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REPORT NO. RN-S-0088

TO

AEC-NASA SPACE NUCLEAR PROPULSION OFFICE

PRE-IRRADIATION ANALYSIS OF TEST 23/L302
TUNGSTEN/TUNGSTEN-RHENIUM THERMOCOUPLES

GROUND TEST REACTOR (GTR) IRRADIATION

TEST NO. 13

NERVA PROGRAM

CONTRACT SNP-1

MAY 1964

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MAY 1964

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ABSTRACT

This report presents the results of a pre-irradiation analysis for two Aerojet designed tungsten/tungsten-rhenium thermocouple probes (Test 23/L302) which are scheduled to be irradiated at the Ground Test Reactor facility during May 1964 (GTR Test 13).

Based on the analysis presented, temperature errors are predicted for both Test 23/L302 and NRX-A2 operation. The analysis indicates that the performance of these thermocouples is not limited by the radiation environment as the decalibration anticipated in GTR-13 and NRX-A2 because of nuclear effects, is less than 2%, which is within design specifications.

W. D. Stinnett
REON Technical Systems Manager

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Report No. RN-S-0088

PRE-IRRADIATION ANALYSIS OF TEST 23/L302
TUNGSTEN/TUNGSTEN-RHENIUM THERMOCOUPLES

(GTR-13 - May 1964)

I. INTRODUCTION

This report describes the predicted effects of nuclear radiation on the performance of two models of tungsten/tungsten-rhenium thermocouples which have been designed by Aerojet for measuring the thrust chamber temperature in the NRX-A2 tests.

One unit of each design is scheduled to be tested for 100 hours at the Ground Test Reactor at GD/FW during May 1964 (GTR-13). The test specifications and the operational procedures for this test (Test 23/L302) indicate that these thermocouples will be tested in a helium atmosphere which will be maintained at approximately 2000°F (Reference 1). The purpose of this radiation effects test is to evaluate the performance of the units in a radiation environment to determine reliability, radiation sensitivity, and to obtain operational data on temperature transducers identical to those to be mounted on the NRX-A2 nozzles for measurement of thrust chamber temperature. These thermocouples will be used to make measurements THNC-1, -2, -3, and -4.

The scope of this analysis includes: (1) a determination of the unperturbed and perturbed radiation environment as sensed by the subject transducers in both the NRX-A2 application and in the GTR test; (2) a temperature profile of both the test fixture and test component during all phases of the test; (3) an evaluation of the effect of nuclear radiation on the materials selected and the design of the transducer; and (4) a prediction of errors in temperature measurement during the test at GTR. This analysis has been performed in conjunction with the test fixture design and test procedure preparation and all pertinent information from this analysis has been incorporated into these documents.

It should be noted that the analyses presented in this report are not the only analyses or testing that have been performed on the subject transducers,

as they have been analyzed and tested in the laboratory by the Aerojet Instrumentation group. The results of their testing and evaluation are summarized in References (2) through (4). The evaluation in this report is concerned only with the effects of radiation on transducer performance and the applicability of these GTR test results to NRX-A2. The design, frictional heating caused by exhaust gases, response characteristics, accuracy, noise characteristics and the results of laboratory tests are discussed in References (2) through (4).

II. SUMMARY AND RECOMMENDATIONS

Various nuclear and non-nuclear sources of temperature-measurement errors were investigated for both thermocouple probes. The predicted temperature-measurement errors are summarized in Table I for both GTR-13 and NRX-A2 test conditions and a predicted error band is shown in Figure 1 for GTR-13 test conditions. As noted in Table I, below, the largest single source of errors is due to non-nuclear reasons; namely, reproducibility of thermocouple measurements. Because of the high temperatures anticipated in NRX-A2, the insulation resistance of BeO decreases to such an extent that the additional decrease caused by radiation will result in leakage currents and temperature measurement errors. This problem is very acute and a more detailed analysis for NRX-A2 is recommended. (This analysis is in progress.) Also, it should be noted that if the electrical input power cannot be measured to within 1%, the error introduced could mask out any errors caused by nuclear effects.

Both AGC designed tungsten/tungsten-rhenium thermocouple systems are relatively radiation-resistant and based on this analysis it is anticipated that a pre- and post-calibration should indicate less than a 2% variation which is within design specifications although during both GTR-13 and NRX-A2 tests, errors as great as 3% may occur.

Although it is desirable to operate the thermocouple probes at the highest temperatures expected in NRX-A2, it is recommended that the test be performed at temperatures below 2700°F. The thermal analysis presented in this report indicates 2700°F to be the highest possible temperature for the materials and components of the test fixture. Based on thermal considerations, the temperature of the test fixture should be raised and lowered on a programmed temperature-time profile to minimize the possibility of heating element breakage caused by thermal shock.

The thermal analysis indicates that severe thermal gradients may exist in the thermocouple probes during NRX-A2 operation and it is recommended that a more detailed analysis be performed for the NRX-A2 conditions. (This detailed thermal analysis is in progress and a report summarizing these results will be published.)

TABLE I
PREDICTED TEMPERATURE MEASUREMENT ERRORS

Source of Error	Temperature Error ($^{\circ}\text{F}$)		Remarks
	GTR-13 [*]	NRX-A2 ^{**}	
Thermal neutron absorbtion	<-1	<-1	No effect expected
Fast neutron lattice defects	-20	-20	Varies linearly through- out test
Gamma heating	+40	+60	Output can be calibrated for this effect
Insulation degradation	-10	-60	Most of change expected at start of test with gradual reduction during test
Reproducibility	<u>+20</u>	<u>+50</u>	Reproducibility will be determined during pre- irradiation data cycles
Input power variations	< <u>+11</u>	--	Requires measuring input power to within 1%

^{*}GTR-13 test conditions: 2500 $^{\circ}\text{F}$ temperature; 100 hours $\phi_{\text{th}} = 2 \times 10^{12}$ nv;
 $\phi_{\text{fast}} = 4.5 \times 10^{11}$ nv; gamma = 7×10^8 ergs/gm(C)-hr

^{**}Assumed NRX-A2 test conditions: 4100 $^{\circ}\text{F}$ temperature; 30 minutes
 $\phi_{\text{th}} = 2 \times 10^{14}$ nv; $\phi_{\text{fast}} = 2.5 \times 10^{13}$;
gamma = 2×10^{10} ergs/gm(C)-hr.

III. NUCLEAR ENVIRONMENT

A. NERVA ENVIRONMENT

A two-dimensional map of the isoflux contours for fast neutrons ($0.9 \text{ Mev} < E_n < 10 \text{ Mev}$) about the NERVA reactor is illustrated in Figure 2. The encircled areas on the map are the general locations for each of the test transducers. The service locations for NRX-A2 application were obtained from Reference 5, the NERVA Instrumentation Data Book. A similar approach was taken to obtain the nominal gamma ray environment for these transducers. The estimated fast neutron and gamma ray environments are summarized in Table II.

TABLE II

NOMINAL NRX-A2 SERVICE ENVIRONMENT FOR THE TEST TRANSDUCERS

<u>Transducer Designation</u>	Fast Neutron Flux ($E_n > 0.9 \text{ Mev}$)	Gamma Dose-Rate (ergs/gm(C)-sec)
	<u>($n/\text{cm}^2\text{-sec}$)</u>	
THNC-1	2.5×10^{13}	5.0×10^6
THNC-2	2.5×10^{13}	5.0×10^6
THNC-3	2.5×10^{13}	5.0×10^6
THNC-4	2.5×10^{13}	5.0×10^6

At the present time, only nominal values can be specified for the NRX-A2 environment. These nominal values should be correct within a factor of two of the true environment. The effect of radiation scattering from the test facility must be evaluated before a more precise prediction of the NRX-A2 test environment can be made.

B. TEST ENVIRONMENT - UNPERTURBED

The unperturbed test environment as measured for the north position in GTR has been reported by General Dynamics, Fort Worth, Texas (Reference 6). Using the data provided for the north position at an elevation corresponding to the reactor centerline, the two dimensional neutron flux and gamma dose-rate

maps, illustrated in Figures 3 and 4, were generated. The anticipated position of the Mark III environmental chamber and the high temperature test fixture are drawn on the isoflux and iso-dose maps. The thermocouple locations in the test fixture are also noted in these figures.

Using the information contained in Figures 2 and 3, it is possible to specify the unperturbed radiation environment anticipated for the thermocouple probes. These results are summarized in Table III.

TABLE III

UNPERTURBED TEST ENVIRONMENT FOR THE THERMOCOUPLE PROBES

Fast neutron flux rate

$$(E_n > 2.9 \text{ Mev}) \quad 8.5 \times 10^{10} \text{ neutrons/cm}^2\text{-sec}$$

Gamma Dose Rate $3.0 \times 10^5 \text{ ergs/gm(C)-sec}$

C. COMPARISON OF NRX-A2 AND GTR-13 RADIATION ENVIRONMENTS

Test 23/L302 employs two thermocouple probes which will be irradiated at elevated temperatures for a period of 100 hours using the test fixture illustrated in Figure 5. Two of these test fixtures will be placed in a Mark III environmental chamber as shown in Figure 3. The flux perturbations caused by the test fixtures were calculated, and these results are shown in Table IV. For comparison purposes, the fast neutron flux is given relative to $E > 0.9 \text{ Mev}$ in order that the comparison to NRX-A2 values reflect the most reliable information.

TABLE IV

COMPARISON OF NRX-A2 AND PERTURBED TEST ENVIRONMENT

	NRX-A2	Test GTR-13
Fast neutron flux rate (n/cm^2 -sec) ($E_n > 0.9$ Mev)	2.5×10^{13}	4.5×10^{11}
Integrated fast neutron flux (n/cm^2) ($E_n > 0.9$ Mev)	$4.5 \times 10^{16}^*$	1.6×10^{17}
Gamma dose rate (ergs/gm(C)-hr)	2×10^{10}	7×10^8
Integrated gamma dose (ergs/gm(C))	$1 \times 10^{10}^*$	7×10^{10}

* Assumes a 30 minute NRX-A2 reactor test.

IV. TEST FIXTURE EVALUATION

The thermocouple probes will be placed in the high temperature test fixtures shown in Figure 5, which in turn will be placed in a GTR Mark III environmental test chamber and irradiated for 100 hours.

A. MATERIALS REVIEW

Since it is planned to scrap the test fixture after the irradiation test, only a cursory materials evaluation was performed. The materials used in the construction of the test fixtures have been irradiated by various investigators to higher integrated fluxes without incident; hence, no material failure problems are anticipated for the test fixtures. Because of thermal aging and nuclear radiation degradation, the thermal characteristics of the test fixture may be effected. A pre- and post-calibration examination should reveal any material changes in the test fixture which might effect the test data. The materials employed do not have large cross sections for nuclear activation; therefore normal handling and disassembly techniques can be followed in the disassembly and component post-irradiation tests.

B. TEST FIXTURE TEMPERATURE PROFILE

A parametric thermal analysis was performed with an analog computer to investigate the temperature profile throughout the test fixture for the test described in Reference 1. The following conditions were assumed:

1. Uniform gamma heating throughout all materials and components of 0.03 watts/gm (GTR gamma heating rate) and 0.00 (pre-irradiation).
2. Electrical heat input from 0 to 1 kilowatt.
3. Constant temperature in Mark III environmental chamber surrounding test fixture of 150°F.
4. Volume inside the test fixture contains helium at 1 atmosphere.
5. Test fixture dimensions and materials are as indicated in Figure 5.

The details of this parametric thermal analysis are described in Appendix A and the results are summarized below.

1. Figure 6 shows the equilibrium temperature of the walls, copper leads, heating elements and sensing elements as a function of input electrical power. It should be noted that the temperature of the sensing element is relatively unaffected by reactor operation, but the temperature of the walls and copper electrode increases by about 200°F when the reactor is operating. Figure 6 indicates that 2500°F can be achieved at about 400 watt electrical input which checks with values obtained in the laboratory for this test fixture.

2. Figures 7 and 8 show the effects of inserting the thermocouple probe into the heating cavity for input power of 400 watts and 1000 watts. It should be noted that the temperature of the sensing element is relatively constant for insertions greater than 0.7 inches.

3. Figures 9 and 10 show the temperature profile throughout the test fixture for an input power of 400 watts and 1000 watts respectively.

4. Figure 6 indicates that the electrical input to the heating element must be accurately measured and controlled as the sensing element temperature has a sensitivity of $2.6^{\circ}\text{F}/\text{electrical watt}$.

5. Based on thermal considerations, the temperature of the test fixture should be raised and lowered on a programmed temperature-time profile to minimize the possibility of heating element breakage caused by thermal shock.

6. The thermal analysis concerning the thermocouple probes are discussed in Section V of this report.

V. RADIATION EFFECTS ANALYSIS

A. MATERIALS AND DESIGN ANALYSIS

The design drawings for the tungsten/tungsten-26% rhenium thermocouple probes are shown in Figures 11 and 12, respectively. The sensing element of the thermocouple probe shown in Figure 11 consists of a pure tungsten tube which acts as one leg of the thermocouple; the other leg is a 4.0 mil tungsten-26% rhenium wire. The concentric region of the first 1.5 inches of the probe, between the thermoelements, is filled with helium (STP). The remaining portions of the probe uses hard packed BeO to insulate the thermoelements. The probe of the thermocouple shown in Figure 12 consists of a tungsten-26% rhenium tube which contains two 1.5 mil thermocouple wires; one tungsten-26% rhenium and the other tungsten-5% rhenium. The insulation in this probe is hard packed BeO. Both probes are 0.145 inches in diameter and have immersion lengths of 1.5 inches.

The relative radiation resistance of these probes can be noted from Tables V and VI which list the materials and weight breakdown for these thermocouple probes.

TABLE V

MATERIALS LIST - AUTO CONTROL LABORATORIES, TUNGSTEN VS
TUNGSTEN WITH 26 PERCENT RHENIUM

	<u>Estimated Weight - lb</u>
Tungsten (Sensor & Lead Wire)	0.09
Rhenium (Sensor & Lead Wire)	0.01
MgO (Insulation - Sheath & Probe)	0.15
Type 303 Stainless Steel	0.20
Type 304 Stainless Steel	0.20
Silver Solder - Brazing Material	Trace
<hr/>	
Total Weight =	0.65 lb

All materials are metals or ceramics whose radiation-damage thresholds (greater than 10^{19} nvt; Reference 7) are several orders of magnitude higher than either the anticipated NRX-A2 radiation environment (ϕ_{fast} (E 1.0 Mev) = 4.5×10^{16} nvt; gamma dose = 2×10^{10} ergs/gm(C)) or the GTR radiation environment (ϕ_{fast} (E 0.9 Mev) = 1.6×10^{17} nvt; gamma dose = 7×10^{10} ergs/gm(C)). Since all materials employed have been proven in radiation environments much greater than anticipated, no structural problems are anticipated because of material degradation. The degradation caused by radiation, coupled with the high temperature, can adversely effect the insulation resistance of BeO and cause errors in temperature measurement from leakage currents. This is discussed in detail in Section V-B-4.

B. RADIATION INDUCED ERRORS IN THERMOCOUPLE OUTPUT

The emf generated by these thermocouple junctions are shown in Figure 13 as a function of temperature. The errors in the emf generated by the W/W-Re thermoelectric junction are due primarily to the following:

- Changes in chemical composition which result from thermal neutron transmutations
- Lattice defects which result from fast neutron bombardment
- Temperature errors which result from gamma heating
- Degradation in insulation resistance
- Miscellaneous non-nuclear effects

The magnitude of each of these potential sources of error are analyzed below.

1. Effect of Transmutations on Thermocouple Output

The change in chemical composition of each thermoelement involved was calculated for both GTR-13 and NRX-A2 test conditions. The following nuclear reactions were considered:

The results of these calculations are summarized in Table VI.

TABLE VI

MATERIALS LIST - AGC DWG. NO. 701517, THERMOCOUPLE IMMERSION,
TUNGSTEN WITH 5 PERCENT RHENIUM VS TUNGSTEN WITH 26% RHENIUM

	<u>Estimated Weight - lb</u>
Tungsten (Sensor & Lead Wire)	0.11
Rhenium Sensor and Lead Wire	0.03
BeO (Insulator-Sheath)	0.003
MgO (Insulator - Probe & Extension Lead)	0.14
Type 304 SST Probe Body	0.15
Type 347 SST Extension Lead Sheath	0.23
Silver Solder - Brazing Material	Trace
<hr/>	
Total Weight =	0.66 lb

As a result of the change in chemical composition, the emf produced by the dissimilar materials will also change. Various investigators (Ref. 8) have measured the change in emf as a function of rhenium content. At temperatures near 2500°F, their results indicate a change in emf of 1 millivolt per % change in rhenium. Based on the information contained in Table VII, the error in emf resulting from changes in chemical composition will be about 1 microvolt which corresponds to a temperature error of approximately 0.5°F. On the basis of the above calculations it can be concluded that thermal neutron absorption will not cause any significant temperature measurement errors.

TABLE VII

CHEMICAL COMPOSITION OF THERMOCOUPLES

	<u>Element</u>	<u>Composition before irradiation</u>	<u>After NRX-A2 30 min at 2×10^{14} nv</u>	<u>At end of 100 hr at 2×10^{12} nv</u>	<u>GTR-13 post mortem - 10 days after test</u>
Thermo- element Material No. 1	Tungsten	95.0000%	94.9996%	94.9992%	94.9986%
	Rhenium	5.0000%	5.0003%	5.0006%	5.0011%
	Osmium	-	0.0001%	0.0002%	0.0003%
Thermo- element Material No. 2	Tungsten	74.0000%	73.9997%	73.9994%	73.9942%
	Rhenium	26.0000%	26.0000%	26.0000%	26.0010%
	Osmium	-	0.0003%	0.0006%	0.0008%
Thermo- element Material No. 3	Tungsten	100.0000	99.9995	99.9990	99.9985
	Rhenium	0.0000	0.0005	0.0010	0.0015

2. Errors Caused by Lattice Defects

Tungsten/tungsten-rhenium thermocouples have never been irradiated in a combined high temperature/nuclear environment. Since the effects of lattice defects are analogous to cold working, it is believed that the errors caused by fast neutron bombardment can be approximated from the work of D. D. Pollock and D. T. Finch (Ref. 9) of Leeds and Northrup, who investigated the effect of cold working on the thermal emf of various thermocouples.

In their experiments, the thermoelements were cold drawn at 0°C and tested as a thermocouple against a fully annealed thermoelement of the same material in the "as received" condition. The results of their investigations are abstracted below:

"... Table 3 (Table VIII in this report) shows that almost all of the stress relief which does occur, as evidenced by the potential differences between the worked and unworked specimens, takes place between 300 and 500°C,

depending upon the material. These temperatures represent the completion of the recovery process. It will be noted that the emfs of the various specimens, with the exceptions of copper and Chromel-P, remain essentially constant after recovery has occurred. This implies that the levels of the internal stresses remain nearly unchanged and that their effects are not a function of temperature. These residual stresses can only be relieved by recrystallization. The recrystallization temperatures of the alloys being considered here are considerably above 900°C . Had recrystallization occurred, the potential differences between any set of worked and unworked specimens would have been much closer to zero....

... The results of the tests on the heavy gauge iron and constantan wires are given in Tables 4 and 5" (Tables IX and X of this report).

The data show that the recovery mechanism in iron is virtually completed at about 300°C . It is noteworthy that the effect of stress on emf is practically constant. This is in good agreement with the work of Baliki on Armco iron. He shows that the emf of specimens which were cold drawn in the range from 15 to 70% Reduction of Area evidence little differences in emf.

Iron also shows the effects of the allotropic change beyond 700°C . The slope of the emf-temperature function changes significantly. The recrystallization, complicated by the phase change as well as by differences in state, prevent the potential differences from being much closer to zero.

The constantan specimens complete recovery in the 300 to 400°C range. Like the iron wires, their change in emf is nearly independent of the amount of internal stress. The specimens given 50.3% reduction in area show a slightly greater degree of recovery than those which received smaller reductions."

TABLE VIII (Ref. 9)

EFFECTS OF STRESS ON EMF (IN MICROVOLTS) OF THERMOELEMENTS AS A
FUNCTION OF TEMPERATURE (STRESS EQUIVALENT OF 20% R.A.)

<u>(°C)</u>	<u>Copper</u>	<u>Chromel-P</u>	<u>Alumel</u>	<u>Platinum</u>	<u>Platinum 10% rhodium</u>
26.9	+1.9	-13.8	-0.1	+2.3	-0.4
60.0	+2.4	-31.4	-0.8	+3.0	-1.3
100.0	+3.9	-53.4	-3.2	+4.5	-2.5
150.0	+5.0	-81.9	-7.8	+4.4	-5.3
200.0	+6.8	-106.6	-16.3	+7.2	-6.4
300.0	+8.4	-157.8	-29.8	+9.4	-7.9
400.0	+7.4	-185.5	-33.7	+8.4	-8.3
500.0	+7.0	-195.6	-33.5	+11.0	-9.8
600.0	+6.3	-181.0	-31.4	+11.9	-10.3
700.0	+6.3	-198.2	-31.5	+11.0	-10.6
800.0	+6.8	-208.5	-32.2	+11.7	-11.2
900.0	+8.2	-234.7	-36.3	+10.7	-12.2

TABLE IX (Ref. 9)

EFFECTS OF STRESS AND TEMPERATURE ON EMF
(IN MICROVOLTS) OF THERMOCOUPLE IRON

Temperature (°C)	Percent reduction of area				
	<u>9.1</u>	<u>15.8</u>	<u>26.4</u>	<u>30.3</u>	<u>45.6</u>
26.1	-6	-6	-5	-7	-7
60.0	-13	-13	-13	-14	-16
100.0	-21	-20	-21	-21	-25
150.0	-26	-25	-29	-27	-31
200.0	-31	-30	-34	-32	-38
300.0	-35	-35	-40	-37	-45
400.0	-36	-36	-43	-39	-47
500.0	-36	-36	-43	-39	-48
600.0	-34	-35	-41	-39	-49
700.0	-34	-34	-40	-39	-49
800.0	-28	-5	-31	-19	-49
900.0	+5	+132	+38	+101	+204

TABLE X (Ref. 9)EFFECTS OF STRESS AND TEMPERATURE ON EMF (IN MICROVOLTS)
OF CONSTANTAN

Temperature (°C)	Percent Reduction of Area				
	<u>28.4</u>	<u>34.3</u>	<u>40.0</u>	<u>45.3</u>	<u>50.3</u>
27.9	+8	+10	+10	+10	+10
60.0	+17	+21	+21	+21	+21
100.0	+28	+33	+34	+34	+32
150.0	+44	+51	+52	+52	+49
200.0	+55	+62	+65	+65	+61
300.0	+72	+80	+81	+80	+71
400.0	+77	+85	+84	+81	+69
500.0	+79	+86	+87	+85	+71
600.0	+78	+82	+88	+85	+71
700.0	+83	+84	+92	+92	+73
800.0	+80	+81	+90	+89	+70
900.0	+85	+86	+94	+98	+76

Based on the above data, the following results are anticipated in Test 23/L302 from fast neutron bombardment:

- a. Since annealing begins at approximately 200°C , most of the defects created will be annealed in the GTR-13 test.
- b. As indicated by the data the error increases as the temperature approaches recrystallization and decreases thereafter. This means that the error in GTR-13 caused by lattice defects should be larger than the corresponding error in NRX-A2 tests.
- c. The error increases as cold working approaches 15% and remains fairly constant thereafter. Since it is estimated that 10^{17} nvt of fast neutrons is equivalent to less than 10% cold working, the error caused by fast neutron bombardment is expected to increase linearly throughout both GTR-13 and NRX-A2.
- d. By normalizing the data of Pollock and Finch with respect to recrystallization temperature (absolute) the error in emf and equivalent temperature error for tungsten and tungsten-rhenium thermocouples is estimated in Table XI.

Based on the above data it is estimated that the temperature error caused by fast neutron bombardment will be less than 20°F in both GTR-13 and NRX-A2 tests.

TABLE XI

ESTIMATED TEMPERATURE ERRORS CAUSED BY STRESS

Thermoelement Data Used*	GTR-13 (2500°F)		NRX-A2 (4200°F)	
	emf (microvolts)	Temperature (°F)**	emf (microvolts)	Temperature (°F)***
Copper ($T_R^{****}=325^\circ\text{F}$)	+8	+1	+7.2	+1
Chromel-P ($T_R=1000^\circ\text{F}$)	-210	-19	-170	-17
Alumel ($T_R=1000^\circ\text{F}$)	-34	-3	-25	-3
Platinum ($T_R=1470^\circ\text{F}$)	+11	+1	+10	+1
Iron ($T_R=900^\circ\text{F}$)	-36	-3	-20	-2
Constantan ($T_R=650^\circ\text{F}$)	+83	+8	+80	+8
Platinum-10% Rhodium ($T_R=1470^\circ\text{F}$)	-12	-1	-11	-1

* Data for 20% reduction of area which should be representative of NRX and GTR-13 tests.

** Figure 13 indicates a sensitivity of 11 microvolts per °F at 2500°F.

*** Figure 13 indicates a sensitivity of 10 microvolts per °F at 4200°F.

**** T_R is recrystallization temperature.

3. Temperature Errors Which Result from Gamma Heating

A detailed parametric thermal analysis for the thermocouple probes and test fixtures is described in Appendix A. The results of this detailed analysis are summarized below:

a. The temperature of the sensing element is approximately 40°F higher than pre-irradiation temperatures for the same electrical input power when the GTR reactor is operating at 3 Mw.

b. The temperature of the sensing element is dependent on insertion depth into the heating cavity as is indicated in Figures 7 and 8. It is fairly constant for insertions greater than 0.7 inches.

c. Figures 14 and 15 depict the temperature profile throughout the thermocouple probes as a function of insertion depth for electrical input power of 400 and 1000 watts, respectively. It should be noted that severe thermal gradients are anticipated at the junction of the stem and probe body. This could cause source problems in NRX-A2 and a more detailed thermal analysis for NRX-A2 conditions is recommended. This detailed analysis is in progress and the report summarizing the results will be published.

d. The temperature error caused by gamma heating in NRX-A2 is estimated to be approximately 60°F. The error is not directly proportional to the ratio of the gamma fluxes because the heating of test fixtures and other installation components in the GTR have a greater effect on the temperatures of the environment than the NRX-A2 test conditions.

e. The error caused by gamma heating should be the same for both thermocouple probes as the heat transfer path from the sensitive region to the heat sink is basically the same for both units.

4. Insulation Degradation

In order to assess the maximum possible error caused by insulation leakage, the theoretical error for the following thermocouple assembly was calculated:

AGC Part No. 701517

Thermocouple, immersion type

Tungsten with 5% rhenium vs tungsten with 26% rhenium

Sheath 0.145-in. OD

Sheath wall thickness 0.030-in.

Wire diameter 0.015-in.

The insulation resistance per unit length of wire material was determined from the relation

$$R = \frac{p}{\pi} \log_e \frac{2S}{D_1} \left(\frac{D_2^2 - S^2}{D_2^2 + S^2} \right)$$

where

p = resistivity

S = center-to-center wire spacing

D_1 = wire diameter

D_2 = inside diameter of sheath

Figure 16 is a plot of the variation in leakage resistance of the probe assembly for various wire spacings. Using average temperature values taken at specific points on the probe temperature profile of Figure 17 (Reference 31), the specific resistance of BeO insulation in Figure 18, and an assumed wire spacing of 0.040-in. the insulation resistance per linear inch of insulator was determined from Equation (1) as follows:

$$\begin{aligned} R_{\text{STA. 1}} &= \frac{1.7 \times 10^5 \text{ ohm cm}}{\pi \times 2.54} \log_e 2 \left(\frac{0.040}{0.015} \right) \left(\frac{0.085^2 - 0.040^2}{0.085^2 + 0.040^2} \right) \quad (1) \\ &= \frac{1.7 \times 10^5}{8.97} \log_e 3.4 = 1.7 \times 10^5 \times 0.1535 \\ &= 26,100 \text{ ohms per inch} \end{aligned}$$

In order to account for possible errors in the resistivity measurements in the curve of Figure 18 a worst case resistivity one order of magnitude lower was used in preparing the following table.

<u>Probe Station</u>	<u>Temp °R</u>	<u>p ohm-cm x 10⁴</u>	<u>R ohms/inch</u>
0 through .3	3060	1.7	2,610
.4	2980	2.5	3,840
.5	2940	3.0	4,600
.6	2880	4.5	6,920
.7	2810	6.0	9,200
.8	2710	10	15,300
.9	2590	20	30,800
1.0	2420	45	69,200

Employing resistivity values for tungsten-rhenium alloys from Figure 19, the resistance per linear inch of W - 26% Re wire 0.015 in. diameter is given by the relation

$$R = \frac{pl}{d^2} \quad (2)$$

where

p = resistance per mil foot

l = length in feet

d = diameter in mils

thus,

$$\begin{aligned}
 R_{\text{STA. 1}} &= \frac{412}{225 \times 12} = 412 \times 3.7 \times 10^{-4} \text{ ohms/inch} \\
 &= 0.153 \text{ ohms/inch}
 \end{aligned}$$

and for various probe locations

Probe Station	Temp °R	p (W-26Re) ohm cmf	Resistance 15 Mil W-26Re Wire ohms/inch	p W-5Re ohm cmf	Resistance 15 Mil W-5Re Wire ohms/inch
0 through .3	3060	412	0.153	322	0.119
.4	2980	405	0.150	314	0.116
.5	2940	400	0.148	305	0.113
.6	2880	395	0.146	300	0.111
.7	2810	390	0.144	295	0.109
.8	2710	380	0.141	285	0.105
.9	2590	365	0.135	270	0.100
1.0	2420	360	0.133	255	0.094

In order to assess the maximum possible error caused by nuclear radiation, an increase in insulation leakage which would result in an additional insulation resistance degradation of 10^{-3} is assumed, and the equivalent electric circuit of Figure 20, where the resistance of one tenth inch segments are used to represent the first inch of the insulated thermocouple, is employed. Then using a equivalent circuit for two terminal network as follows

$$E' = \frac{26.1 E}{26.1 + 0.0272} = 0.99896 E \text{ volts}$$

$$R' = \frac{26.1}{26.1273} = 0.99896 \times 0.0273 = 0.02727 \text{ ohms}$$

and continuing in the following manner

$$R'' = 0.05436$$

$$E'' = \frac{26.1 \times 0.99896E'}{26.1 + 0.05447} = 0.9979 \times 0.99896E = 99686E$$

$$R'' = \frac{26.1 \times 0.05447}{26.15447} = 0.9979 \times 0.0547 = 0.05436$$

for Figure 20 the following equivalent circuit is substituted

or the error in emf, due to insulation leakage in a high radiation field in the extreme case considered here amounts to less than 2%.

In a non-radiation environment, the thermocouple assembly considered here should show no output droop due to insulation resistance degradation at 3060°R . For comparison, the median of the output of seven thermocouples with a 0.062 in. OD TA Sheat, BeO insulation, using 0.010 in. dia W - 5% Re vs W-26% Re wire along with the bare wire calibration is shown in Figure 21.

5. Miscellaneous Non-nuclear Effects

Based on data from Hoskins Manufacturing Company (Reference 34) for tungsten/tungsten-26% rhenium thermocouples, the reproducibility of measurements for six thermocouples indicated a spread of $30\text{-}40^{\circ}\text{F}$ for three readings on the same thermocouples at 2500°F and a spread of $70\text{-}90^{\circ}\text{F}$ at 3800°F , the highest temperature investigated. Assuming that the equilibrium temperature is exactly the same during each cycle, the errors in reproducibility should be of the same order of magnitude in GTR-13 and NRX-A2. The degree of reproducibility will be determined in pre-irradiation data cycles.

The input power to the induction heaters must be accurately determined or large errors may be recorded. Figure 6 indicates that the sensitivity of the sensing element temperature is $2.60^{\circ}\text{F}/\text{watt}$ of input power. If the input power can be determined to within 5%, the deviations in temperature should be less than 52°F for the 400 watt operating condition in GTR-13. By measuring the input power to within 1%, compensations to the data can be accomplished thus reducing the error to 11° .

C. REVIEW OF PRIOR RADIATION EXPERIENCE WITH THERMOCOUPLES

Thermocouples have been employed for temperature measurements in the vicinity of nuclear reactors for many years and, in addition, the effects of nuclear radiation on thermocouples have been studied both analytically and experimentally by many investigators. A brief list of material pertaining to the irradiation of thermocouples are included in References 8 through 30. Some of the more important data discussed in these references are summarized in the following paragraphs.

Reference 18: M. J. Kelly, et al.

"Operating experience with thermocouples in nuclear reactors indicates that no gross effect in thermocouple output is caused by the presence of the radiation field. However, limitations exist on the types of insulation which may be used. Plastics are particularly susceptible to degradation on exposure to gamma radiation; refractory metal oxides are the most satisfactory insulating materials. It has been reported that an open thermocouple circuit in an in-pile location developed a measured potential of several volts between the two conductors. This was attributed to the photoelectric effect. Although nuclear radiation affects all materials to some extent, a well-made and properly insulated thermocouple will give temperature results as satisfactorily in a high radiation environment as in a normal installation.

"... Chromel-Alumel Studies (Note: integrated fast fluxes were between 6.1×10^{19} and 4.1×10^{20} nvt

"... The results from these thermocouple wires ... seems to show that little of the effect observed is attributable to the irradiation process. The scatter observed for all wires and all thermal cycles is probably caused by cold-working effects.

"... Pertinent observations from complete data are:

- (1) Annealing reduces error at high temperatures.
- (2) Results from Alumel are much more irregular than those from Chromel.
- (3) Error observed on Chromel wires is always less than 3/4%
- (4) Chromel error reduces on cycling.
- (5) Alumel has a larger percentage deviation than chromel.

"... Platinum-Platinum - 10% Rhodium Studies

(Note: integrated fast fluxes were between 6.1×10^{19} and 4.2×10^{20} nvt.)

"The most graphic case of the difference between irradiated and unirradiated couples is shown in Figure 5. This thermocouple had received

14 weeks of neutron exposure in the Oak Ridge reactor. (Note: $\phi T = 4.2 \times 10^{20}$ nvt). The maximum percentage deviation occurs at the higher temperature and amounts to 3% of normal output. Figure 6 is a cumulative plot of results from thermocouples irradiated in three reactors. All data were taken at 1000°C. The correlation between neutron exposure and observed error is fairly good.

(Note Figure 6 Data)

<u>Integrated Flux (nvt)</u>	<u>Deviation from Calibration (microvolts)</u>
6×10^{19}	14
8.2×10^{19}	26
1.2×10^{20}	29
1.9×10^{20}	48
2.3×10^{20}	82
4.2×10^{20}	280

Reference 20: G. F. Levy, et al.

"The measurements presented in this paper are part of a series of tests in progress on platinum versus platinum-rhodium.....thermocouple systems. The purpose of this investigation is to measure the amount of de-calibration experienced by a thermocouple system under simultaneous temperature and nuclear irradiation conditions.

".... After installation in the reactor, the furnace capsule is brought up to a temperature of 2500°F and maintained at this temperature for the duration of the irradiation period. The emf output of the thermocouples is then recorded continuously with a potentiometer during the irradiation cycle. The insulation resistance of the insulation resistance test unit is also recorded continuously with a potentiometric recorder, and periodically measured with a resistance bridge.

"The measurements presented are for 20-gage platinum vs platinum-10% rhodium thermocouples insulated by a high-purity and density alumina insulator and operating at a constant temperature of 2500°F. (The fast neutron flux was defined in terms of neutrons having threshold energies above 0.18 Mev.)

... To ascertain the nature of the permanent effects, such as diffusion or transmutation, post irradiation measurements were performed on the irradiated thermocouples....The conclusions drawn from these measurements indicate that for the particular configuration tested and for the given irradiation conditions, the de-calibration was under 0.8%.)

... Post-irradiation measurements on the insulation unit at a constant temperature of 2500°F gave essentially the same insulation resistance as before irradiation. Thus, it may be concluded that the insulation resistance of this particular configuration of thermocouple insulator remained unchanged under simultaneous high temperature and nuclear irradiation conditions...."

Reference 13: G. W. Kielholtz, et al.:

"... The nuclear test consisted of two pairs of Pt/Pt-10% Rh wiresthe capsule temperatures were 1000°F and 1180°F....The percent temperature errors have been plotted in Figures 3..."

(Note data from Figure 3 which corresponds to an integrated thermal flux of 1.8×10^{20} .)

Temperature <u>(°F)</u>	Percent Error <u>(% °F/°F)</u>
450	0.37
550	0.40
650	0.42
750	0.45
950	0.47
950	0.49
1050	0.51
1150	0.54
1250	0.58
1350	0.60
1450	0.62
1550	0.64
1650	0.67
1750	0.70

Reference 12: A. R. Druymer, et al.

"Tungsten/tungsten-rhenium thermocouples have been successfully used for various hydrogen gas temperature measurements in the Kiwi-A reactors of the Rover nuclear propulsion program. The most useful combination for these thermocouples has been tungsten coupled with a tungsten-25 weight percent rhenium alloy. This alloy exhibits a solidus temperature slightly over 3100°C , has considerably more room temperature ductility than tungsten, and yields an electromotive force of about 40 millivolts against tungsten at 2300°C ."

"The W/Re emf increases very slowly after 2000°C , and the Re/W-25 Re emf is much lower and has a reversal at about 1250°C . Although the W/W-25 Re calibration has been carried out only to 2300°C , one would expect that a stable calibration could be extended to some temperature below 3100°C . Even if the wire were well supported in order to minimize high temperature creep, diffusion between the two thermoelements would probably limit the maximum calibration temperature to the 2800°C to 3000°C range, depending strongly on exposure time."

"Although tungsten has the highest melting point and lowest thermal expansion of any metal, it unfortunately exhibits rapid grain growth at elevated temperatures with resultant brittleness on cooling to lower temperatures."

"... One distinct advantage of W/W-Re thermocouples is that they may be used in a hydrogen atmosphere (as well as in vacuo and in inert gas atmospheres) at all temperatures with absolutely no problem of reaction. In their recent article entitled "Reactor Core Temperature Measurement," Shinault and McGrath state that "...at elevated temperatures, tungsten in contact with hydrogen will form tungsten hydrogen under continuous gamma and neutron bombardment. This effect has not been observed in any of the Kiwi-A reactors. However, it is essential that the atmosphere be free from oxygen and nitrogen, since the oxides of tungsten and rhenium are quite volatile, and tungsten forms fairly refractory nitrides....Nuclear radiation effects on the thermocouple assemblies fortunately are well controlled at the high temperatures of Kiwi-A reactor operation by thermal annealing. Although research on radiation effects is clearly indicated, it would be expected that radiation might influence the rates of known chemical reactions, and would produce minute quantities of new elements, with neither effect causing any significant change in thermocouple performance."

"... Four thermocouples were used to measure the exit gas temperature in Kiwi-A3. Two were the bare wire type, two the sheathed type. All four survived the test and gave similar readings. Three of them agreed within 1/2%. The bare wire thermocouples will probably be used in an automatic exit gas temperature control system in some subsequent Rover tests."

Reference 19: W. E. Browning, et al.:

This report discusses chemical changes in thermocouple composition of tungsten/tungsten-rhenium thermocouples caused by thermal neutron absorption for periods up to 20 years in a thermal neutron flux of 1×10^{14} nv.

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Figure 1

Temperature Measurement Error Band for GTR-13

NOTE: The contours shown are for a 4" thick reflector. For the 2" case, increase the dose rate levels by 60%

X = Transducer locations

Dose rates given in
fig. 4 in sec.

Figure 3

GTR Gamma Isodose Map

NOTE: The contours shown are for a 4" thick water reflector. For the 2" case, increase the flux levels by a factor of two.

*flux given in neutrons/cm² sec
E_N > 1.0 Mev*

Figure 4

GTR Fast Neutron Isoflux Map

Figure 5

Thermocouple Test Fixture AGC Drawing 095411

Figure 6

Fixture Temperature vs Electrical Heat Input

Figure 7

Thermocouple Temperature vs Insertion Depth (400 Watts)

Figure 8

Thermocouple Temperature vs Insertion Depth (1000 Watts)

NOTE: All Temperatures in °R
Depth of Box = 5 in.

Figure 9

Temperature Profile of Test Fixture (400 Watts)

NOTE: All Temperatures in °R
 () Signifies Temperature with Heat Generation
 Depth of Box = 5 in.

Figure 10

Temperature Profile of Test Fixture (1000 Watts)

Figure 11

Thermocouple Probe Design: Drawing 701571 - 701580

Figure 12

Thermocouple Probe Design: Drawing 701515

Figure 13

Thermocouple EMF vs Temperature

Figure 14

Temperature Profile of Thermocouple Probe (400 Watts)

Figure 15

Temperature Profile of Thermocouple Probe (1000 Watts)

Figure 16

Resistance of Bed Insulator

Figure 17

Temperature Profile of Test Thermocouple for GTR-13

Figure 18

Electrical Resistivity of Bed

Figure 19

Electrical Resistivity - Tungsten and Tungsten-Rhenium Alloys

Figure 20

Equivalent Circuit of Sheathes Thermocouple

Figure 21

Thermocouple Output

Figure 22

Temperature of Heating Element and Walls

NOTE: $R_e = \frac{1 - \epsilon_i}{A_i \epsilon_i}$
 UNMARKED RESISTORS = $\frac{1}{A_i F_{i-k}}$

Figure 23

Simplified Electrical Analog for Radiation Analysis

APPENDIX A

STEADY-STATE THERMAL ANALYSIS OF
THERMOCOUPLE TEST FIXTURE AND
THERMOCOUPLE PROBES

By

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A steady-state thermal analysis of the thermocouple and the thermocouple test fixture was performed with the aid of the Aerojet Thermal Analyzer. The objectives of this analysis were:

1. Determination of the sensing element temperature as a function of the depth of insertion of the thermocouple probe into the heater cup.
2. Determination of the temperature profile of the thermocouple for each depth of insertion.
3. Determine (1) and (2) for electrical energy depositions of 1 KW and 0.40 KW, and for the "reactor on" and "reactor off" conditions. These conditions indicate internal heat generation in the former and no internal heat generation in the latter.

In order to determine the temperature distribution on the stainless steel enclosing walls, a preliminary analysis was performed. This analysis considered only the heating element and the enclosure. Figure 22 presents the results of this investigation. The total thermal energy radiated from the heating element is shown on the abscissa. It can be seen that in each case ("reactor on" and "reactor off") the six stainless steel surface temperatures all fall within a narrow band for a given level of energy emission. Also

*Figure numbers in this appendix refer to the figures in the body of this report.

evident from this figure is the fact that although the wall temperatures increase approximately 200°F in the "reactor on" condition, the heating element temperature increases only about 40°F. This relatively small affect on the heating element is caused by the relative magnitudes of the emissive powers of the element and the walls.

Once it was established that the stainless steel walls were all at essentially the same temperature, the entire test fixture was analyzed.

The model used in this analysis included the thermocouple, copper electrodes, and stagnant helium within the enclosure.

An analysis was performed with 1 KW of thermal energy generated in the heating element. Figure 8 illustrates the variation of sensing element temperature with depth of insertion in the heating element. The temperature profile along the thermocouple probe for various depths of insertion is provided by Figure 15. Typical temperatures in the test fixture are sketched in Figure 10.

The results of an analysis in which 0.40 KW of thermal energy is generated in the heating element are presented in Figures 7, 14, and 9. These figures provide information corresponding to that presented in Figures 8, 15, and 10, respectively.

Comparison of Figure 8 with Figure 7 (sensing element temperature) reveals a relatively sharp knee in the former curve, while the latter appears to be a smoother curve. In the first case the high probe temperature just above the heated section provide a high emissive power compared to that of the walls, resulting in a relatively high radiant heat transfer rate from the probe to the walls. Examination of the temperature profile of the probe (Figure 15) will show that the probe temperature becomes lower than the wall temperature somewhere between the heating element and the stainless steel shield at the top of the test fixture. It is also to be noted that as the depth of probe insertion decreases, the portion of the probe radiating to the walls decreases. Another factor to consider is that the total quantity of heat transferred from

the heater to the probe decreases as the probe is removed, also resulting in a shorter section of probe radiating to the wall. As shown in Figure 8, when the depth of insertion reaches about 0.6 in., a sharp transition in the curve results. This is caused by the above phenomena. At the lower power level (0.40 KW) the probe is at a higher temperature than the wall all the way to the upper shield. Thus, although the quantity of heat radiated to the probe from the heater decreases as the probe is removed, the entire probe (between heater and shield) is radiating to the wall. Also, at the lower temperatures (as compared to the 1 KW case) the emissive power of the surfaces is decreased significantly and the conduction along the probe to the GN_2 sink is competitive with the radiant mode of heat transmission.

The foregoing discourse also applies to Figures 15 and 14 (temperature profile of the probe).

Comparison of Figures 10 and 9 appear to show a discrepancy in the temperature of the aluminum GN_2 housing. A temperature of 415°R for the 1 KW case is shown and 790°R is shown for the 0.4 KW case. In the first analysis, heat transfer coefficients to the GN_2 were approximated and used in the analysis. Test data, which became available after this analysis, indicated that the temperature in question was 790°R . This temperature was used as a boundary condition for the 0.40 KW analysis. Evaluation of the effect of the aluminum temperature on the results obtained showed that the relatively low temperature levels existing on this surface have little or no influence on the thermal behavior of the regions of interest.

Both analyses (1 KW and 0.4 KW) were performed for the "reactor off" condition. For depths of sensing element insertion greater than 0.6 in., heat generation effects on the sensor would be small, while the temperature profiles along the probe would be elevated along the probe section that "sees" the walls.

The effect of heat generation on the thermocouple in actual operation was estimated. If the thermocouple is radiating to a body at 4000°R , and it is assumed that the heat generated internally is conducted radially to the surface of the thermocouple, the internal temperature will be less than 4005°R , and less than 4025°R for heat generation rates of 0.03 (GTR-13) and 1.0 (NRX-A2) watts/gm, respectively.

Figure 6 is obtained by combining the data of Figure 22 with the results obtained for heater power levels of 1 KW and 0.4 KW. This figure illustrates temperatures of the heating element, sensing element, and copper electrodes as a function of heater power level. It is evident from Figure 6 that the temperatures existing in the test fixture at the higher heater power levels are in excess of the melting points of several of the materials. It is recommended that the power input to the heater be increased slowly in order that temperatures in the system may be monitored and maintained within the operational range.

ANALYSIS

As previously mentioned in this appendix the first analysis was performed to determine the thermal radiation characteristics of the test fixture. It was assumed that the heating element was suspended in the test chamber and that thermal radiation was the only mode of heat transfer from the element. Additional simplifying assumptions made in this analysis were:

1. The material properties could be described by Kirchoff's Law (emissivity is equal to absorptivity).
2. Each of the six enclosing stainless steel surfaces were irradiated uniformly over their areas, but not necessarily in equal amounts.

An electrical analog of the system was formulated utilizing the Oppenheim Network Method¹. Basically, this method provides the solution of two simultaneous equations per nodal point:

$$Q_i = \sum_k A_i F_{i-k} (B_i - B_k) \quad (1)$$

and

$$Q_i = A_i \frac{\epsilon_i}{1-\epsilon_i} (e b_i - B_i) \quad (2)$$

where

- Q_i = net heat exchange between surface i and the rest of the enclosure, Btu/hr
 A_i = Area of surface, i, ft²
 F_{i-k} = shape factor between surface i and surface k, dimensionless
 B_i = total radiative flux leaving surface i, Btu/hr-ft²
 B_k = total radiative flux leaving surface k, Btu/hr-ft²
 ϵ_i = emissivity of surface i, dimensionless
 e_{bi} = black body emissive power of surface i, Btu/hr-ft²

It is to be noted that e_{bi} and B_i are related in the following manner:

$$B_i = \epsilon_i e_{bi} + (1 - \epsilon_i) H_i \quad (3)$$

where H_i is the radiative flux impinging upon surface i, Btu/hr-ft². Thus B_i is composed of emitted and reflected energy, and e_{bi} is a function of surface temperature only:

$$e_{bi} = \sigma T_i^4 \quad (4)$$

σ = Boltzman constant, 0.173×10^{-8} Btu/hr-ft²-°R⁴

T_i = absolute temperature of surface i, °R

A simplified electrical network (with front and back walls of the enclosure omitted) is shown in Figure 23. An electrical current proportional to the heater power level is introduced at the element node, and the current into each surface node is determined. This current is analogous to the heat flow Q_i Btu/hr passing through the surface i. This heat flow is then used to calculate the temperature of the stainless steel walls:

$$T_{ss} = \Delta T_{ss} + \Delta T_{asb} + \Delta T_f + 590^\circ\text{F} \quad (5)$$

$$\Delta T_{ss} = Q_i L / KA + (Q' L^2 / 2K)_{ss}$$

$$\Delta T_{asb} = (Q_i + Q_{ss}) / L / KA + (Q' L^2 / 2K)_{asb}$$

$$\Delta T_f = (Q_i + Q_{ss} + Q_{asb}) hA$$

where

T = temperature drop across a thermal resistance, $^{\circ}\text{R}$

Q_i = heat flow caused by incident thermal radiation, Btu/hr

Q' = internal heat generation rate, Btu/hr-ft³

Q = total quantity of heat generated within a material, Btu/hr

L = length of heat transfer path, ft

K = thermal conductivity of material, Btu/hr-ft - $^{\circ}\text{R}$

A = area of heat transfer path, ft²

h = heat transfer coefficient between asbestos and air, Btu/hr-ft²- $^{\circ}\text{R}$

590 $^{\circ}\text{R}$ = ambient air temperature

Subscripts:

ss = stainless steel

asb = asbestos

f = boundary layer between asbestos and ambient air

The terms Q' , Q_{ss} and Q_{asb} are zero for the reactor off condition.

Thus, from the measured W_i , T_i is determined by means of equation (5) and e_{bi} by equation (4). This potential (e_{bi}) is then set at the appropriate node and the procedure repeated until the new Q_i is compatible with the stainless steel temperature.

This procedure is applicable to all surfaces but the top of the fixture. The aluminum housing was assumed to have zero emissive power and was set at ground potential. This assumption is valid since the temperature of this surface would have to be above 1000 $^{\circ}\text{R}$ before the emissive power would become significant.

The analysis of the complete test fixture, including heat transmission through the thermocouple, copper electrodes, and convection to the stagnant helium, was then performed. Again an electrical analog of the system was developed. The analogy between electrical and thermal parameters is different than that which exists in the Oppenheim method. The following table summarizes the analogous quantities:

Electrical System	Radiation Analysis (Oppenheim)	Radiation Convection & Conduction Analysis
Voltage	Emissive Power, e_{bi} , σT^4 , Btu/HR-FT ²	Temperature °R
Current	Heat flow Q , $\frac{\text{Btu}}{\text{HR}}$	Heat Flow Q , $\frac{\text{Btu}}{\text{hr}}$
Resistance	$\frac{1}{AF}$ or $\frac{(1-\epsilon)}{A\epsilon}$ FT ⁻²	$\left. \begin{array}{l} \frac{1}{hA} \\ \frac{L}{KA} \end{array} \right\} \frac{\text{HR} - ^\circ\text{F}}{\text{Btu}}$

In order to simulate heat transfer by radiation when the other two modes of heat transfer are occurring simultaneously, it is necessary to manipulate the basic radiation equation:

$$Q_{\text{net}} = (F_{12})\sigma A_1 (T_1^4 - T_2^4) \quad (6)$$

where (F_{12}) is a radiant interchange factor (which includes configuration and surface emissivities) by defining a radiation coefficient:

$$h = \frac{(F_{12})\sigma(T_1^4 - T_2^4)}{T_1 - T_2} \quad (7)$$

The radiation interchange factor (F_{12}) is defined by Christiansen's equation² of net radiation as:

$$(F_{12}) = \frac{1}{1 + \epsilon_1 \left(\frac{1}{\epsilon_2} - 1 \right) A_1/A_2} \quad (8)$$

The electrical analog, based on column three of the above table and on equations 6, 7, and 8, was synthesized, and boundary conditions were applied. These boundary conditions were the known heat sink temperatures and the power input. The temperature dependent resistors were iterated until the proper temperature distribution was obtained. At the top of Figure 3 is a sketch of the thermocouple probe showing the number of nodes utilized in the simulation of the probe. Two nodal points were used to simulate the section of the copper electrode within the enclosure. The heat conducted along the copper electrode is gradually lost to the atmosphere by natural convection. In fact, the quantity of heat transmitted from the enclosure by this rod, and the base temperature (in the plane of the asbestos-air interface) can be expressed by:

$$Q_c = \sqrt{hCKA} (T_B - T_{amb}) \tanh (mL) \quad (9)$$

which is the solution to the classical problem of a cylindrical rod transferring heat to an ambient gas along its surface.

Q_c = heat input to the base of the fin. Btu/hr

h = heat transfer coefficient, Btu/hr-ft²-°F

C = circumference of fin, ft

K = thermal conductivity of the fin material, Btu/HR-FT-°F

A = cross-sectional area of the fin, ft²

T_B = temperature at the base of the fin, °R

T_{amb} = ambient temperature

$m = hC/KA$

L = length of the fin, ft

Since $\tanh(mL)$ approaches 1 asymptotically as (mL) goes to infinity, and is greater than 0.9999 when $mL = 6$, substitution of the parameters for m , results in an effective fin length of 100 in. Beyond this length no cooling effect is present. Equation (9) reduces to:

$$Q = \sqrt{hCKA} (T_B - t_a) \quad (10)$$

The thermal resistance of the entire cooling length can thus be represented by:

$$R_{Th} = \frac{1}{\sqrt{hCKA}} \frac{HR - ^\circ R}{Btu} \quad (11)$$

Property Values:

The thermal emissivity of stainless steel as a function of temperature can be expressed as:

$$E_{ss} = 0.37 + 1.59T (10^{-4})$$

where T = surface temperature, $^\circ R$. This equation was developed from data presented by McAdams³.

Zirconium Dioxide, aluminum, and copper were assumed to be gray bodies with emissivities³ of 0.52, 0.6, and 0.50, respectively.

Shape factors were determined with the aid of charts⁴, and the results are tabulated below:

SURFACES	F
Heating element to:	
front	0.850
side	0.027
top	0.130
bottom	0.028
Base to:	
front	0.31
side	0.14
top	0.10
Front to Side	0.14
S. S. to Al	0.374

The heating element was assumed to be a flat plate in the determination of these factors.

The heat transfer coefficients from the asbestos to the ambient and from the copper rod to the ambient were evaluated by³:

$$h = 0.29 (\Delta T/L)^{0.25}$$

h = heat transfer coefficient, Btu/Hr-ft²-°F

ΔT = temperature difference between surface and ambient, °R

L = characteristic length (height of wall, or rod diameter) ft

Heat transfer coefficients for the stagnant helium were evaluated by³.

$$Nu = C\bar{X}^n$$

where

Nu = Nusselt number

$\bar{X}$ = Reynold number x Prandtl number

c, n = Constants

These film coefficients ranged between 2.88 and 6.00 Btu/hr-FT²-°F. Results indicate that the heat transmitted by convection was negligible.

The percentage of the total power dissipation by the several heat transfer modes can be obtained from the following table:

Heat Transfer Path:	Depth of Insertion				
	1 in.	.8 in.	.6 in.	.4 in.	.2 in.
Radiation to the thermo-couple	5.6%	3.0%	1.8%	1.1%	.8%
Convection	4	4	4	4	4
Radiation to top S.S.	9	10	10	10	10
Radiation to the copper rod	20	21	21	21	21
Radiation to the wall	61	62	63	64	65

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