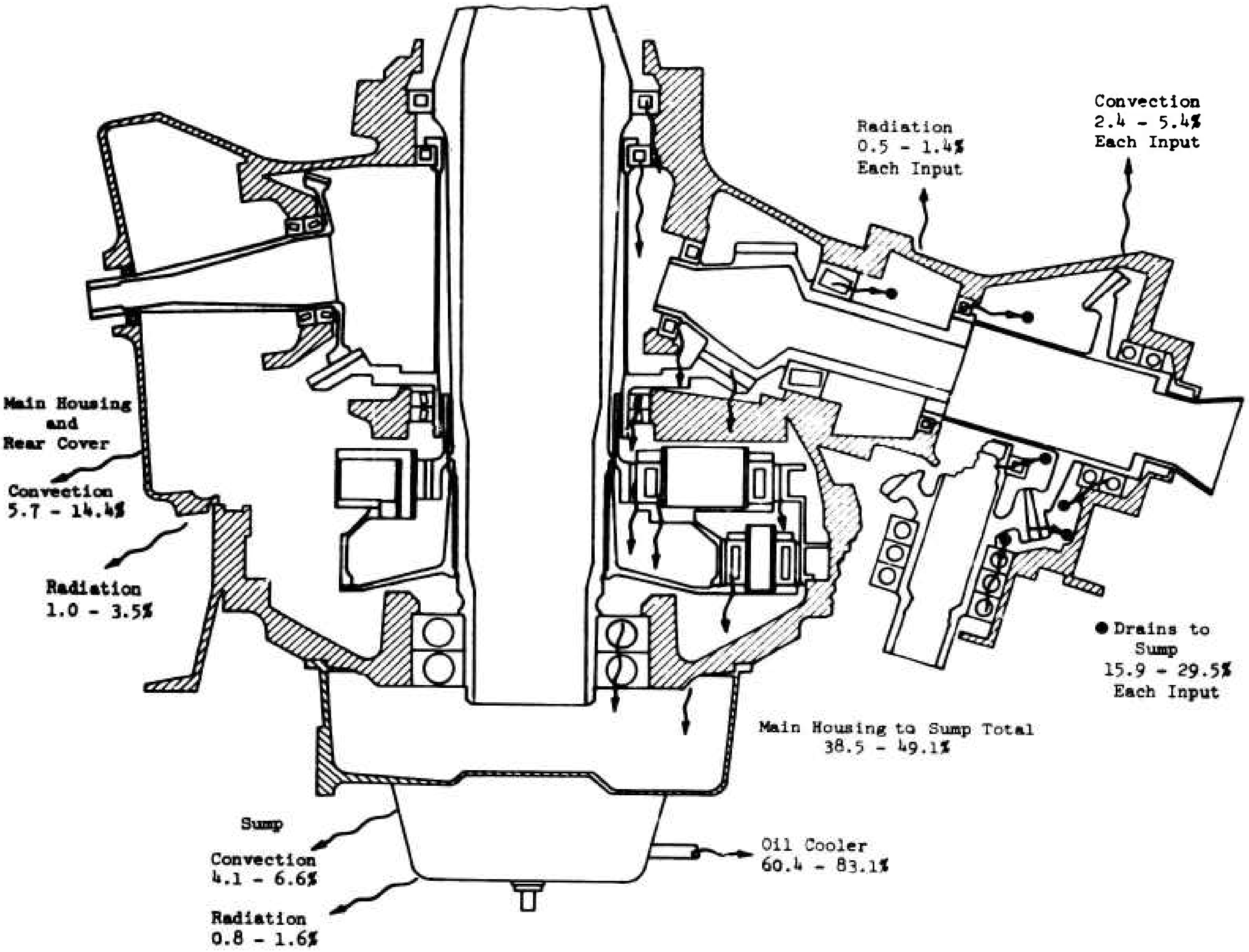


Figure 41. Heat Rejection Paths.

CONCLUSIONS

1. The internal and external thermal maps, heat sources, and heat rejection paths identified in this report represent an accurate thermal evaluation of the CH-54B main transmission.
2. The present transmission will not operate at rated maximum continuous power with no external oil cooling without exceeding present component and lubricant temperature limits.
3. Gearbox heat sources may be accurately predicted by analytical techniques.
4. Thermal expansion of the housing may be accurately predicted using analytical methods and handbook values for thermal expansion coefficients.

RECOMMENDATIONS

The results of the tests conducted during this program have suggested that additional research is required to develop the technology which will lead to a reduction in helicopter gearbox susceptibility to loss of lubrication. The ability to bypass lubricant around a damaged oil cooler or lines is a necessary initial step, and much research has been performed in this area. An example is the work conducted during transmission zero-lubrication tests sponsored by the Eustis Directorate; see Reference 2. Ultimately, however, the goal must be to eliminate an exposed lubrication system.

In order to increase the technology which will lead toward a self-contained gearbox, additional research in the following areas is recommended:

- Investigate methods of improving free convection within a gearbox possibly through the use of internal and external cooling fins.
- Investigate methods of improved heat rejection through forced-air convection.
- Continue development of higher heat stabilized bearing and gear materials and designs.
- Develop lubricants with high vaporization temperature properties which retain good lubricating characteristics at both elevated and normal operating temperatures.
- Continue the development of heat pipes beyond the work reported in Reference 2 to reject heat from bearings.
- Investigate the use of truss type housings with thin walls to aid in heat rejection.
- Investigate the use of baffling and scavenging to integral sumps to reduce churning or aerating of lubricants in gearboxes.

LITERATURE CITED

1. Storm, et al, HELICOPTER TRANSMISSION OIL HEAT REJECTION INVESTIGATION, Sikorsky Engineering Report SER 50558.

2. Wilson, Donald F., EVALUATION OF METHODS TO IMPROVE TRANSMISSION SURVIVABILITY AFTER LOSS OF LUBRICATION, USAAMRDL Technical Report 73-56, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia (to be published).

APPENDIX
THERMOVISION®

Thermovision® is a device employed to visually depict the temperature distribution of an object on a cathode-ray tube display whose intensity or color contours vary with surface temperature. The Thermovision® system consists of an infrared camera and a black and white visual display unit. An auxiliary color display unit is also included as an accessory component. The camera scans the object of interest and produces an output signal proportional to the infrared radiation emitted by the object, which is in turn proportional to the object's surface temperature. The camera signal is transformed by the display unit into a visual image on a cathode-ray tube. The intensity of the image is proportional to the object's surface temperature. By employing high scanning frequencies, a real-time display is produced. The Thermovision® unit is shown in Figure 42.

Two alternate black and white display modes and a color display mode may be selected. The primary black and white display mode depicts the object as a continuous series of gray-tone contours, each representative of a particular temperature. The intensity of the image at any location is proportional to the surface temperature of the object at that location. The alternate display mode is to depict, as a saturated white contour, the temperature zones which fall within a discrete temperature range. This range may be varied to produce a series of images, or isotherms, which together describe the temperature distribution of the object.

The Thermovision® in the primary display mode may also be used to detect hot spots on the gearbox housing or a major heat source within the gearbox. Figure 43 is a photograph of the infrared emissions of the CH-54B main gearbox as it cooled down after the fourth test in the thermal mapping series. The arrows indicate a major heat source which is radiating from within the gearbox. Examination of the photo and a drawing of the gearbox clearly identify the heat sources as the first-stage and second-stage planetaries.

A third display mode utilizes the color display unit to depict multiple isotherms simultaneously as contours of varying colors.

The Thermovision® system permits real-time transient temperature analysis between -30°C and 2000°C. A Polaroid camera attachment allows permanent records of the display image to be produced both in black and white and in color. Thermovision^{R} is manufactured by AGA Aktiebolag, Infrared Instruments, Lidingo, Sweden.

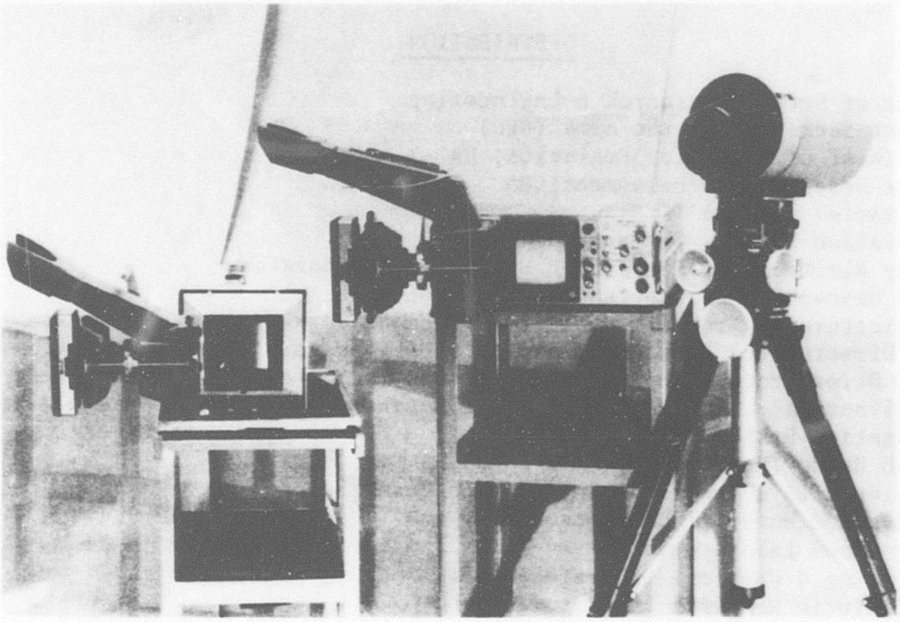


Figure 42. Thermovision® Unit.

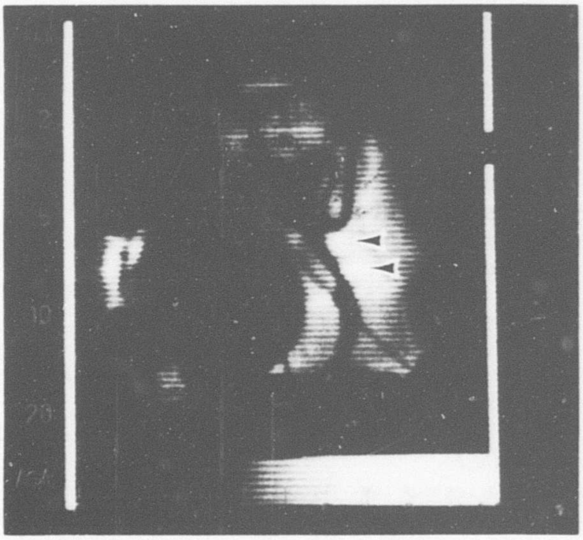


Figure 43. Infrared Display of CH-54B Main Gearbox, Post Test Cool-Down.