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REPORT NO. RN-S-0300
TO
AEC - NASA SPACE NUCLEAR PROPULSION OFFICE

THERMAL AND ERROR ANALYSES FOR THERMAL
CONDUCTIVITY TEST 37/R004

AUGUST 1966

NERVA PROGRAM

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ROCKET ENGINE OPERATIONS - NUCLEAR

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ABSTRACT

This document contains the error and thermal analysis for thermal conductivity test, 37/R004, to be performed during the GTR-18 run at General Dynamics' Fort Worth Facilities.

The error analysis includes:

1. input power measurement
2. dewar pressure measurement
3. temperature measurement
4. test specimen electrical resistance measurements

The thermal analysis includes:

1. the time required to chill test specimens and test cells from ambient temperature to liquid hydrogen with a vacuum in the test cell
2. the power requirements to achieve equilibrium for specified temperature gradients across test specimens
3. the maximum temperature gradient between the heater element and the heat sink during irradiation
4. the heat loss from heater power leads and the instrument leads during the conductivity measurements,
5. time to reach equilibrium at each hold temperature for each material

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I. INTRODUCTION

An investigation of the effects of radiation on the thermal conductivity of selected NERVA materials at LH_2 and LN_2 temperatures will be conducted during GTR-18 at General Dynamics' Fort Worth facility. The materials to be investigated are Titanium Al10-AT, Inconel 718, Aluminum 7039-T61, Steel A-286, graphites: 4HIM, PO-3, ATJ; and beryllium. Details of the investigation are included in REON Report RN-S-0299.

The proposed conductivity tests will be made using test cells designed by Dynamic Sciences Corporation. Thermal conductivity measurements will be made on each specimen before and after nuclear irradiation.

The thermal analysis and error analysis data contained in this report constitutes independent sections of information; each is composed of a summary, technical discussion, figures, tables, and references.

An error analysis of the input power circuit, dewar pressure measurement, temperature measurements, and electrical resistivity measurement is made to determine the accuracy of the test data.

The thermal analysis information on test cell cooldown time, power requirements, thermal gradients during radiation, heat losses, and equilibrium times are required to set up and schedule the test.

II. MEASUREMENT ERROR ANALYSIS

THERMAL CONDUCTIVITY TEST 37/ROO4

II. MEASUREMENT ERROR ANALYSIS

A. SUMMARY

The results obtained from the area of measurements error analysis are summarized as follows:

1. Input power uncertainty was a maximum of $\pm 0.32\%$.
2. Dewar pressure measurement uncertainty was a maximum of $\pm .0699$ psi at a ΔP of ± 5 psi (uncertainty values at lower pressure differential are shown in Figure II-1).
3. Temperature measurement uncertainties were compiled covering 14 parameters (these are listed in Subsection B-3-g).
4. Electrical resistance measurement uncertainty was a maximum of $\pm 15.12\%$ at a specimen temperature of 20.4°F (LH_2 temp). Uncertainty values at LN_2 and LH_2 temperatures with ΔT across specimen from 0° to 100°K are also contained in Subsection B-3-g.

Figure II-1
Typical Heater Circuit

B. TECHNICAL DISCUSSION

1. Input Power Measurement Error Analysis

Figure II-2 is a typical heater circuit schematic.

a. Circuit Element Information

The following will be used:

- (1) Power Supplies - Harrison Lab. Model 895A or 865C or equivalent
- (2) Digital Volt Meter (DVM) - NLS Model M24 or equivalent
- (3) Variable Resistors
 - (a) 250 Ω - Ohmite Model H, 25W
 - (b) 3 Ω - Ohmite Model H, 25W
- (4) Fixed Resistors
 - (a) 10 Ω - IRC Model WW2J, 2W
- (5) Leadwire - Raychem TRC 20(1) STIR 0-0
#20 AWG Shielded TC Grade Copper
- (6) Heaters - Special
 - (a) Sample - Approx. 51 Ω
 - (b) Shield - Approx. 625 Ω
- (7) Connectors, Terminal Strips, Switches - Not identified

b. Sample Heater Power

(1) Measurement is based on the relationship $P = EI$ where $I = \frac{V_1}{R_1}$, since the loading effect of the DVM is negligible (DVM $R_{in} = 10$ Megohms), and $E = V_2 - IR_k$ (again neglecting loading effects of the DVM).

(2) V_1 and V_2 can be determined to an accuracy of ± 1 digit (in a 4-digit display), $\pm 0.01\%$. The range of the DVM is from $\pm .0000$ to ± 999.9 volts.

* ONE DVM USED FOR ALL MEASUREMENTS
SWITCHING PROVISIONS NOT SHOWN

—•— CABLE TRANSITION

Figure II-2
Dewar Pressure Measurement Schematic

(3) R_ℓ consists of approximately 2 ft. of leadwire (0.02Ω) plus the resistance of the connector contacts (0.02Ω max). The leadwire resistance will decrease to approximately 0.0002Ω at LH_2 temperature and to approximately 0.002Ω at LN_2 temperature. Consequently, $R_\ell \approx 0.04 \pm 0.0$
 $- 0.0198 \Omega$ (for LH_2) = $0.0301 \pm$
 $.0099 \Omega$ and $R_\ell \approx 0.04 \pm 0.0$
 $- 0.018 \Omega$ (for LN_2) = $0.031 \pm .009 \Omega$

(4) The tolerance of R_1 is given as $\pm 0.1\%$.

(5) In estimating the maximum error caused by the DVM performance specifications it will be assumed that no reading of magnitude less than .1000 volts will be made with this instrument. The maximum error is then, ± 1 digit $\pm 0.01\% = \pm 0.11\%$.

(6) The maximum uncertainty in the determination of "I" will then be:

$$I = \frac{V_1 \pm 0.0011 V_1}{R_1 \pm 0.001 R_1}$$

$$I_{\max} = 1.002 \frac{V_1}{R_1} \quad I_{\min} = 0.998 \frac{V_1}{R_1}$$

$$U_{I_{\max}} = \pm 0.2\%$$

and the RSS uncertainty will be:

$$U_{I_{\text{RSS}}} = \pm 0.15\%$$

NOTE: If R_1 were known to greater accuracy, this uncertainty would approach $\pm 0.11\%$.

(7) The value of V_2 differs from the value of "E" by the amount of the loss in the test cell connectors and leadwire:

$$IR_{\ell} = V_2 \frac{R_{\ell}}{R + R_{\ell}} \approx V_2 \cdot \frac{R_{\ell}}{R}$$

$$\text{IN LH}_2, \frac{R_{\ell}}{R} = 0.0006 \pm 0.0002$$

$$\text{IN LN}_2, \frac{R_{\ell}}{R} = 0.00062 \pm 0.00019$$

The maximum uncertainty in the determination of "E" will then be:

$$E = V_2 \pm 0.0011 V_2 - V_2 (0.0006 \pm 0.0002)$$

$$E_{\max} = 1.0007 V_2 \quad E_{\min} = 0.9981 V_2$$

$$U_{E_{\max}} = \pm 0.13\%$$

and the RSS uncertainty will be:

$$U_{E_{\text{RSS}}} = \pm 0.112\%$$

(8) The RSS uncertainty in the determination of "P" will then be:

$$U_{P_{\text{RSS}}} = \pm 0.24\%$$

and the maximum $U_{P_{\max}} = \pm 0.33\%$

c. Shield Heater Power

(1) Measurement is based on the relationship $P_1 = E_1 I_1$ where $I_1 = \frac{V_3}{R_3}$ (as for sample heater power) and $E_1 = V_4 - I_1 R_L - I \frac{R_L}{2}$

(2) The same conditions as paragraph 1.b.(2) and 1.b.(5) apply for DVM measurements of V_3 and V_4 .

(3) The tolerance of R_3 is given as $\pm 0.1\%$.

(4) R_L consists of approximately 200 ft. of leadwire (2Ω) plus the resistance of connector contacts (0.04Ω max). Temperature induced changes in leadwire resistance (in the cryostats) will be neglected since the magnitudes of these changes are small in comparison to line resistance.

(5) The maximum uncertainty in the determination of I_1 will be the same as for the sample heater circuit, that is:

$$U_{I_{\max}} = \pm 0.2\%$$

and the RSS uncertainty will be:

$$U_{I_{\text{RSS}}} = \pm 0.15\%$$

(6) The value of V_4 differs from the value of E_1 by the amount of the loss in the long leadwires (primarily) plus the loss in the return current flow from the sample heater circuit. To calculate the uncertainty in the determination of E_1 , the following assumptions are made:

(a) Total lead resistance (R_L) is 2 ohms, and varies $\pm 5\%$ in the temperature range from 32°F to 120°F .

(b) The sample heater current (I) is approximately equal to the shield heater current (I_1).

The loss in the long lead wire is:

$$I_1 R_L + I \frac{R_L}{2} = \frac{3 R_L}{2} I = \left(\frac{3}{2}\right) \frac{V_4}{R_1 + R_L} \cdot R_L \approx \left(\frac{3}{2}\right) \frac{R_L}{R_1} V_4$$

The limits of $\frac{R_L}{R_1}$ are:

$$\text{at } 32^\circ\text{F}, \frac{R_L}{R_1} = .0031$$

$$\text{at } 120^\circ\text{F}, \frac{R_L}{R_1} = .0034$$

The maximum uncertainty in the determination of E_1 will then be:

$$E_1 = V_4 \pm 0.0011 V_4 - \frac{3}{2} V_4 (0.00325 \pm 0.00015)$$

$$E_{1\max} = 0.9962 V_4 \quad E_{1\min} = 0.9938 V_4$$

$$U_{E_{1\max}} = \pm 0.12\%$$

and the RSS uncertainty will be:

$$U_{E_{1\text{RSS}}} = \pm 0.111\%$$

(7) The RSS uncertainty in the determination of P_1 will then be:

$$U_{P_{1\text{RSS}}} = \pm 0.233\%$$

and the maximum $U_{P_{1\max}} = \pm 0.32\%$

2. Dewar Pressure Measurement Error Analysis

Figure II-3 is the dewar pressure measurement schematic.

a. System Component Information

The following will be used:

(1) Pressure Transducer - CEC Model 4-312-0002 $\pm$ 5 PSID
 $\pm$ 0.5% FS $\pm$ 0.01% FS/°F (-65°F to + 250°F)

(2) Data System - DYMEC DY 2010D MOD 16

Input through guarded crossbar scanner (DY-2911B-M11)
and guarded data amplifier (DY-2411A), visual indication on DVM (DY-2401B)

Accuracies: DY-2401B; .015% of reading $\pm$.005% full
scale $\pm$ 1 digit

DY-2411A; .02% of reading $\pm$.03% full scale. For full scale =
 $\pm$ 10 MV. DVM sample period = 1 sec, amplifier gain = X10,
system input impedance = 10^{10} ohms in parallel with 180 pf.

(3) Power Supply - Harrison Labs Model 801C

Stability: 0.1% + 5 MV

Load Regulation: 2 MV, Zero-to-full load

Line Regulation: 2 MV, 105V to 125V (60 HZ)

(4) Leadwire - Raychem TRC 20 (1) Stir 0-0

#20 AWG shielded TC grade copper

The following assumptions concerning the pressure measurement system are made for this analysis.

Figure II-3
Dewar Pressure Measurement Uncertainty

(1) The data system sampling time will be one second for each pressure measurement.

(2) Atmospheric pressure at the reference port of the ΔP transducer will be known to within ± 0.015 PSIA.

(3) Temperature variations along leadwires and at the ΔP transducer location will be between 32°F and 120°F.

(4) The pressure difference between the dewar and transducer inlet is negligible.

b. ΔP Measurement

Measurement is based on the assumption that the dewar pressure (P) is equal to atmospheric pressure (P_A) plus the differential pressure (ΔP).

$$P = P_A + \Delta P$$

(1) The largest source of uncertainty in this measurement is the transducer, with a static error band of $\pm 0.5\%$ F.S. and an uncertainty of $\pm 0.44\%$ FS from operating temperature variations.

(2) Transducer sensitivity will also change because of power supply variations and leadwire resistance changes. Combined effects of power supply stability, line regulation, and leadwire resistance changes will result in a transducer sensitivity variation of $\pm 0.3\%$.

(3) Uncertainties from the data system (assuming the 10 MV full scale range is used) are relatively insignificant in comparison to those previously noted in paragraph (1) and (2), so they will not be included.

(4) The total maximum uncertainty will then be

$$\pm \left[0.094 \text{ PSI} + 0.003 (\text{indicated pressure}) \right]$$

c. Total Pressure Determination

Assuming a random occurrence of uncertainties:

$$U_{\text{RSS}} = \left([.015]^2 + [.044]^2 + [.05]^2 + [.003 \Delta P]^2 \right)^{\frac{1}{2}}$$

P (PSID)	U_{RSS} (PSI)
0	$\pm .0682$
± 1	$\pm .0683$
± 2	$\pm .0685$
± 3	$\pm .0688$
± 4	$\pm .0693$
± 5	$\pm .0699$

3. Temperature Measurement Error Analysis

Two test assemblies will be provided. One to be used for liquid hydrogen, the other for liquid nitrogen. Each assembly will contain five vacuum test cells each containing one thermal conductivity specimen. Each specimen employs a heater to provide temperature differentials which are measured with thermocouple circuits as shown in Figure II-4. Chromel/constantan thermocouples are connected in a differential mode, being referenced to the test cell reference block. Although not shown in Figure II-4, the temperature of the test cell block is compared to a dewar reference block. For a more complete description of the measurement channels, refer to General Dynamics Drawing No. NTE 295.

The manner in which the various error modes combine to produce an uncertainty in the temperature measurements will be discussed, after a short description of individual error modes. The probable temperatures of the various measurement stations are derived in the following manner:

Since heat transfer calculations are not feasible, a 5°K rise in cell block temperature will be assumed when the differential temperature between thermocouple stations TC3 and TC1 is 270°K. We will further assume that the boiling point of Hydrogen (see Reference 1) and Nitrogen (see Reference 2) are, 20.3°K and 77.2°K, respectively. Thus, cell block temperatures are described by:

$$\left. \begin{array}{l} \text{Cell Block Reference Temperature} \\ \text{when Employing Liquid Hydrogen} \end{array} \right\} = (20.3 + \frac{5}{270} \Delta T) ^\circ\text{K} = (20.3 + 0.0185 \Delta T) ^\circ\text{K}$$

$$\left. \begin{array}{l} \text{Cell Block Reference Temperature} \\ \text{when Employing Liquid Nitrogen} \end{array} \right\} = (77.2 + \frac{5}{270} \Delta T) ^\circ\text{K} = (77.2 + 0.0185 \Delta T) ^\circ\text{K}$$

where " ΔT " is the temperature differential between thermocouple stations TC3 and TC1. Since the distance from the TC3 thermocouple clamp and the cell top is approximately one-quarter the distance between the clamps for TC3 and TC1, it shall be assumed that:

$$T_{CB} - TC3 = 0.25 (TC3 - TC1) ^\circ\text{K} = 0.25 \Delta T ^\circ\text{K}$$

Figure II-4
Temperature Measurement Thermocouple Arrangement

By employing the previous equations and assumptions, temperature measurements may be estimated and listed in tabular form shown in Table II-1,

Table II-1

Estimated Station Temperatures

(ΔT) °K	HYDROGEN TEST				NITROGEN TEST			
	(T_{CB}) °K	$(TC3)$ °K	$(TC2)$ °K	$(TC1)$ °K	(T_{CB}) °K	$(TC3)$ °K	$(TC2)$ °K	$(TC1)$ °K
0	20.300	20.300	20.300	20.300	77.20	77.20	77.20	77.20
10	20.485	22.985	27.985	32.985	77.39	79.89	84.89	89.89
20	20.670	25.670	35.670	45.670	77.57	82.57	92.57	102.57
30	20.855	28.355	43.355	58.355	77.76	85.26	100.26	115.26
40	21.040	31.040	51.040	71.040	77.94	87.94	107.94	127.94
50	21.225	33.725	58.725	83.725	78.13	90.63	115.63	140.63
60	21.410	36.410	66.410	96.410	78.31	93.31	123.31	153.31
70	21.595	39.095	74.095	109.095	78.50	96.00	131.00	166.00
80	21.780	41.780	81.780	121.780	78.68	98.68	138.68	178.68
90	21.965	44.465	89.465	134.465	78.87	101.37	146.37	191.37
100	22.150	47.150	97.150	147.150	79.05	104.05	154.05	204.05
110	22.335	49.835	104.835	159.835	79.24	106.74	161.74	216.74
120	22.520	52.520	112.520	172.520	79.42	109.42	169.42	229.42
150	23.075	60.575	135.575	210.575	79.98	117.48	192.48	267.48
180	23.630	68.630	158.630	248.630	80.53	125.53	215.53	305.53
210	24.185	76.685	181.685	286.685	81.09	133.59	238.59	343.59
240	24.740	84.740	204.740	324.740	81.64	141.64	261.64	381.64
270	25.295	92.795	227.795	362.795	82.20	149.70	284.70	419.70

a. Thermocouple Calibration Uncertainty Induced Errors

Based upon I.S.A. Standards (see Reference 3):

Accuracy of Chrome/Constantan (ch/cn) at 600°F = $\pm$ 3°F

Accuracy of Copper/Constantan (cu/cn) at 600°F = $\pm$ 4.5°F

thus

$$\text{ch/cn thermocouple accuracy} = \pm \left(\frac{3}{4.5}\right) (\text{cu/cn Accuracy}) \text{ } ^\circ\text{F}$$

The approximate accuracy of cu/cn thermocouples in cryogenic regions is ($\pm 2\%$) of the measurement junction temperature in ($^\circ\text{F}$) (Reference 4). By combining the above equation with I.S.A. error recommendations, the following uncertainty table is developed.

Table II-2

Calibration Uncertainty for Chromel/Constantan

Temperature Range $^\circ\text{K}$	0 $\rightarrow$ 148 $^\circ\text{K}$	148 $^\circ\text{K}$ $\rightarrow$ 589 $^\circ\text{K}$
Calibration Uncertainty	$\pm \left\{ 1.67 + 0.0133 (148 - T) \right\} ^\circ\text{K}$	$\pm 1.67^\circ\text{K}$

By employing the calibration uncertainty values of Table II-2 and REON thermocouple calibration Table No. RN-DR-0065, the calibration uncertainty band for chromel/constantan thermocouples may be plotted. A simplified error band plot is presented in Figure II-5.

By employing the uncertainty curves, errors from thermocouple calibration uncertainty may be determined. As an example, assume that the sample differential temperature. (ΔT) is 10°K and that we are interested in the millivolt uncertainty when measuring ($T_{\text{CB}} - T_{\text{CI}}$). From Table II-1, we find that the test cell reference block temperature (T_{CB}) is 20.485°K and that (T_{CI}) is 32.985°K when liquid hydrogen is used. By noting the point of curve intersection, the following computation table can be developed.

Figure II-5
Chromel-Constantan Calibration Uncertainty Curves

Table II-3

Computed Calibration Induced Uncertainty

Curve	Temperature ($^{\circ}\text{K}$)		Measured Millivolt Signal
	$T_{\text{CB}} = 20.485^{\circ}\text{K}$	$\text{TC1} = 33.985^{\circ}\text{K}$	
Upper Limit Curve	- 9.700 mv	- 9.554 mv	- 0.146 mv
Lower Limit Curve	- 9.759 mv	- 9.635 mv	- 0.124 mv

Thus, if the thermocouple were characterized by the upper curve, the measured output signal would be 0.022 mv larger than if the thermocouple were characterized by the lower curve. Therefore, the thermocouple calibration induced measurement (3 sigma) uncertainty will be ± 0.011 millivolts for $(T_{\text{CB}} - \text{TC1})$ when (ΔT) is 10°K .

b. Measurement Uncertainty Caused by the Uncertainty in LH_2 or LN_2 Temperatures

We shall assume that the atmospheric pressure varies by at least $\pm 0.2 \text{ lb/in}^2$ ($\pm 10.34 \text{ mm hg}$). Then, by employing the "Hydrogen Vapor Pressure - Temperature Data" contained in the (GTR-18) Test Specification,

<u>Temperature ($^{\circ}\text{C}$)</u>	<u>mm of Hg</u>
-252.92	727.8
-252.74	760.0
-252.45	823.7

the sensitivity of LH_2 temperatures to changes in atmospheric pressures may be approximated by:

$$\frac{(\Delta T) \text{ LH}_2}{\Delta \text{ mm}} = \frac{(-252.92) - (-252.45)}{727.8 - 823.7} = 0.0049 \text{ }^{\circ}\text{K/mm.}$$

Then the temperature variation of LH₂ caused by a (± 10.34 mm Hg) variation in atmospheric pressure variation is:

$$(\Delta T)_{LH_2} = \pm (0.0049) (10.34) = \pm 0.051^\circ K$$

Thus, errors resulting from LH₂ temperature uncertainties shall be considered insignificant since error in measuring atmospheric variations are much smaller than the actual variation.

c. Transition-Induced Uncertainties

It should be noted that all wire materials having the same nominal composition do not possess identical thermoelectric characteristics. This should be obvious when one considers the impossibility of controlling, exactly, the chemical and physical properties of wire. In this way, a typical thermocouple circuit employs several discrete sections, each of which differs thermoelectrically from all other sections. The following millivolt uncertainties are assumed for each type of metal transition, where brass is the assumed switch material

<u>Transition</u>	<u>Uncertainty</u>
cu/cn - - - - -	<u>±</u> 0.0165 mv
Copper/Brass - - - - -	<u>±</u> 0.0020 mv
Copper/Copper - - - - -	<u>±</u> 0.0010 mv
Brass/Brass - - - - -	<u>±</u> 0.0010 mv

The constantan/copper transition was inferred from the ± 0.75°F I.S.A. limit of error for cu/cn thermocouples and the fact that the thermoelectric variability of constantan is normally five times that of copper. The copper/copper variability is taken from Reference 5, while all other values are assumed. By noting the number of various transitions appearing in the test circuit drawing (General Dynamics Dwg. No. NTE-295), the following table is generated to yield the total transition induced, millivolt uncertainty being generated within each measurement channel where individual uncertainties have been combined by RSS summation.

Table II-4

Transition-Induced Millivolt Uncertainty

Measurement Channel	Liquid Hydrogen Test					Liquid Nitrogen Test				
	Number of Channel Transitions				Transition Uncertainty	Number of Channel Transitions				Transition Uncertainty
	Cu/Cu	Cu/Br	Cu/Cn	Br/Br		Cu/Cu	Cu/Br	Cu/Cn	Br/Br	
Tcb - TC1	10	8	2	8	± 0.02438 mv	8	8	2	8	± 0.02434 mv
Tcb - TC2	10	8	2	8	± 0.02438	8	8	2	8	± 0.02434
Tcb - TC3	10	8	2	8	± 0.02438	8	8	2	8	± 0.02434
TC3 - TC1	12	16	4	16	± 0.03437	10	16	4	16	± 0.03433
TC3 - TC2	14	16	4	16	± 0.03439	12	16	4	16	± 0.03436
TC2 - TC1	13	16	4	16	± 0.03438	11	16	4	16	± 0.03435
Tcb { Dewar Block	10	4	2	4	± 0.02396	8	4	2	4	± 0.02392

d. Recorder Measurement Uncertainty

The limit of error for the Leeds and Northrup K-3 Potentiometer is:

<u>Range</u>	<u>Uncertainty</u>
High Range: (0 - 1.611 volts) - - - - -	$20 \mu V \pm 0.01\%$ of reading
Medium Range: (0 - 0.1611 volts) - - - - -	$2 \mu V \pm 0.015\%$ of reading
Low Range: (0 - 0.01611 volts) - - - - -	$0.5 \mu V \pm 0.015\%$, of reading

e. Wire Inhomogeneities

Spurious emf's will be generated along the length of any metal conductor possessing inhomogeneities in its chemical composition or physical condition if the inhomogeneous region occurs in a temperature gradient zone. The effects of

inhomogeneity in a copper lead wire pair may be additive or subtractive and, as the emf developed along an inhomogeneous wire depends upon local temperature distributions and wire characteristics, attempts to predict inhomogeneity effects are impractical if not impossible. Since the circuit employs "thermocouple grade" copper wire, inhomogeneity effects shall be considered insignificant when compared to the other error modes.

f. Total Measurement Millivolt Uncertainty

The total measurement millivolt uncertainty will be the RSS summation of:

- (1) Thermocouple Calibration Uncertainty (see paragraph a)
- (2) Transition Induced Uncertainty (see paragraph c)
- (3) Potentiometer Meter Uncertainty (see paragraph d)

As an example, when the sample differential temperature (ΔT) is 10°K, ($T_{cb} - T_{cl}$) is the differential temperature being measured, and a hydrogen test is being conducted, the measurement millivolt uncertainty is:

$$\begin{aligned}
 & (T_{CB} - T_{Cl}) \text{ Millivolt} \\
 \text{Measurement Uncertainty} &= \pm \left\{ \left(\begin{array}{c} \text{Wire} \\ \text{Calibration} \\ \text{Uncertainty} \end{array} \right)^2 + \left(\begin{array}{c} \text{Transition} \\ \text{Uncertainty} \end{array} \right)^2 + \left(\begin{array}{c} \text{Meter} \\ \text{Uncertainty} \end{array} \right)^2 \right\}^{\frac{1}{2}} \\
 &= \pm \left\{ (0.011)^2 + (0.02438)^2 + (0.0005)^2 \right\}^{\frac{1}{2}} \\
 &= \pm 0.02675 \text{ mv}
 \end{aligned}$$

g. Total Measurement Uncertainty in Degrees Kelvin

The measurement uncertainty in degrees kelvin is found by multiplying the millivolt uncertainty by the channel sensitivity (°K/mv). As an example,

when the sample differential temperature (ΔT) is 10°K and ($T_{CB} - TC1$) is the differential temperature being measured during a hydrogen test, the channel sensitivity is found from the values presented in paragraph a as shown below:

$$\text{Channel Sensitivity} = \frac{\Delta T}{\text{Avg. } \Delta \text{mv}} = \frac{32.985 - 20.485}{0.5 (0.146 + 0.124)} = 92.593 \frac{^{\circ}\text{K}}{\text{mv}}$$

The measurement uncertainty in degrees kelvin now becomes:

$$\begin{aligned} \text{Measurement Uncertainty } (^{\circ}\text{K}) &= \pm \left\{ \left(\text{Measurement Uncertainty (mv)} \right) \left(\text{channel sensitivity } (^{\circ}\text{K/mv}) \right) \right\} \\ &= \pm (0.02675) (92.593) ^{\circ}\text{K} \\ &= \pm 2.48^{\circ}\text{K} \end{aligned}$$

The above calculations are repeated for other measured parameters and the results presented in Table II-5.

Table II-5

Total Measurement Uncertainty in Degrees Kelvin

ΔT		Measured Parameter Uncertainty						
		$T_{CB} - TC1$	$T_{CB} - TC2$	$T_{CB} - TC3$	$TC3 - TC1$	$TC3 - TC2$	$TC2 - TC1$	$T_{CB} - \text{Dewar Block}$
Hydrogen Test	10	$\pm 2.48^{\circ}\text{K}$	$\pm 2.51^{\circ}\text{K}$	$\pm 2.72^{\circ}\text{K}$	$\pm 3.10^{\circ}\text{K}$	$\pm 3.29^{\circ}\text{K}$	$\pm 2.81^{\circ}\text{K}$	$\pm 1.78^{\circ}\text{K}$
	30	± 2.46	± 2.52	± 2.47	± 2.46	± 2.68	± 1.84	± 2.22
	50	± 2.29	± 2.44	± 2.41	± 2.02	± 2.20	± 1.41	± 2.47
	120	± 1.84	± 1.98	± 2.30	± 1.28	± 1.38	± 0.90	± 2.55
	240	± 1.74	± 1.69	± 2.06	± 1.05	± 0.97	± 0.69	± 2.57
Nitrogen Test	10	± 0.87	± 0.89	± 0.93	± 1.20	± 1.23	± 1.18	± 0.91
	30	± 0.80	± 0.94	± 0.89	± 1.09	± 1.22	± 1.04	± 0.86
	50	± 0.75	± 0.80	± 0.86	± 1.01	± 1.07	± 0.94	± 0.96
	100	± 0.85	± 0.73	± 0.82	± 0.90	± 0.89	± 0.76	± 0.93
	210	± 1.13	± 0.77	± 0.74	± 1.13	± 0.86	± 0.74	± 0.89

The tabular listing in Table II-5 is plotted on Figures II-6 through II-19. It should be noted that the curves do not pass through all plotted points. Because of the difficulty in translating small values from curves, some data points are assumed to be in error. However, the plotted curves can be considered as good estimations of the inherent measurement uncertainties for this test.

Figure II-6
Measurement Uncertainty, Cell Block to TC1 using LH₂

Figure II-7
Measurement Uncertainty, Cell Block to TC2 using LH₂

Figure II-8
Measurement Uncertainty, Cell Block to TC3 using LH_2

Figure II-9
Measurement Uncertainty, Cell Block to TC3 to TC1 using LH_2

Figure II-10
Measurement Uncertainty, TC3 to TC2 using LH₂

Figure II-11
Measurement Uncertainty, TC2 to TC1 using LH₂

Figure II-12
Measurement Uncertainty, Cell Block to Dewar Block using LH_2

Figure II-13
Measurement Uncertainty, Cell Block to TCl using LN_2

Figure II-14
Measurement Uncertainty, Cell Block to TC2 using LN₂

Figure II-15
Measurement Uncertainty, Cell Block to TC3 using LN₂

Figure II-16
Measurement Uncertainty, TC3 to TC1 using LN₂

Figure II-17
Measurement Uncertainty, TC3 to TC2 using LN₂

Figure II-18
Measurement Uncertainty, TC2 to TC1 using LN₂

Figure II-19
Measurement Uncertainty, Cell Block to Dewar Block using LN₂

4. Test Specimen Electrical Resistance Measurement Error Analysis

Figure II-20 is the electrical resistance measurement schematic.

a. System Component Information

The following components will be used:

- (1) Power supply - Harrison Labs Model 859A or 865C or equivalent.
- (2) Digital Volt Meter (DVM) - NLS Model M24 or equivalent.
- (3) Resistor, ohmite, 10-Ohm wire-wound power resistor (100 W). Resistance will be determined to ± 0.006 Ohms in Lab.
- (4) Leadwire - Raychem TRC 20 (1) STIR 0-0 #20 AWG shielded TC grade copper.
- (5) Potentiometer - Leeds and Northrup, type K-3

b. Experiment Procedure

The technique which will be used to determine the specimen electrical resistance is as follows:

- (1) The power supply output will be adjusted until the ratio V/R indicates a current (I) of 500 milli-amperes is flowing in the resistor (R).
- (2) The voltage (E) across the specimen resulting from the current (I) will be measured with a potentiometer so that negligible current is shunted through the measuring circuit.
- (3) The electrical resistance of the specimen will be computed from the relationship $R_s = E/I$.

Figure II-20
Electrical Resistance Measurement Schematic

c. Error Analysis Assumptions

(1) The value of the resistance (R) will be between 9.5 and 10.5 ohms and will be determined via a resistance bridge measurement to within $\pm (.05\% \text{ reading} + 0.001)$ ohms. It will be assumed that "R" is determined to be 9.5 ohms at 70°F with a total uncertainty of $\pm .006$ ohms. Resistance variations of "R" caused by temperature changes will be assumed to be $0.003\% \text{ R}/^\circ\text{C}$, and the operating temperature range will be assumed to be from 20°C to 40°C. Total uncertainty because of temperature changes will then be $\pm .003$ ohms.

(2) A negligible current will flow through the DVM, so it will be assumed that the uncertainty in the determination of the voltage (V) will be solely the result of accuracy limitations of the meter, given as $\pm (1 \text{ digit} + .01\% \text{ reading})$ and magnitude of the voltage (V) will be adjusted to 0.5×9.5 or 4.750 volts (see paragrage b(1)) so the uncertainty in the determination of "V" will be ± 1.5 millivolts.

(3) It will be assumed that the resistance of the copper T.C. clamps (to which the leadwires are soldered), plus the contact resistance between the clamps and the test specimen, will be 10 micro-ohms at room temperature and will vary by ± 4 micro-ohms because of temperature changes.

(4) It will be assumed that the specimen material will be beryllium with an approximate room temperature resistance of 320 micro-ohms, an LN_2 resistance of 86^* micro-ohms, and an LN_2 resistance of 98^* micro-ohms.

(5) All leadwire connecting from the test specimen to the readout potentiometer will be copper. The distance spanned by the leadwire will be 120 feet; and there will be 20 junctions between cable segments, feed through's, switch elements, binding posts, T. C. clamps, and the test specimen. The following assumptions will be made concerning contact potential uncertainties at the various junctions:

*Based on McDonald and Mendelssohn data plotted in Part IV, WADD Technical Report 60-56, NBS, Boulder, Colorado, pages 263-265.

(a) Where leadwire segments from the same spool are joined together the contact potential will be within ± 1 microvolt.

(b) Where leadwire segments from different spools are joined together the contact potential will be within ± 1 microvolt.

(c) Where the leadwire connects to elements such as the T. C. clamps on the specimen and the binding posts on the potentiometer the contact potential will be within ± 1 microvolt.

(d) Where the leadwire connects to switch elements the contact potential will be within ± 2 microvolts.

(e) Contact potential between elements within the switch assembly will be within ± 1 microvolt.

The basis of assumptions (a) through (e) is explained in the specimen temperature measurement portion of this analysis.

(6) The contact potential between the copper T. C. clamps and the beryllium specimen is not defined at this time. Since potential measurements will be accomplished with temperature differences existing between the two clamps it will be necessary to subtract the output caused by the copper-beryllium/copper differential thermocouple. It will be assumed here that the temperature-vs-EMF characteristics of the Cu/Be combination will be known to within ± 2 microvolts, and measured potentials will be corrected to eliminate the thermocouple contribution.

d. Measurement Errors

(1) The uncertainty in the determination of the current (I) depends on the uncertainty in the resistor (R) and the error in the voltage (V) determination. From paragraphs c(1) and c(2),

$$I_{\max} = \frac{4.7515}{9.491} = 0.50063 \text{ amps}$$

$$I_{\min} = \frac{4.7485}{9.509} = 0.49937 \text{ amps}$$

$$U_{I_{\max}} = \pm 0.126\%$$

$$U_{I_{\text{rss}}} = \pm 0.105\%$$

(2) The uncertainty in the determination of the voltage (E) is a function of the uncertainties in the resistances of the T. C. clamps and the contacting surfaces of the clamps and the test specimen (paragraph c(3)), plus the uncertainties resulting from contact potentials (paragraphs c(5) and c(6)) and those of the measuring instrument. Uncertainties caused by the IR-drop in the T. C. clamps and contact resistances will be ± 2 microvolts. Assuming random distribution of these and of the contact potentials of paragraphs c(5) and c(6) as well as those in the measuring instrument, the total RSS uncertainty in the determination of the voltage (E) is:

$$\sqrt{42.25} = \pm 6.5 \text{ microvolts}$$

(3) The voltage-drop in the specimen caused by the current (I) will be small (at LH_2 temperature, approximately $43 \mu\text{V}$ and at LN_2 temperature, approximately $49 \mu\text{V}$). The uncertainty in "E" can then be expressed as:

$$U_{E_{\text{rss}}} = \pm \frac{6.5}{43} = \pm 15.12\% \text{ at } 20.4^\circ\text{K}$$

$$U_{E_{\text{rss}}} = \pm \frac{6.5}{49} = \pm 13.27\% \text{ at } 77.3^\circ\text{K}$$

(4) The uncertainty in the computation of the specimen resistance (R_s) is determined principally by the uncertainty in "E".

$$U_{R_s} = \pm 15.12\% \text{ at } 20.4^\circ\text{K}$$

$$U_{R_s} = \pm 13.27\% \text{ at } 77.3^\circ\text{K}$$

(5) The uncertainties of voltage drop and specimen resistance are based on the assumptions of this analysis and assumed constant steady-state temperature distributions in the test specimens. These uncertainties will decrease as the specimen temperatures are increased, since the magnitudes of the specimen resistances will also increase. Figure II-21 shows the uncertainties as functions of the differential temperatures across the specimens.

Figure II-21
Electrical Resistance Measurement Uncertainty

C. REFERENCES - PART II, MEASUREMENT ERROR ANALYSIS

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III. THERMAL ANALYSIS

THERMAL CONDUCTIVITY TEST 37/ROO⁴

III. THERMAL ANALYSIS

A. SUMMARY

The results obtained from the thermal analysis are summarized as follows:

1. Times for specimen and test unit to chill from room temperature to -423°F , with evacuated test unit. (0.1% of steady state conditions).

<u>Specimen</u>	<u>Time</u>
Aluminum	1 hour 37 minutes
Beryllium	4 hours 55 minutes
A-286	12 hours 38 minutes
Titanium	14 hours 20 minutes
Inconel 718	14 hours 37 minutes

2. The electrical power required by the specimen and shield heaters at various temperatures is computed mathematically, and is discussed in Subsection B-2.

3. The time delay to reach equilibrium at each hold for each material is as follows:

<u>Specimen</u>	<u>Time</u>
Aluminum	14 minutes
Beryllium	16 minutes
Inconel 718	3.6 hours
Iron Alloy A-286	3.1 hours
Titanium	3.5 hours

4. The maximum temperature across the specimen (from heater to sink) during nuclear irradiation at 3 mw (using stagnant helium as a coolant) is as follows:

<u>Specimen</u>	<u>ΔT - °F</u>
Aluminum	29
Titanium A-110-AT	97
A-286	129
Beryllium	31
Inconel 718	141

5. The heat loss from the power leads and thermocouple leads is shown graphically in Figure III-1.

Figure III-1
Heat Leakage During Thermal Conductivity Measurements

B. TECHNICAL DISCUSSION

The apparatus to be used in the thermal conductivity measurement program is the Dynamic Science Corporation Drawing No. S/N 30-1000, Conductivity Test Cell Assembly. (See Figure III-2). The test specimen is a rod of the material to be tested. The rod is 10 in. long and has a diameter of 0.175 in. One end of the rod is screwed into a copper plate which serves as a heat sink. The opposite end of the rod is attached to an electric heater element. Three thermocouples are attached to the rod: the lower one 30 mm above the heater, the middle one 70 mm above the lower, and the upper one 70 mm above the middle one and 30 mm below the face of the copper heat sink. A thin-wall shield surrounds the specimen rod. For the aluminum, titanium and beryllium specimens the shield is aluminum, and for the A-286 and inconel specimens the shield is 347 stainless steel. The shield has a heater at the lower end in order to maintain the shield at the same temperature as the specimen to minimize heat leakage. The entire apparatus is enclosed in a stainless steel shell. The unit is then submerged in liquid hydrogen, being suspended from a hanger. The copper heat sink is in contact with liquid hydrogen. During the conductivity measurements the test unit will be evacuated to 10^{-6} mm Hg.

Figure III-2
Conductivity Test Cell Assembly

1. Time to Achieve Equilibrium at LH₂ Temperature
with Evacuated Test Cell

During this cooldown the primary mode of heat transfer will be conduction. The following assumptions were made:

- a. Heat transfer across evacuated spaces negligible.
- b. One-dimensional conduction.
- c. Heat transfer from case and heat sink by boiling of LH₂.
- d. Room temperature value for thermal diffusivity used.

The cooldown times for the case and copper heat sink were computed by first computing a boiling LH₂ film coefficient from Figure 2.7 of Reference 1. The computed value is 58 Btu/hr ft²°R. The times to achieve 0.1% of thermal equilibrium were computed using Heisler charts for transient unidirectional conduction, Reference 2. The times for each specimen to achieve 0.1% of thermal equilibrium were computed in a similar manner except it was assumed that the specimens were initially at room temperature and then one end was suddenly chilled to -423°F. Because of the much greater thermal diffusivity of copper, the heat sink will cool much more rapidly than the other materials. The cooldown time for the heat sink was added to that of each of the specimens to obtain the total time, this adds a small amount of conservatism. Thermal conductivity, specific heat, and density data were not available for all materials down to -423°F; therefore, a constant room temperature value was used. This results in some conservatism as thermal diffusivity increases with decreasing temperature for most materials. Thermal properties data were obtained from Reference 3.

The following table contains the results of the above calculations.

TABLE III-1

Time Required for Specimens and Shields to Chill From Room
Temperature to -423°F With the Test Cell Evacuated
(0.1% of Steady State Conditions)

1.	Aluminum specimen and shield	
a.	Specimen and heater	1 hour 21 minutes
b.	Shield and heater	1 hour 37 minutes
2.	Titanium specimen, aluminum shield	
a.	Specimen and heater	14 hours 20 minutes
b.	Shield and heater	1 hour 37 minutes
3.	A-286 specimen, 347 S.S. shield	
a.	Specimen and heater	12 hours 37.5 minutes
b.	Shield and heater	10 hours 51 minutes
4.	Beryllium specimen, aluminum shield	
a.	Specimen and heater	4 hours 55 minutes
b.	Shield and heater	1 hour 37 minutes
5.	Inconel Specimen, 347 S.S. shield	
a.	Specimen and heater	14 hours 37 minutes
b.	Shield and heater	10 hours 51 minutes

The time required to reach thermal equilibrium for the titanium and A-286 specimens is excessive for the condition where the test unit is evacuated. Since the primary mode of heat transfer is conduction to the cap assembly which is copper and immersed in LH_2 , the thermal diffusivity of the test specimen is the controlling factor. The cooldown time for the titanium and A-286 specimens can be greatly reduced by utilizing convective cooling of helium to approach thermal equilibrium and then evacuating the test unit.

2. Power Requirements

The power requirements for each hold, (See Table III-2) were computed from the unidirectional conduction equation: $q = KA \, dt/dx$, where "dt" is the required temperature gradient between the upper and lower thermocouples and "dx" is the distance between them. "K" is the thermal conductivity evaluated at the average temperature. "A" is the cross-sectional area of the specimen, "q" is the power requirement in watts. The aluminum 6061 and 7039 conductivities were estimated from Figure 22 of Reference 4. The conductivity of Stainless Steel 347 was taken from Figure 23 of Reference 4. The conductivity of A-286 was assumed to be the same as for Stainless 347. Inconel 718 was estimated from Figure 25 of Reference 4. Conductivity of Beryllium parallel to the hexagonal axis was obtained from Reference 5.

TABLE III-2

Power Requirements - Watts

T - °C	Aluminum 7039 Specimen	Aluminum 6061 Shield	Titanium A-110-AT Specimen	A-286 Specimen	CRES 347 Shield	Inconel 718 Specimen	Beryllium Specimen
10	0.026	0.352	0.004	0.003	0.016	0.003	0.011
20	0.069	0.723	0.009	0.008	0.041	0.008	0.027
30	0.120	1.207	0.014	0.014	0.073	0.014	0.047
40	0.182	1.567	0.019	0.022	0.114	0.022	0.076
50	0.250	2.143	0.024	0.031	0.160	0.031	0.106
60	0.320	2.794	0.030	0.040	0.209	0.040	0.140
80	0.471	4.064	0.042	0.062	0.325	0.060	0.213
100	0.667	5.223	0.054	0.083	0.436	0.078	0.300
120	0.868	6.985	0.067	0.107	0.557	0.097	0.387
170	1.418	10.415	0.104	0.179	0.937	0.151	0.614
220	2.073	14.804	0.144	0.257	1.341	0.206	0.831
270	2.855	19.661	0.187	0.345	1.803	0.264	1.050

3. Time Delay Between Holds

The time required to achieve equilibrium at each hold was computed by solving the unidirectional, transient conduction, equation $\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$ with the following boundary conditions:

- a. One end is held permanently at -423°F
- b. To the other end a constant source of heat is applied.

The resulting solution reduces to:

$$T = \frac{2q}{KA} \sqrt{\frac{\alpha t}{\pi}} \quad (\text{Reference 2})$$

where: T = temperature, $^\circ\text{F}$
 t = time, hours
 x = distance, ft
 α = thermal diffusivity, ft^2/hr
 q = heat flow, Btu/hr
 K = thermal conductivity, $\text{Btu/hr ft}^\circ\text{F}$

The time to reach equilibrium at each hold for each material specimen is as follows:

<u>Specimen</u>	<u>Time</u>
Aluminum	14 minutes
Titanium	3.5 hours
A-286	3.1 hours
Beryllium	16 minutes
Inconel 718	3.6 hours

4. Maximum Temperature Differential

The maximum temperature differential between the base of the heater element and the heat sink was computed for the nuclear irradiation phase (in which stagnant gaseous helium was used as a coolant). A heating rate of 5.4×10^8 ERG/gm(C)hr, corresponding to 3 mw reactor power, was used. Cooling was assumed to be from natural convection of gaseous helium at one atmosphere pressure. The following correlation for vertical enclosed air spaces was used:

$$\frac{HX}{K} = \frac{.20}{(L/X)^{1/9}} \left[(Gr) (Pr) \right]^{0.25} \quad (\text{Reference 6})$$

where:

h = convective film coefficient, Btu/hr ft²°R
X = clearance in enclosed space, ft
L = Height of vertical surface, ft
K = Fluid thermal conductivity, Btu/hr ft °R
Gr = Grashof number, dimensionless
Pr = Prandtl number, dimensionless

The calculations for maximum temperature gradient are purposely conservative because of the complexity of the heat transfer mechanism. The temperatures quoted in this analysis are the upper limit rather than expected temperatures. The degree of conservatism is roughly 100%.

Maximum temperature differentials across specimens during irradiation are as follows:

<u>Specimen</u>	<u>Temperature - °F</u>
Aluminum	29
Titanium	97
A-286	129
Beryllium	31
Inconel 718	141

5. Heat Leakage During Thermal Conductivity Measurements

The amount of heat leakage from the specimen heater power leads and thermocouple leads was calculated. The power leads were assumed to be two 10-mil copper wires, 2 feet long, connected at one end to the specimen heater and at the other to a terminal strip immersed in liquid hydrogen. The thermocouple leads consist of three sets of 5-mil chromel and constantan wires 2 feet long, also connected to the terminal strip immersed in LH_2 . In addition there are two pairs of 5-mil copper wire connected to the specimen at the upper and lower thermocouples and to the cryogenic terminal strip. The heat loss through these conductors causes an error in the power input to the specimen, as only the total power input to the specimen heater is measured. This loss can be minimized if all of the leads can be kept inside of the specimen shield, which is maintained at the same temperature as the specimen. However, about 20 to 25% of each lead is outside the shield. The conduction losses and anticipated conduction plus radiation losses are plotted in Figure III-1.

C. REFERENCES - PART III, THERMAL ANALYSIS

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