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AEROJET GENERAL TIRE GENERAL

REPORT NO. RN-DR-0044

DEVELOPMENT OF NERVA COPPER-CONSTANTAN IMMERSION THERMOCOUPLES

ROCKET ENGINE OPERATIONS—NUCLEAR

CONTRACT SNP-1 DECEMBER 1964 NERVA PROGRAM

RELEASED FOR ANNOUNCEMENT

IN NUCLEAR SCIENCE ABSTRACTS

AEROJET-GENERAL CORPORATION
A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY

The information in this report is presented to improve temperature measurements by thermocouples and to document the results of tests conducted by the NERVA Systems and Controls Department.

Written by

H. C. Chandon
Staff Engineer

APPROVED BY:

T. F. McGrath
Senior Department Manager
Instrumentation and Controls
REON Component Development Division

W P Gilles

W. P. Gilles, Manager
Instrumentation Development
Instrumentation and Controls
REON Component Development Division

INTRODUCTION

This report describes the development of immersion type copper-constantan thermocouples for NERVA NRX-A2 testing. All significant analyses and testing performed during the development of the copper-constantan thermocouples and the test results are described.

Two additional thermocouple combinations, chromel-alumel and chromel-constantan, were developed simultaneously for subsequent NERVA tests. All tests performed on the copper-constantan thermocouples have also been completed on the chromel-alumel and chromel-constantan thermocouples except the testing of complete radiation resistant immersion thermocouple assemblies. Since neither of these immersion thermocouple types have been required for provisioning of NRX kits, they have not been purchased for evaluation. Standardized tables and equations for chromel-constantan and chromel-alumel have also been completed.

A fourth thermocouple, platinel, was calibrated to determine the output and sensitivity characteristics below 32°F. Development of the platinel thermocouple was discontinued when it was determined the output was not as great as copper-constantan. Data on the platinel thermocouple are not included in this report.

Of the four thermocouple combinations tested, chromel-constantan has the greatest output and sensitivity. The output is -9.7334 millivolts at 423°F, as compared with -6.4309 for chromel-alumel and -6.1503 for copper-constantan when referenced to a 32°F junction. The sensitivity for chromel-constantan at -423°F is 3.8 microvolts per degree Fahrenheit as compared with 2.5 for chromel-alumel and 2.8 for copper-constantan. Complete details on the development of both chromel-constantan and chromel-alumel thermocouples will be published in a later report.

Temperatures in this report are reported in degrees Fahrenheit. To specify accuracy requirements in terms of degrees Rankine would require a table of many lines to cover the thermocouple ranges rather than the accepted three or four values

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as used in this report. To aid the reader, the frequently discussed temperatures are converted by the relationship $T_{(°R)} = T_{(°F)} + 459.67$.

Approximate liquid helium boiling point	-452.1°F or 6.8°R
Approximate liquid hydrogen boiling point	-423.0°F or 36.7°R
Approximate liquid neon boiling point	-410.6°F or 49.1°R
Approximate liquid nitrogen boiling point	-320.4°F or 139.7°R
Approximate sublimation point for carbon dioxide	-109.3°F or 350.4°R
Melting point of ice	32.0°F or 491.7°R
Temperature of oil bath	+200.0°F or 659.7°R
Temperature of salt bath	+400.0°F or 859.7°R

In future NERVA specifications, if it is desired, all temperatures will be reported in degrees Rankine and an accuracy requirement technique for specifications will be developed. It appears that an error band concept expressed in allowable microvolt spread could offer an improvement for thermocouples. This is quite apparent when analyzing errors for a complete system because all digital systems express their errors in terms of microvolts or digital counts.

For an up-to-date status on NERVA immersion thermocouples for NRX-A2, refer to the Instrumentation Data Book, code numbers T-65 through T-68, and T-74.

TABLE OF CONTENTS

Table of Contents (cont.)

Table of Contents (cont.)

I. OBJECTIVE

The objective of this program was to develop copper-constantan thermocouples for the NRX-A2 instrumentation kit which were capable of: (1) operating within the NRX-A2 environment, (2) measuring temperatures in the -425 to +700°F range, (3) converting the output millivolt signal to temperature by one master electromotive force versus temperature table, and (4) having an accuracy of ± 2%* over the -425 to -300°F range; ± 1% over the -300 to -100°F range; ± 1°F over the -100 to +200°F range; and ± 0.5% over the +200 to +700°F range.

This program was also intended to provide the basic technology for the fabrication of all types of copper-constantan thermocouples for subsequent NRX-A instrumentation kits and diagnostic instrumentation requirements.

* Accuracy, when specified in percent, shall be defined to be percent of the point or temperature in degress Fahrenheit.

II. SUMMARY

When copper and constantan thermocouple wires are subjected to a temperature gradient between the measurement junction and the reference junction, an emf is induced along the wire. The magnitude of this voltage is dependent upon the wire chemical composition and the grain size as well as the temperature difference between the junctions and the absolute temperature of both junctions. Grain size can best be controlled by fully annealing each thermocouple wire in a furnace. For example, the emf actually increased 64.2 microvolts for a copper-constantan thermocouple when annealed and calibrated at liquid helium (-452.1°F) in reference to 32°F. The Temptron facility was found to be a satisfactory source for providing a uniform output for thermocouples regardless of configuration. Temptron anneals the wire by passing it thorugh a 1800°F temperature zone in an argon atmosphere for three minutes, followed by a cooldown cycle at 100°F for six minutes in a water cooled jacket. The wire is continuously passed through the furnace at a uniform rate.

This program resulted in the selection of new electromotive force versus temperature values for the -459 to +32°F temperature range. When these values are combined with a National Bureau of Standards (NBS) Washington Table, one master table is formulated for the range of -459 to +750°F which has a 32°F reference junction. From this master table, equations for temperature as a function of emf output were derived for a 32°F reference temperature. There are eight equations, one 5th, one 6th, and six 7th degree polynominals, required to cover the -459 to +750°F range. All eight equations may be translated to any reference junction temperature by a simple mathematical substitution and recombination of like powers for the millivolt term. New emf data for the -459 to +32°F range were based on a 51 point calibration of a copper-constantan thermocouple made from two large spools of wire. This thermocouple was fully annealed and insulated with teflon tubing. All readings were made in reference to a 32°F junction. Forty-seven data points were within the development objective of ± 0.5°F for the -425 to +32°F range. The other four data points were within ± 1.1°F at the very low temperatures between -425 and -400°F.

Calibrations have been made on several types of thermocouple wire configurations used in the fabrication of complete thermocouple assemblies to determine thermal emf shifts. The configurations tested included eight, swaged, thermocouple-stem assemblies with four types of junctions and two, ceramic-coated wire samples, one of which was fabricated into a complete cable assembly; all were well within the development objective of ± 1% over the -425 to -100°F range, ± 1°F over the -100 to +200°F range, and ± 0.5% over the +200 to +700°F range.

Temptron supplied several spools of 22 and 26 gage candidate wire for calibration by Aerojet. Of this wire, 21,400 feet of constantan, 9,670 feet of copper 22 gage wire, 9,078 feet of constantan and 18,000 feet of copper 26 gage wire were reserved for manufacturing NERVA thermocouples. All of this wire matches the Aerojet copper-constantan thermocouple table. To prove the acceptability of wire to be used, a sample thermocouple was calibrated at six temperatures over the -459 to +700°F range. The calibration points were liquid helium (-452°F), liquid neon (-411°F), liquid nitrogen (-320°F), carbon dioxide (-110°F), ice (+32°F), and oil (+200 and +400°F); each point must be within the limits of ± 20 microvolts at -452°F, ± 1% from -425 to -100°F, ± 1°F from -100 to +200°F, and ± 0.5% from +200 to +700°F. The 22 gage wire is used in the fabrication of 0.125 in. OD swaged stems and lead wire for the NRX-A2 immersion thermocouples and the 26 gage wire is used to fabricate the NRX-A2 surface thermocouple cables.

Additional samples of 36 gage wire are scheduled to be tested. Thirty-six (0.005-in. OD) gage wire is to be used in the fabrication of fast response immersion thermocouples as requested by The Westinghouse Astronuclear Laboratories.

Thirty-one thermocouples of the NRX-A2 design have been purchased and delivered for the NERVA program. Detailed requirements for the NRX-A2 design are contained on AGC-SCD-701530 through 701554 and in Component Specification AGC-42136/12. As part of acceptance testing, each thermocouple was calibrated at four temperatures and the response was measured. The calibration points were liquid neon (-411°F), liquid nitrogen (-320°F), ice (+32°F), and oil (+400°F). All calibration data for each thermocouple were within Aerojet specification limits and the response for one time constant was considerably less than the

actual specification requirement of 0.5 sec maximum. All thermocouples have a time constant of less then 0.2 sec when subjected to a step from ambient air to 170°F water flowing at 3 ft/sec. Three of these thermocouples have been non-nuclear tested at an outside laboratory and were subjected to vibration tests of 20 g sine wave, 32 g random, 38 g sine and random, 300°F high temperature, and -100°F low temperature.

Four copper-constantan thermocouples were tested on Ground Test Reactor (GTR) Test 14 in liquid hydrogen. All units measured the dewar temperature within 13°F when filled with liquid hydrogen. Two of the thermocouples were of the NRX-A2 design except they were modified to adapt to the dewar. The other two thermocouples were fabricated from pre-calibrated stems. There was no measurable gamma heating and the neutron damage is estimated to be less than 3°F.

There are six tables in this report and all are presented in Appendix A:

1. Table I, NBS Boulder Copper vs Constantan Thermocouple Table with 0°K and 32°F Reference, tabulates the calculated data used in the conversion of the NBS Boulder Table to an equivalent table with a 32°F reference junction.

2. Table II, NBS Boulder/Washington Copper vs Constantan Table, is a table of emf values for the -425 to +750°F temperature range in 1°F increments. This table is based upon the NBS Boulder published data below 32°F and NBS Washington published data above 32°F.

3. Table III, Test Results - Aerojet Calibration Data Reduced per NBS Boulder/Washington Copper vs Constantan Thermocouple Table, tabulates all the calculated temperature and output deviations for 34 of the 96 tested thermocouples. The test results are in reference to Table II.

4. Table IV, Test Results - Aerojet Multipoint Calibration Data Reduced per NBS Boulder/Washington and Aerojet Copper vs Constantan Thermocouple Tables, tabulates all calibration data and calculated temperature and output deviations for three thermocouples. These thermocouples were calibrated at 51 temperatures of 32°F or below. The test results are in reference to Tables II and V.

5. Table V, Aerojet Copper vs Constantan Table, is a table of emf values for the -459 to +750°F range in 1°F increments. This table is based on the calibration data from two spools of wire being retained for the fabrication of NERVA thermocouples.

6. Table VI, Test Results - Aerojet Calibration Data Reduced per Aerojet Copper vs Constantan Thermocouple Table, tabulates all the calculated temperature and output deviations for 66 of the 96 tested thermocouples. The test results are in reference to Table V.

III. CONCLUSIONS AND RECOMMENDATIONS

A general program was conducted during the development of NERVA copper-constantan thermocouples which will allow their fabrication regardless of the configuration. All component parts of the thermocouple, starting at the junction and ending with the leadwires, have been evaluated.

Copper wire as drawn by the Hudson Wire Company and constantan wire as drawn by the Wilbur B. Driver Company can be selected and matched to the Aerojet tables. Each piece of wire used in the construction of a thermocouple must be annealed. The process used by Temptron for annealing bare wire and swaged wire is satisfactory and is recommended for the NERVA program.

All thermocouples may be standardized to have one master table or equations to convert emf to temperature. The table and equations included in this report are based on a 32°F reference junction but may be converted mathematically to any reference junction temperature. The pre-selection of bare wire is necessary to have complete standardization of the emf vs temperature for any thermocouple.

A. RECOMMENDED COMPONENT PARTS FOR THERMOCOUPLES:

1. Physical Sciences Corporation cable with 22 gage wire. This cable has operated successfully in vibration tests at high and low temperatures and in a combined cryogenic and nuclear/irradiation environment.

2. Temptron swaged leadwire (TEMPAK) with 22 gage wire. This leadwire has operated successfully in vibration tests at high and low temperatures and nuclear irradiation environments.

3. Temptron custom-built thermocouples with 22 gage wire. The Model 2925 thermocouples have qualified for the NERVA NRX-A2 kit in accordance with AGC-SCD 701530 through 701554.

B. DESIGN CONSIDERATIONS (COPPER-CONSTANTAN THERMOCOUPLES)

1. All thermocouples should be fabricated from one lot of wire which has a basic calibration table. The basic calibration of the wire lot should be made on a fully annealed sample.

2. Splice junctions between the reference junction and the measurement junction should be eliminated. If a splice junction is essential to facilitate fabrication of the thermocouple, strict adherence to item 1, above, is necessary. It is also necessary that the wire be from the same spool and as close as possible to the original separating point.

3. Anneal all wire, including the leadwire, in the thermocouple assembly.

4. The temperature gradients between the thermocouple reference junction should be kept to an absolute minimum. It is preferred to have the largest gradient along the stem of immersion thermocouples because the inherent ridged design of the stem generally precludes work hardening the wire.

5. Ice and ambient reference junctions are preferred over a cryogenic bath for cryogenic measurements because they will generally eliminate one unnecessary large temperature gradient. A statement must be made to qualify this recommendation; the temperature of the reference bath must be extremely stable and free from drift. The sensitivity of a copper-constantan thermocouple is approximately ten times as high at room temperature as at liquid hydrogen temperature. For example, a 1°F ice bath or hot reference junction shift will indicate a 10°F error in the emf output at liquid hydrogen temperatures.

6. To improve the resolution of the thermocouple readout system for cryogenic measurements, it is recommended that a bias precision voltage substitution be used over a cryogenic reference bath. There are cases where a

cryogenic bath has an advantage over the ice bath, however, these are infrequent and should be evaluated as a special application.

7. For high precision temperature measurements a high quality platinum resistance temperature transducer should be used, e.g., Model 134EB (nuclear service) or 134CT (non-nuclear service) manufactured by Rosemount Engineering Company. The Aerojet developed constant-current system is recommended for signal conditioning these transducers.

IV. DISCUSSION

There are two accepted sets of copper-constantan thermocouple tables, NBS Washington Table (Reference 1, Table 21) and NBS Boulder Table (Reference 2a, Table 2), which list the electromotive force in millivolts corresponding to temperature. The NBS Washington Table includes temperatures of -313 to +750°F in increments of 1°F and has a 32°F reference junction. The NBS Boulder Table includes temperatures of 0 to 300°K in increments of 1°K and has a 0°K reference junction. The data published in each table are intended to be a guide for output of a copper-constantan thermocouple. Both NBS Boulder and Washington recommended that each thermocouple be calibrated to obtain a correction curve. Both tables overlap in the -313°F (81.48°K) to 80.33°F (300°K) region and are displaced by 6.2039 millivolts at -313°F to 6.2649 millivolts at 80.33°F. The displacement at 32°F (273.17°K) is 6.2587 millivolts.

Several thermocouple suppliers sell calibrated and matched spools of wire which are in close agreement with the NBS Washington Table from -150 to +750°F as catalog items. The Instrument Society of America (ISA) has standardized on the NBS Washington Table and has established standard and special limits of error for this combination. These tolerances are:

(1) ±2% for -150 to -75°F, ±1.5°F for -75 to +200°F, and ±0.75% for +200 to +700°F for the standard limits of error for thermocouple wire, or

(2) ±1% for -300 to -75°F, ±0.75°F for -75 to +200°F, and ±0.375% for +200 to +700°F for the special limits of error for thermocouple wire (Reference 3, Table II). Copper-constantan has an ISA designation of Type T. Wire which meets special limits of error is often called premium grade wire.

Standardization of thermocouple outputs below -300°F had not previously been achieved. Very few thermocouple suppliers are willing to guarantee that their products will conform to any table below -300°F. The lack of standardization below -300°F is attributed to the many alloys of constantan that are available from each wire manufacturer. Constantan will vary from 60 to 45% copper with the balance nickel (Reference 4, Table 2.2). Two wire manufacturers with the trade name and the approximate chemical composition for constantan wire are: (1) The Wilbur B. Driver Company, Newark, New Jersey; trade name - Cupron; chemical composition - 55% copper, 45% nickel, and (2) The Driver-Harris Company, Harrison, New Jersey; trade name - Advance; chemical composition - 57% copper, 43% nickel. Both of these wires are catalog items. To complicate the problem, most thermocouple manufacturers, i.e., Leeds and Northrup Company, Philadelphia, Pennsylvania; Minneapolis-Honeywell Regulator Company, Minneapolis, Minnesota; and Thermal Electric Company, Saddle Brook, New Jersey, purchase their wire to specifications which can alter the chemical composition for constantan wire from the listed catalog composition.

Laboratory tests were conducted during this development program which detected that one spool of copper wire will produce large thermal emf when compared with a different copper wire spool. The wire spools used were of the same size, purchased at the same time, drawn by the same manufacturers, and annealed in the same facility.

In summary, there is *no single* table published or recommended by NBS Washington or Boulder for copper-constantan thermocouples that include the -425 to +700°F range. The output of a copper-constantan thermocouple will vary greatly with the chemical composition and the degree of annealing when subjected to temperature gradients at a low temperature and referenced to 32°F.

A. COMPONENT SPECIFICATION AGC 42136

Component Specification AGC 42136 (Reference 5) is a general thermocouple specification which controls welding, materials, cleaning, packaging, etc., and the requirements for the procurement of all test area thermocouples and the NRX-A2 immersion thermocouples. The original issue and Revision A required that the output of all chromel-alumel, iron-constantan, and copper-constantan thermocouples be standardized to a set of ISA tables (Reference 6). Table 9 of the ISA Recommended Practice (Reference 6) defines the output for copper-constantan thermocouples in 10 degree increments to the nearest microvolt and covers the -310 to +750°F range. Revision B of this specification required that the output of all chromel-alumel, iron-constantan, and copper-constantan thermocouples be standardized to the NBS Washington tables, which limited the lower temperature to -313°F for copper-constantan

thermocouples. During the effectivity of both of these issues, all temperature measurements in the Aerojet Sacramento test area were limited to liquid oxygen (-297°F) for the lower end.

The NBS Boulder/Washington Copper vs Constantan Thermocouple Table was prepared for the NERVA program and has been published in Appendix II of Revision C of Component Specification AGC 42136. This table is the combination of the two NBS tables and is based on NBS Washington data above +32°F and NBS Boulder data below 32°F. The 32°F reference was selected for joining the two tables together. In addition, wire is commercially available in accordance with the NBS Washington Table above 32°F, and NBS Boulder is recognized as the authority for cryogenic measurement problems. To combine these two tables it was necessary to convert the NBS Boulder data from the -459.67°F (0°K) to a 32°F (273.17°K) reference junction and each temperature had to be calculated in degrees Fahrenheit. The temperature was calculated in degrees Fahrenheit by substituting all values from the Boulder table into equation (1).

$$T_{(°F)} = 1.8\, T_{(°K)} - 459.67 \qquad (1)$$

where $T_{(°F)}$ is the calculated temperature in °F

$T_{(°K)}$ is the table value for temperature in °K

The calculated temperature values are tabulated in Column (2) of Table I. The output millivolt data were converted from the 0°K reference junction to an equivalent 32°F reference junction temperature by substituting millivolt values into equation (2).

$$E_{(32°F)} = E_{(0°K)} - 6.2587$$

where $E_{(32°F)}$ is the calculated thermocouple output with a 32°F reference junction in millivolts

$E_{(0°K)}$ is the table value for the thermocouple output with a 0°K reference junction in millivolts

Converted output values are also tabulated in Column (4) of Table I. The -6.2587 millivolt constant in equation (2) was the interpolation value from the Boulder Table for a temperature of 273.17°K.

Using the Boulder data in Columns (2) and (4) of Table I, five polynominal equations (3) thru (7) were derived to express temperature as a function of the output in millivolts. These five equations (Reference 7) cover the -6.204 to 20.80 millivolt range. All data points from columns (2) and (4) are within 0.05°F of the calculated temperature for each millivolt value. Equations (3) thru (8) are valid for the designated millivolt range and equivalent temperature range.

-6.204 to -6.100 millivolt (-425 to -400°F) range

$$T_{(°F)} = 668934.46 + 329301.91\left[E_{(32°F)}\right] + 54037.746\left[E_{(32°F)}\right]^2 + 2957.6793\left[E_{(32°F)}\right]^3 \qquad (3)$$

where $T_{(°F)}$ is the calculated temperature in °F,

$E_{(32°F)}$ is the measured output in millivolts.

-6.100 to -5.955 millivolt (-400 to -375°F) range

$$T_{(°F)} = 94658.797 + 47943.318\left[E_{(32°F)}\right] + 8088.3573\left[E_{(32°F)}\right]^2 + 456.30264\left[E_{(32°F)}\right] \qquad (4)$$

-5.955 to -5.740 millivolt (-375 to -345°F) range

$$T_{(°F)} = -147170.84 - 103026.91\left[E_{(32°F)}\right] - 27090.083\left[E_{(32°F)}\right]^2 - 3167.3191\left[E_{(32°F)}\right]^3 - 139.09737\left[E_{(32°F)}\right]^4 \qquad (5)$$

-5.470 to -4.410 millivolt (-345 to -220°F) range

$$T_{(°F)} = 4387.1672 + 4593.8226\left[E_{(32°F)}\right]\ 1900.7712\left[E_{(32°F)}\right]^2 + 398.90203\left[E_{(32°F)}\right]^3 + 41.941113\left[E_{(32°F)}\right]^4 + 1.7779397\left[E_{(32°F)}\right] \qquad (6)$$

-4.410 to 0.0 millivolt (-220 to +32°F) range

$$T_{(°F)} = 31.997986 + 46.519892\left[E_{(32°F)}\right] - 1.4277624\left[E_{(32°F)}\right]^2 + 0.1075096\left[E_{(32°F)}\right]^3 - 0.013419154\left[E_{(32°F)}\right]^4 + 5.2800791 \times 10^{-3}\left[E_{(32°F)}\right]^5 + 1.8855408 \times 10^{-3}\left[E_{(32°F)}\right]^6 + 2.9533153 \times 10^{-4}\left[E_{(32°F)}\right]^7 \qquad (7)$$

Only one equation (8) is necessary for the +32 to +750°F range to fit all the Washington data points within 0.05°F (Reference 7).

0 to 20.80 millivolt (+32 to +750°F) range

$$T_{(°F)} = 31.990188 + 46.867117\left[E_{(32°F)}\right] - 1.5061342\left[E_{(32°F)}\right]^2 + 0.12210538\left[E_{(32°F)}\right]^3 - 9.2066322 \times 10^{-3}\left[E_{(32°F)}\right]^4 + 4.8634078 \times 10^{-4}\left[E_{(32°F)}\right]^5 - 1.4654069 \times 10^{-5}\left[E_{(32°F)}\right]^6 + 1.8545312 \times 10^{-7}\left[E_{(32°F)}\right]^7 \qquad (8)$$

Based upon equations (3) through (8), Table II was prepared for the evaluation of thermocouples for the NERVA program.

B. EVALUATION OF NBS BOULDER/WASHINGTON THERMOCOUPLE TABLES

Sixteen copper-constantan thermocouples were selected at random from the Aerojet transducer laboratory stock for calibration. Eleven of the thermocouples had a grounded-shielded junction and five had an exposed junction. The calibrations were intended to evaluate the NBS Boulder / Washington Table published in Component Specification AGC 42136C at cryogenic temperatures. These thermocouples were manufactured from premium grade wire in accordance with specification AGC 42136B and were checked at the steam point during receiving inspection. Data results for this calibration are tabulated in Table III, test items C/C-1 through C/C-16. Each thermocouple was calibrated in liquid neon (-411°F) and liquid nitrogen (-320°F). The output deviated an average of 89.0 microvolts or +18.20°F at -411°F and 65.3 microvolts or +7.06°F at -320°F which indicated that the NBS Boulder/Washington Table was not the best combination to match the existing hardware available to the NERVA program.

As a result of the large thermocouple output deviations, eighteen sample bare wire thermocouples were fabricated by Temptron*, Reseda, California, for evaluation at cryogenic temperatures. Both unannealed and annealed samples were calibrated to select a wire from which to fabricate thermocouple assemblies. Each bare wire thermocouple was fabricated from two large spools of wire and was approximately three feet long. The junction was TIG welded and the wires were insulated with Teflon tubing during calibration. Two sizes of wire, 22 and 30 gage, were fabricated with copper wire drawn by the Hudson Wire Co., Ossining, New York, and constantan wire drawn by the Wilbur B. Driver Co. Both annealed and unannealed (off the spool) thermocouples were assembled. Sample bare wire thermocouples are illustrated in Figures 1 and 2.

The spools were selected by Temptron, based on their high temperature calibration data and liquid oxygen calibration data. The output of each spool had to meet the ISA premium grade requirements above +32°F and have an output greater than that published in NBS 561 at liquid oxygen (-297°F). Each of the bare wire thermocouples was subjected to a four point calibration, liquid helium (-452°F), liquid neon (-411°F), liquid nitrogen (-320°F), and the ice point (32°F). The data for the Aerojet calibration are tabulated in Table III, test items C/C-17 through C/C-34.

Calibration data for the unannealed 30 gage thermocouple wire, test items C/C-21 through C/C-25, was the best match to the NBS Boulder/Washington Table. Of these five thermocouples, test item C/C-23 had the greatest deviation and satisfied the calibration development objective. Test item C/C-23 deviated by 24.8 microvolts or 5.64°F at -411°F, 4.0 microvolts or 0.50°F at -320°F, and 0 microvolt or 0°F at 32°F. Unannealed wire calibration data cannot be used for the selection of wire because additional work hardening is generally introduced when the wire is processed

*Temptron was recently acquired by the Consolidated Controls Corporation, El Segundo, California. Temptron has relocated most of its facilities at the El Segundo Plant and has become the Temptron Products Division.

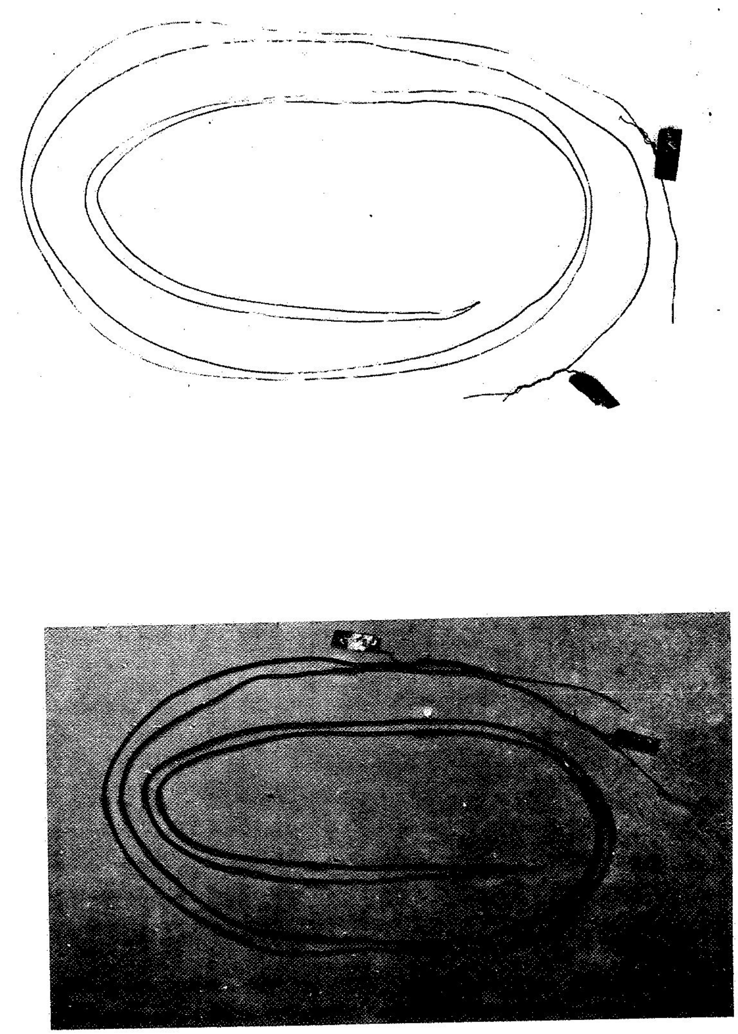

Figure 1
Bare Wire Thermocouples, 22 and 30 Gage Wire

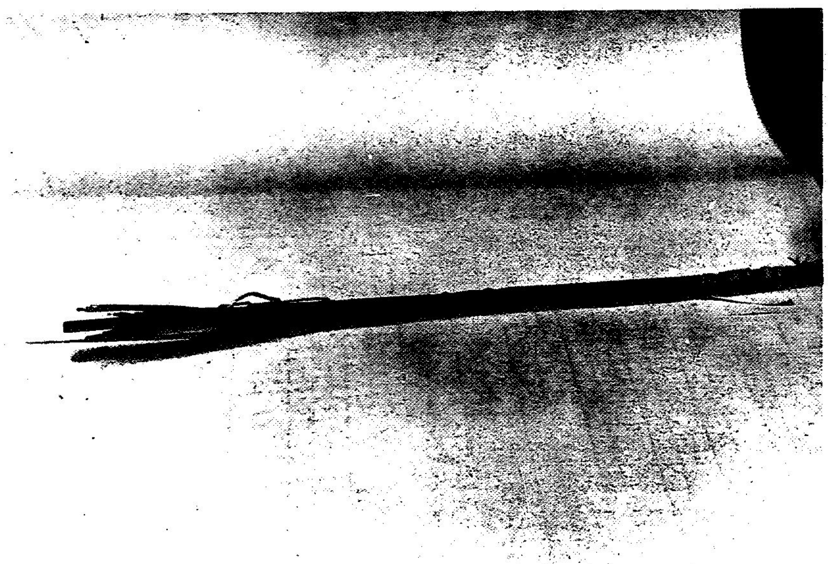

Figure 2
Bare Wire Thermocouples Prepared For Calibration In Fixed Point Baths

during the fabrication of components. Thus, the calibration will shift and not be repeatable for unannealed wire. To overcome the large calibration shifts caused by work handling, only annealed wire calibration data are used. By having each component annealed after fabrication, the calibration data can be repeated.

Calibration data for test items C/C-26 and 27 have the closest emf vs temperature relationship to the NBS Boulder/Washington Table. The data deviated by 52.2 microvolts or 26.7°F at -452°F, 34.8 microvolts or 7.75°F at -411°F, 26.0 microvolts or 1.86°F at -320°F, and 0 microvolt or 0°F at 32°F for C/C-26. Both test items C/C-26 and 27 were fabricated from spool 75-2 vs 75A1 and annealed.

Calibration data from 64 Westinghouse Astronuclear Laboratory (WANL) copper-constantan thermocouples (Reference 8) shipped with NRX-A1 were also evaluated to compare their output against NBS Boulder/Washington Table. All of the WANL thermocouples were manufactured and calibrated by Aero Research Company of Chicago, Illinois. Calibration data were measured at four temperatures, liquid helium (-452°F), liquid nitrogen (-320°F), carbon dioxide (-110°F), and the ice point (32°F), with a 32°F reference junction. The standard deviation was 149 microvolts or 51.7°F at -452°F, 39 microvolts or 4.4°F at -320°F, 18.4 microvolts or 1.4°F at -110°F, and 0 microvolt or 0°F at 32°F for the 64 thermocouples. It is estimated that the standard deviation at -410°F would be 95 microvolts or 18°F.

An analysis of the combined data of the 16 test area thermocouples, 18 bare wire samples, and 64 WANL thermocouples at cryogenic temperatures indicated that an improved table for NERVA would be desirable. A meeting was held with WANL to discuss the evaluation data. It was concluded that a new curve for copper-constantan should be developed for NERVA data reduction and procurement. It was agreed that this curve should be near the average data of the 64 WANL thermocouples and the test area thermocouples to be best utilized. For this reason spools 75-2 vs 75A1, 75-1 vs 75A3, and 80 vs 80A1 were selected for continued development.

Of special interest in support of the Boulder tables, a spool of copper-constantan 20 gage duplex extension wire insulated with a varnish impregnated fiber glass was available for the fabrication of 35 thermocouples for the M-1 program by Aerojet. The wire manufacturer was unknown. All thermocouples were calibrated at liquid neon using a 32°F reference junction and correlated to within 12 microvolts or 5°F of the NBS Boulder tables. Since the supply of wire was limited and the degree of annealing was unknown, no testing was performed under NERVA funds.

C. DEVELOPMENT OF AEROJET THERMOCOUPLE TABLE AND EQUATIONS

At the recommendation of Dr. Flynn, Duane Burgeson, and M. D. Bunch (NERVA advisors retained by SNPO-C) of the Cryogenic Engineering Laboratories, NBS, Boulder, Colorado, the philosophy adopted by Aerojet for the NERVA program was to select at least two large spools of wire, one copper and one constantan, to be calibrated and used in manufacturing all thermocouples. The tables published by NBS Boulder were used as a guide in this development. The wire that was available for calibration by Aerojet was from a different supplier than that used for the basis of the Boulder tables. The Boulder data were based on 28 gage constantan and 36 gage copper wire provided by Thermal Electric Company. The Aerojet table was based on 22 gage constantan (CUPRON) wire from the Wilbur B. Driver Company, and 22 gage copper wire from the Hudson Wire Company.

Three additional copper-constantan thermocouples were fabricated by Temptron using the spools which had been calibrated at four points by Aerojet. These thermocouples were longer to allow for insertion into the helium cooled cryostat and were fabricated from: (1) copper spool 75-2 and constantan spool 75A1 (S/N 3), (2) copper spool 75-1 and constantan spool 75A3 (S/N 3), and (3) copper spool 80 and constantan spool 80A1 (S/N 2). Thermocouples (1) and (2) contained 22 gage wire and thermcouple (3) contained 30 gage wire. Each thermocouple was fully annealed by Temptron in their argon atmosphere furnace with a water-cool stage. The cycle consisted of passing through a constant temperature area of 1800°F (provided by three heating elements) for three minutes, followed by six minutes cooling in a water cooled area.

After annealing, each thermocouple was handled as little as possible and carried in a long tube strapped to a stick. The three copper-constantan, two chromel-alumel, and one chromel-constantan thermocouples were assembled into a bundle with a Rosemount Engineering Co. standard thermometer, Model 162C, as illustrated in Figure 3.

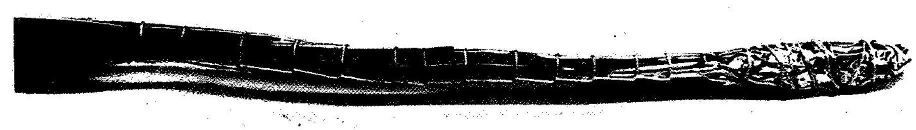

Figure 3
Bare Wire Thermocouples Prepared For Calibration
In Cryostat and Fixed Point Baths

The assembly of six thermocouples was calibrated in fixed point baths of liquid helium (-452°F), liquid neon (-411°F), liquid nitrogen (-320°F), crushed dry carbon dioxide (-110°F), and the ice point of water (32°F). The assembly was then placed in the cryostat and calibrated at 44 points ranging from -427 to -20°F, using a 32°F reference bath. The calibration data for the three copper-constantan thermocouples are tabulated in Table IV, test items C/C-35 through 37. These thermocouples repeated the initial spool calibration at the fixed points within approximately 7 microvolts at -452°F, 11 microvolts or 2°F at -411°F, 6 microvolts or 0.5°F at -320°F and 0 microvolt or 0°F at 32°F for spool 75-2 vs 75A1, S/N 3 (test item C/C-35); 14 microvolts at -452°F, 14 microvolts or 3.6°F at -411°F, 6 microvolts or 0.5°F at -320°F and 0 microvolt or 0°F at 32°F for spool 75-1 vs 75A3, S/N 3 (test item C/C-36); and 5 microvolts at -452°F, 2.5 microvolts or 2.4°F at -411°F, 1 microvolt or 1.2°F at -320°F, and 0 microvolt or 0°F at 32°F for spool 80 vs 80A1, S/N 2 (test item C/C-37), when reduced by the NBS Boulder/Washington Table. Data in reference to the NBS Boulder/Washington Table are plotted in Figure 4 for the three copper-constantan thermocouples.

Spool 75-2 vs 75A1 was selected to be retained for the NERVA program because: (1) it was the largest spool of wire, (2) it had the greatest output, (3) 22 gage wire was needed before 30 gage wire, and (4) it was of sufficient length (4000 feet) to fabricate all anticipated thermocouples for the NERVA program for at least two years. Based on the data obtained from the 51 point calibration of S/N 3, 75-2 vs 75A1 thermocouple calibration, Table V has been formulated (Reference 9). This table is based on a computer analysis to fit the experimental dat. by the least square method. Results of the first computer run were smoothed graphically before the second and final computer analysis. Five equations, (11) through (15), were necessary to fit the measured data within 0.5°F for the -425 to +32°F range. Two additional equations, (9) and (10), were derived to extend the range from -425 to -459°F. Only one equation (16) is necessary to cover the +32 to +750°F range since the output is essentially linear with respect to temperature. The data for the +32 to +750°F range were that developed by NBS Washington and refined by Westinghouse (Reference 2b, Table 3).

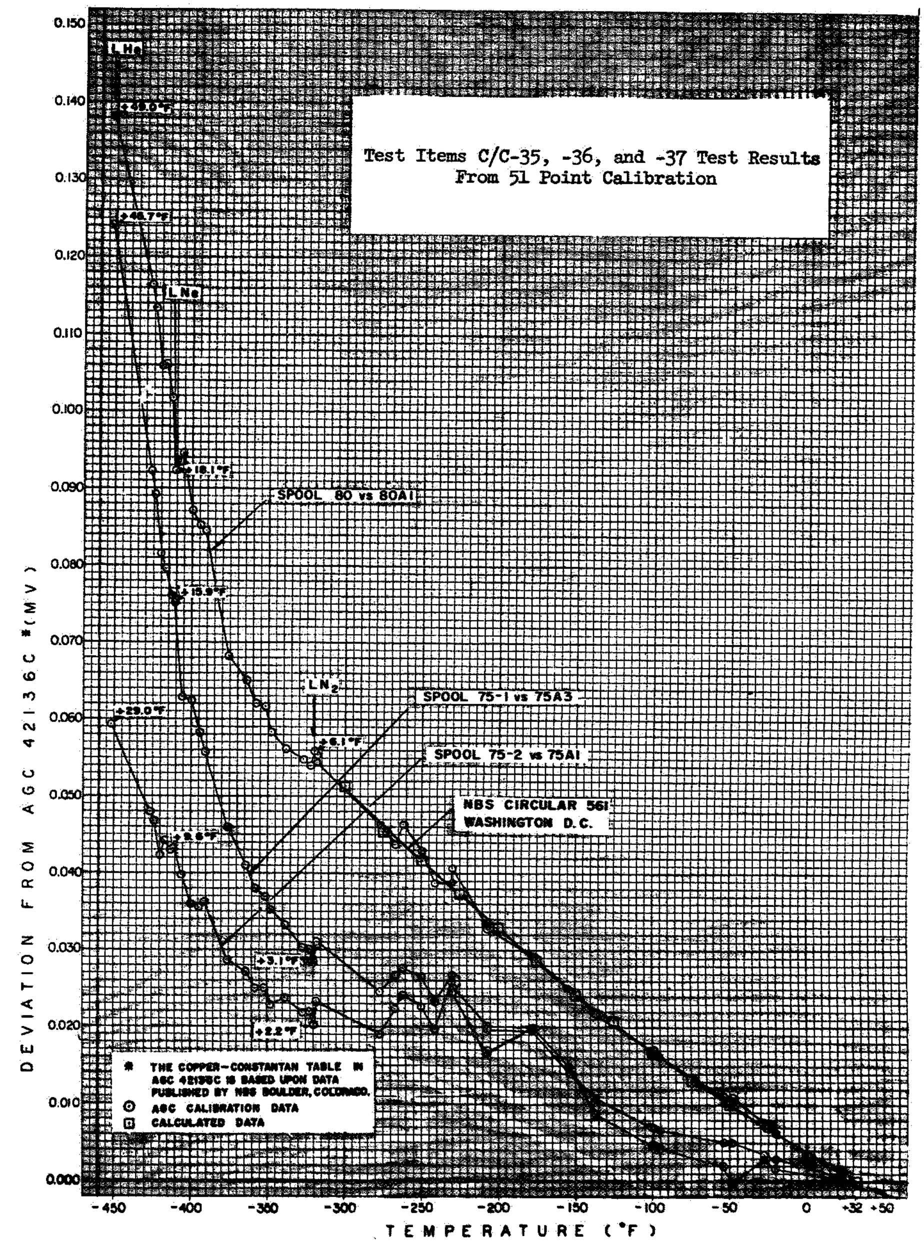

Figure 4

The two additional equations (9) and (10), and the Aerojet tabular values for the -459 to -430°F range are of questionable value. These data were derived graphically by extending the best curve from the -426°F calibration point to the -452°F liquid helium calibration point on a very large (48 by 60 inch) graph. The emf output at liquid helium temperature is accurate and repeatable to 5 microvolts and is very important in the selection of additional wire to fabricate cable and thermocouples.

Equations (9) through (16) are normalized about X for greatest reduction accuracy. In these equations (NX) is $\frac{X - M}{D}$ or the normalized X, and X is millivolts.

-459 to -442°F range

$$°F = -445.3467 + 5.856736(NX) - 3.1845252(NX)^2 + 8.109302(NX)^3 + 4.557098(NX)^4 - 16.42101(NX)^5 - 5.396593(NX)^6 + 11.83448(NX)^7 \quad (9)$$

where M is -6.192050
D is 6.349981×10^{-3}

-442 to -430°F range

$$°F = -432.5927 + 8.708294(NX) - 1.415209(NX)^2 + 0.5284621(NX)^3 - 0.4856088(NX)^4 + 0.2630089(NX)^5 \quad (10)$$

where M is -6.173000
D is 1.760000×10^{-2}

-430 to -400°F range

$$°F = -410.1864 + 18.01230(NX) - 3.667590(NX)^2 + 1.046557(NX)^3 - 0.07896631(NX)^4 - 0.08854434(NX)^5 - 0.5704564(NX)^6 + 0.5418812(NX)^7 \quad (11)$$

where M is -6.108200
D is 6.760001×10^{-2}

-400 to -350°F range

$$°F = -370.2057 + 27.89462(NX) - 6.317931(NX)^2 + 3.552788(NX)^3 + 5.212980(NX)^4 - 4.196173(NX)^5 - 3.229015(NX)^6 + 2.253689(NX)^7 \quad (12)$$

where M is -5.900300
D is 1.830000×10^{-1}

-350 to -275°F range

$$°F = -307.7435 + 42.03493(NX) - 3.705577(NX)^2 - 2.211694(NX)^3 - 0.2672822(NX)^4 + 3.234544(NX)^5 - 0.2963832(NX)^6 - 1.060024(NX)^7 \quad (13)$$

where M is -5.391400
D is 3.941000×10^{-1}

-275 to -200°F range

$$°F = -234.5232 + 41.91168(NX) - 2.540883(NX)^2 + 0.8555740(NX)^3 + 0.2349280(NX)^4 - 1.261019(NX)^5 - 0.1648948(NX)^6 + 0.4863527(NX)^7 \quad (14)$$

where M is -4.577300
D is 5.214000×10^{-1}

-200 to +32°F range

$$°F = -73.32950 + 113.2920(NX) - 10.41095(NX)^2 + 4.859048(NX)^3 - 5.410324(NX)^4 - 1.169196(NX)^5 + 3.249508(NX)^6 \quad (15)$$

where M is -2.094700
D is 2.073300

+32 to +750°F range

$$°F = -428.9411 + 345.1504(NX) - 32.44824(NX)^2 + 11.80743(NX)^3 - 4.339720(NX)^4 + 1.295019(NX)^5 - 1.653322(NX)^6 + 1.238367(NX)^7 \quad (16)$$

where M is 10.39140
D is 10.41280

The values assigned to the Aerojet Table were selected from a computer tabulation for temperatures from -6.1999 to 0 millivolts in 0.1 microvolt increments and from 0 to 20.819 millivolts in 1.0 microvolt increments using equations (9) through (16).

All spool 75-2 vs 75Al, S/N 3, data points for the 51 point calibration deviated 5 microvolts or less from the Aerojet Table (Table IV). Figure 5 illustrates graphically the spread in the data. Forty-seven of the fity-one data points were within the development objective of ±0.5°F over the -425 to +32°F range. The other four points were within 1.1°F at the very low temperatures between -425 and -400°F.

The test results for the five bare wire, 22 gage, annealed thermocouples calibrated at liquid helium, liquid neon, liquid nitrogen, carbon dioxide, and the ice point are tabulated in Table VI (test items C/C-26, 27, 35, 36, and 37). Figure 6 illustrates the deviation for spool 75-2 vs 75Al, S/N 1 and 2.

Repeatability tests were performed on the assembly of the three copper-constantan, two chromel-alumel, and one chromel-constantan thermocouples to determine emf output repeatability at temperatures of liquid helium, liquid nitrogen, carbon dioxide, and the ice point. After each calibration cycle the assembly was warmed to room temperature by immersing it in water. All data points repeated within 5 microvolts, including liquid helium, when referenced to a 32°F reference junction. All repeatability data for test items C/C-35, 36, and 37 are also tabulated in Table VI. Figure 7 graphically illustrates test item C/C-35.

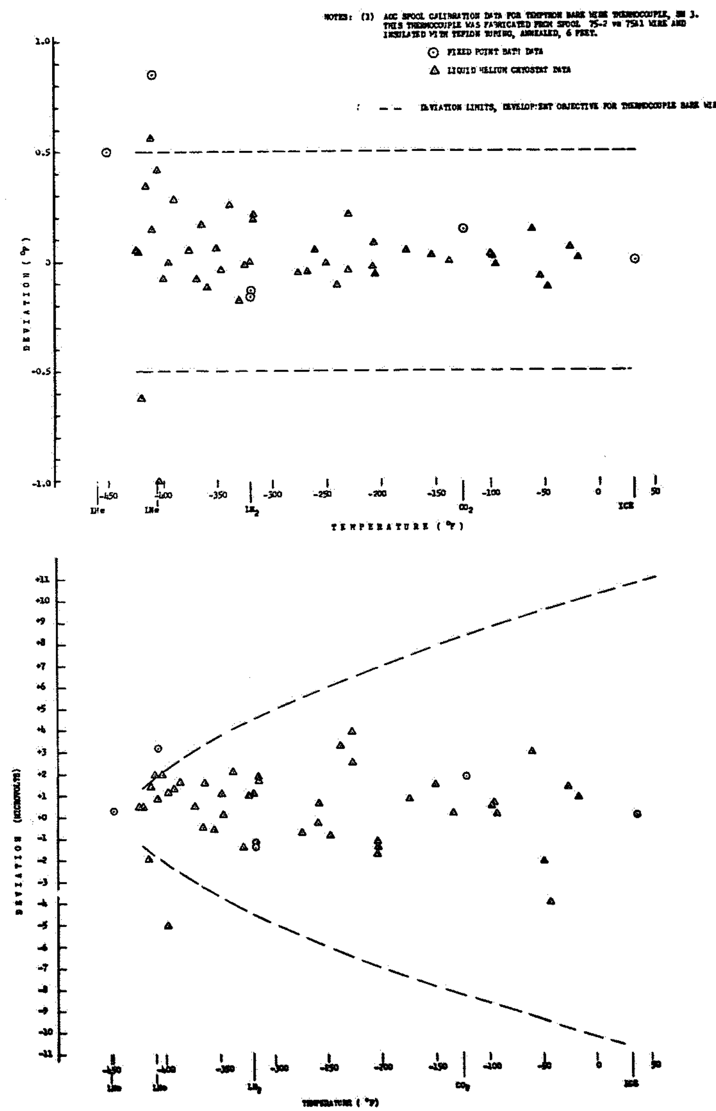

Figure 5
Test Item C/C-35 Test Results From 51 Point Calibration

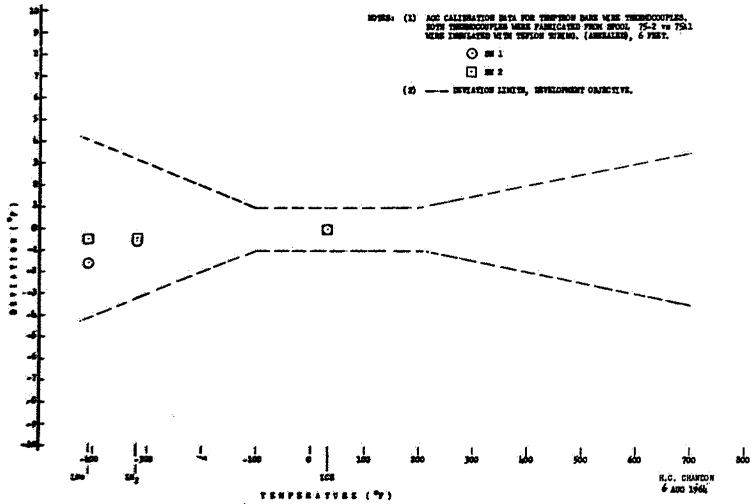

Figure 6
Test Item C/C-26 and -27 Test Results For Annealed Bare Wire

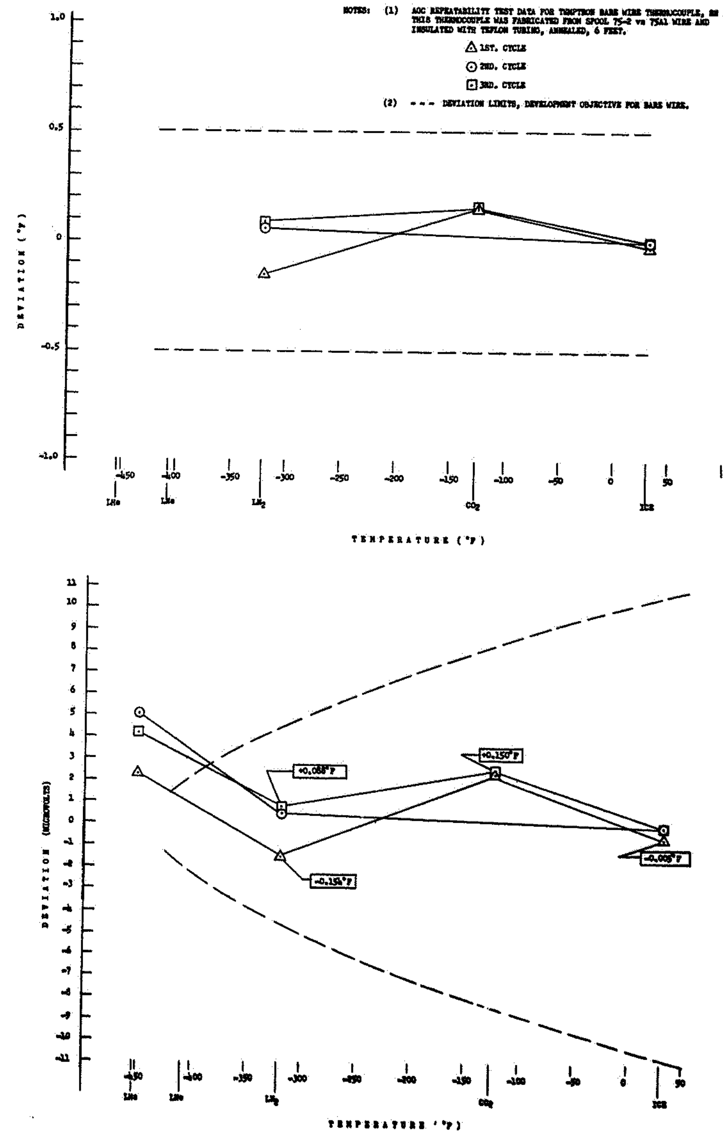

Figure 7
Test Item C/C-35 Test Results From Repeatability Tests

D. EFFECTS OF ANNEALING

The emf induced in a thermocouple of copper-constantan wire is greatly affected by annealing. Two thermocouples were fabricated from spools 75-2 and 75A1 and calibrated at six temperatures in liquid helium, liquid neon, liquid nitrogen, carbon dioxide, ice point, and +200 and +400°F oil. Both thermocouples, S/N 1 and 2, were fabricated from wire directly from the shipping spool or, as called in this report, unannealed. All measurements were made in reference to a 32°F reference junction. The test results are tabulated in Table VI, test items C/C-17 and 18.

As illustrated in Figure 8, the output has shifted outside developmental limits. This can greatly exceed the allowable error for bare wire at temperatures below the carbon dioxide point. To control this effect, wire is selected whose emf output matches the Aerojet tables in an annealed condition.

Samples of wire are presently being cross-sectioned, etched, and analyzed to determine the grain size of each wire for the annealed and unannealed calibrated spools of 75-2 and 75A1.

E. THERMOCOUPLE DEVELOPMENT

In fabricating thermocouples the measure of success is limited primarily by TIG welding and ceramic sealing. Several thermocouples, manufactured to Aerojet prints for testing of NERVA components on cold flow tests, were cross-sectioned and analyzed to support the development of NRX-A2 thermocouples. Thermocouples manufactured by Electrowest Inc., Sacramento, California, and Nugget Manufacturing Inc., Orangevale, California, were removed from Aerojet test area stock and evaluation thermocouples were obtained from Temptron for this purpose.

Electrowest and Nugget both have acceptable welding techniques. Cross-sectioning, polishing, etching, and photomicrographs were completed for all welds (splice junctions in the housing, housing-to-pressure sleeve, and junctions at the tip of the stem) and were satisfactory.

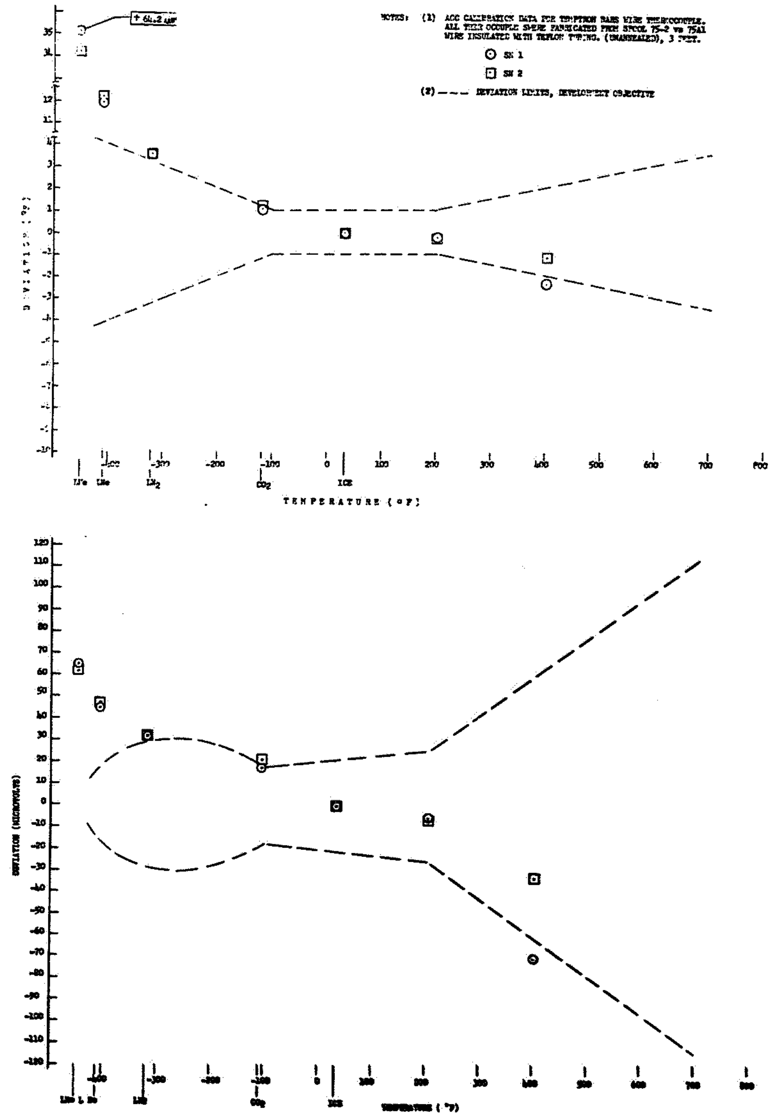

Figure 8
Test Items C/C-17 and -18 Test Results From Unannealed Bare Wire

The initial thermocouple stem junctions submitted by Temptron were not acceptable. Subsequently Temptron submitted several evaluation thermocouples which were cross-sectioned, polished, etched, and photomicrographed and proven satisfactory.

Complete details on these thermocouples will be published in the near future.

These thermocouples were not manufactured entirely with NERVA wire, therefore minor modification will be necessary in the test area thermocouple designs to best support the NERVA cold flow development tests at Sacramento.

The importance of fabricating the entire thermocouple (leadwire and stem) from one copper and one constantan wire was measured during recalibration of the NRX-A1 immersion thermocouples. When all four thermocouples were partially immersed in liquid neon the output was in close agreement (9.7 microvolts or 2.6°F) with the new Aerojet tables. Shifts of 7°F were noted, however, when the housing was fully immersed in liquid neon. The data on these thermocouples are tabulated in Table VI (test items C/C-92 through 95). This discrepancy was caused by the different calibrations of the two pairs of copper-constantan wire used in the construction of the thermocouples. Data from all four thermocouples are valid and accurate enough for most thermocouple parameters. Shifts caused by the change in the housing can also be expected to be less than the 7°F at liquid neon because the housing will be at a considerably warmer temperature than -411°F.

F. DEVELOPMENT OF THERMOCOUPLE STEMS

One of the most important component parts of a thermocouple assembly is the stem. For most immersion thermocouple measurements, the greatest temperature gradient is across the stem such that most of the voltage is induced within the stem. Consequently, it is important that the wire be free from strain, resistant to shock and vibration, and homogeneous. The junction must also have a uniform grain size over the weldment area if gradients exist at the tip.

There are four types of thermocouple stem assembly designs, one of which has a modified tip for improved response. They are: (1) shielded and grounded, (2) shielded and insulated, (3) exposed and insulated, and (4) reduced shielded and grounded. Eight sample stem assemblies (Figure 9) consisting of a 24-in. swaged section of Inconel sheath and a magnesium oxide insulated copper-constantan stem (Tempak) with two 48-in. leadwires, were fabricated by Temptron. As a part of the standard fabrication process for the Tempak, Temptron fully annealed these samples by passing each stem and leadwire through their annealing furnace. All stems were fabricated with NERVA copper-constantan wire from spool 75-2 vs 75A1. Additional details on Tempak products may be found in Reference 10.

Calibration data were well within the development objective of ± 10 microvolts at liquid helium, ± 1% from -425 to -100°F, ± 1°F from -100 to +200°F, and ± 0.5% from +200 to +700°F. Results of the five-point liquid helium, liquid neon, liquid nitrogen, ice, and 400°F calibration are tabulated in Table VI, test items C/C-38 through 45, and graphically illustrated in Figures 10, 11, and 12 for stems 1 through 6. Stems 7 and 8 were calibrated at seven points (the two additional points were carbon dioxide and 200°F oil) and are illustrated in Figure 13.

Stems 7 and 8 were fabricated into a test device by Temptron and irradiated on GTR-14 at General Dynamics. This test was conducted over a period of six days which subjected both thermocouples to liquid hydrogen temperature at the tip of the stem for two days and warm air at the tip of the stem for two days. Part of the data have been evaluated and indicate that the total damage was in the order of 10 microvolts which is equivalent to 3°F at liquid hydrogen. There was no indicated gamma heating measured during the operation of the reactor. Complete data and analyses for this test are forthcoming.

G. DEVELOPMENT OF THERMOCOUPLE LEADWIRE

Flexible thermocouple leadwire (cable) manufactured by Physical Sciences Corporation, Arcadia, California, has been tested. This cable, Part Number 39030-2-22-SL-TC3, manufactured to Aerojet Process Specification AGC 44165 and AGC-SCD 701238, Revision E, is acceptable provided precalibrated and annealed wire is used in its fabrication.

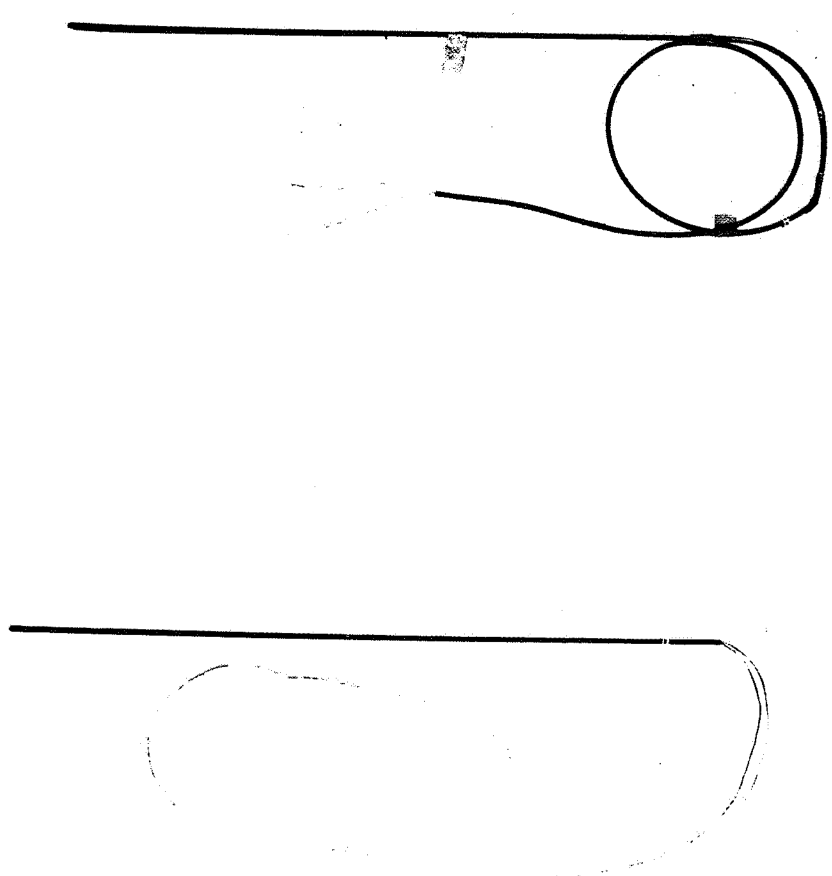

Figure 9
Thermocouple Stem Assemblies

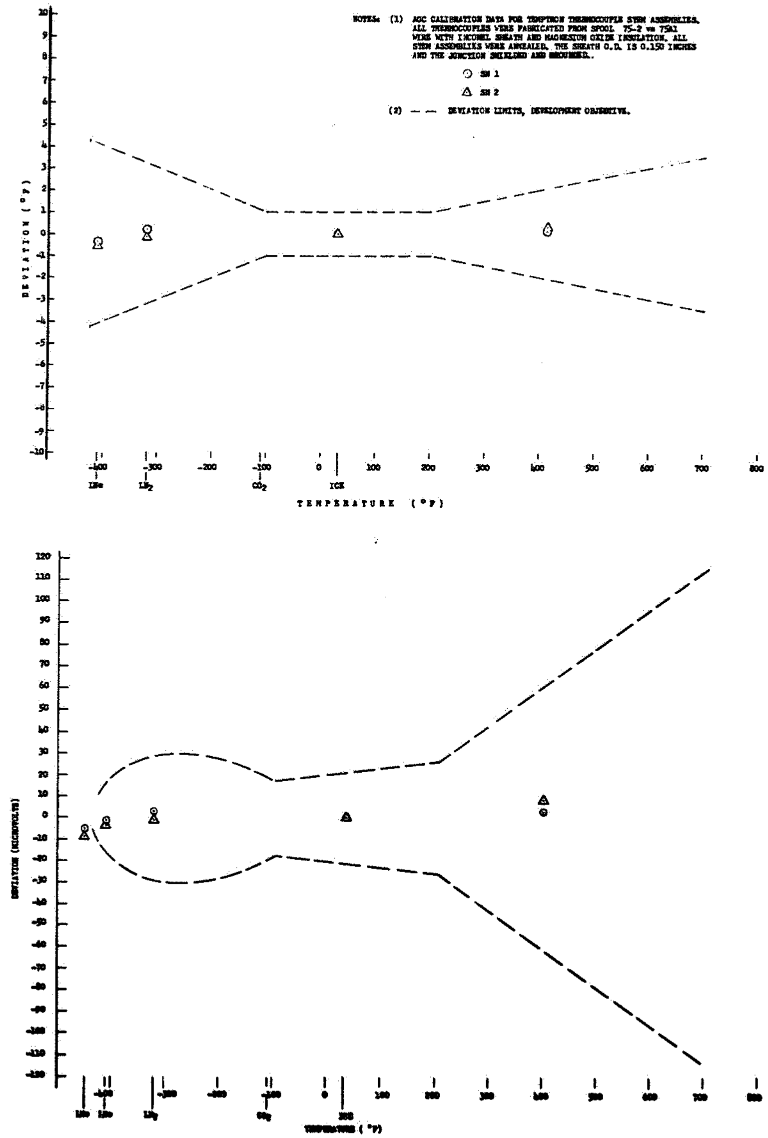

Figure 10
Test Items C/C-38 and -39 Test Results For Grounded Junction Stem Assemblies

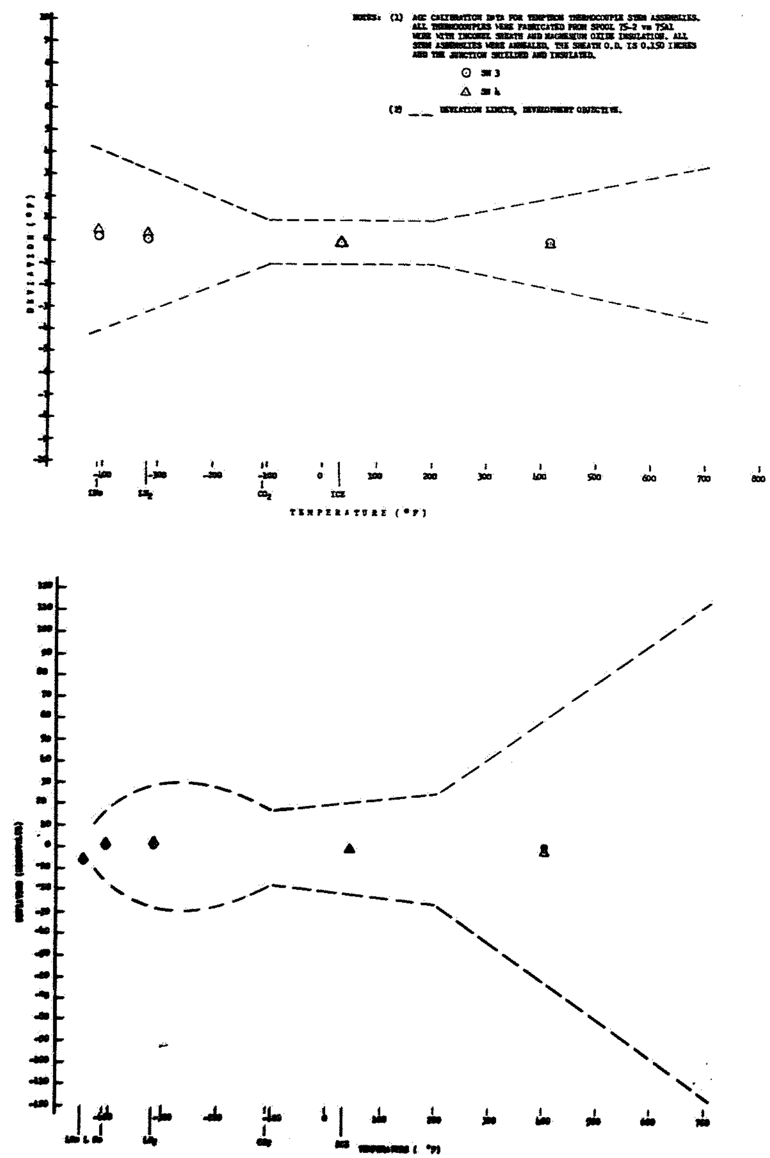

Figure 11
Test Items C/C-40 and -41 Test Results For Shielded Junction Stem Assemblies

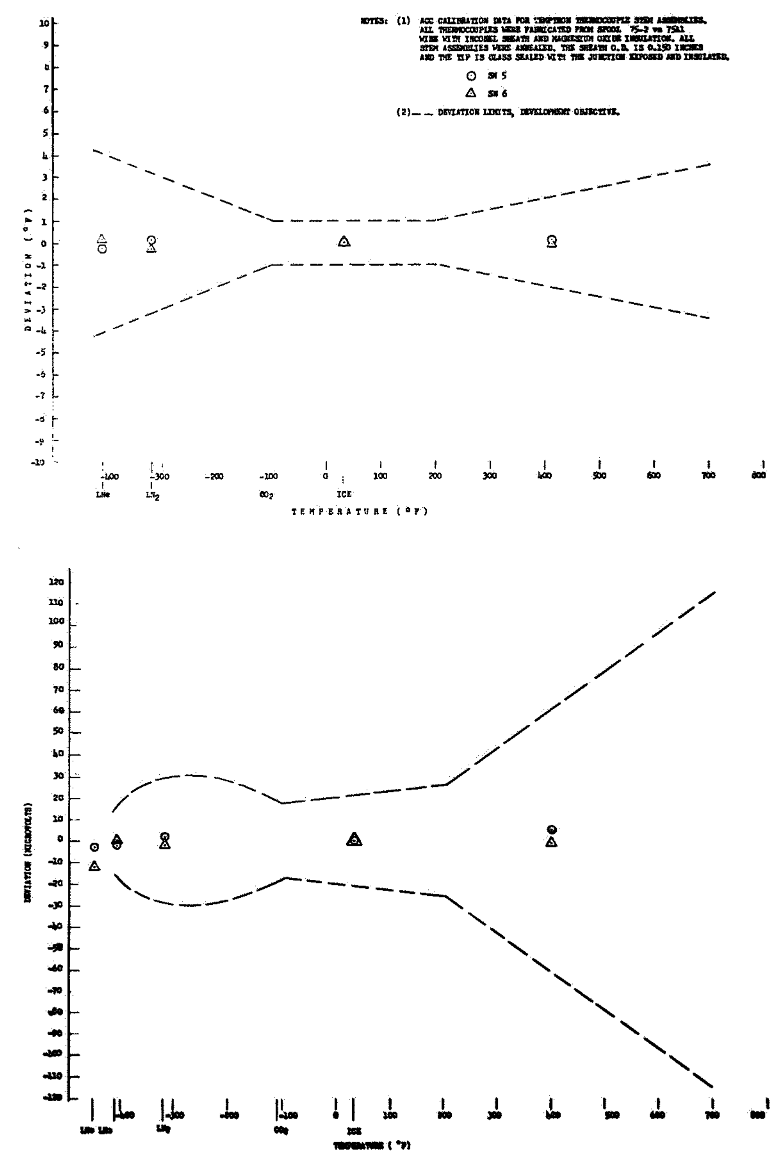

Figure 12
Test Items C/C-42 and -43 Test Results For Exposed Junction Stem Assemblies

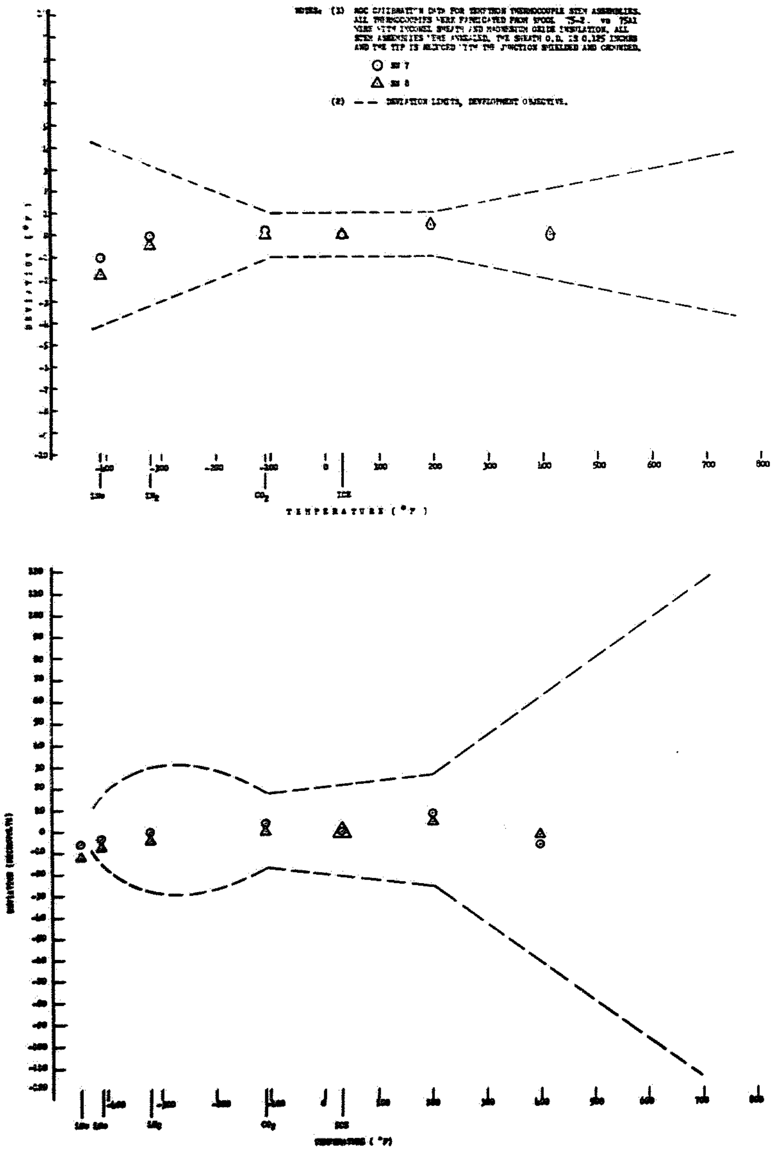

Figure 13
Test Items C/C-44 and -45 Test Results For
Reduced and Ground Junction Stem Assemblies

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Physical Sciences thermocouple cable 39030-2-22-SL-TC3 is a two-conductor (22 gage), quartz-insulated, shielded copper-constantan cable. The conductors are coated with Durock, braided with quartz, then twisted and wrapped with another quartz layer, which is wrapped with a layer of H-film and a stainless steel shield and coated with a layer of quartz impregnated with ML varnish. The H-film and ML varnish provide a moisture seal for the cable. All materials in the cable will operate satisfactorily in temperatures to 1000°F except the moisture sealant. More information on this cable may be found in Reference 11 and the Instrumentation Data Book under Code C-10.

Two samples of Physical Sciences thermocouple cable manufactured to AGC-SCD 701238, Revision C, were calibrated at Aerojet. Revision C required that the wire be solid conductor 26 gage copper-constantan and the output be premium grade in accordance with NBS Circular 561 and the Boulder Table. Each sample was calibrated at several temperatures between liquid helium (-452°F) and +200°F in oil. The output data deviated by approximately +270 microvolts at -452°F to -154 microvolts at 200°F, see Table VI, test items C/C-96 and C/C-97. For Physical Sciences to Durock-coat their wire, it is necessary to pass each conductor through a high temperature furnace (1400 to 1600°F) to bond the Durock to each wire. During this coating process, the wire calibration in undoubtedly caused to shift because of partial annealing. Pre-calibration data were not available for analysis to determine the exact amount of shift. This cable has been successfully fabricated into surface thermocouples for NRX-A2. A special set of tables was prepared, based on a deviation curve, using the calibration data. This table is presented on AGC-SCD 706614 through 706615.

A 20-ft sample of copper and constantan 22 gage annealed wire from spools 75-2 and 75A1 was provided by Temptron to develop the Physical Sciences cable for the NERVA immersion thermocouples. This wire was Durock-coated by Physical Sciences. Two pieces of the Durock coated wire were fabricated into a thermocouple and calibrated to determine if any shifts resulted from the Durock coating. The remaining wire was manufactured into cable in accordance with AGC-SCD 701238, Revision E. All three samples were well within the developmental objective limits of:

± 20 microvolts at liquid helium

± 2% from -425 to -400°F range

± 1% from -400 to -100°F range

± 1°F from -100 to +200°F range

± 0.5% from +200 to +700°F range

when referenced to 32°F. Test results for these three thermocouples are tabulated in Table VI, test items C/C-46 through C/C-48. A graph of the test results for test items C/C-47 and C/C-48 is illustrated in Figure 14.

Thirty-one NRX-A2 immersion thermocouples have been purchased for the NERVA program in accordance with AGC-SCD 701530 through 701554. All of the thermocouples have a 30 foot Physical Sciences cable and have been successfully acceptance tested. The wire used by Physical Sciences in the fabrication of the cables was provided by Temptron from fully annealed, precalibrated spools, of 75-2 and 75A1 wire. Three of these cables have had additional vibration testing during the thermocouple qualification tests which is discussed in Section I, below, entitled "Wire Calibration and Selection."

Two cables were also tested in GTR-14 as a component of two NRX-A2 type thermocouples. Both cables operated satisfactorily and are discussed in Section I.

Precautions must be taken during vibration of the Physical Sciences cable. The cable is flexible but will not withstand flexing or rubbing at high g levels of vibration. By using proper tie-downs, such as those used in the qualification tests, the cable will operate satisfactorily during vibration. For gimbal requirements on future engines, a flexible attachment should be used with this cable. A failure experienced on the multiconductor pressure transducer and temperature transducer cable was caused by the abrading or tearing of the quartz fibers. The quartz fibers used by Physical Sciences are very short. A minor redesign, to include an additional layer or substitute the outside layer with Owens Corning S-994 quartz fibers, appears to be a possible solution to the cable abrading problem.

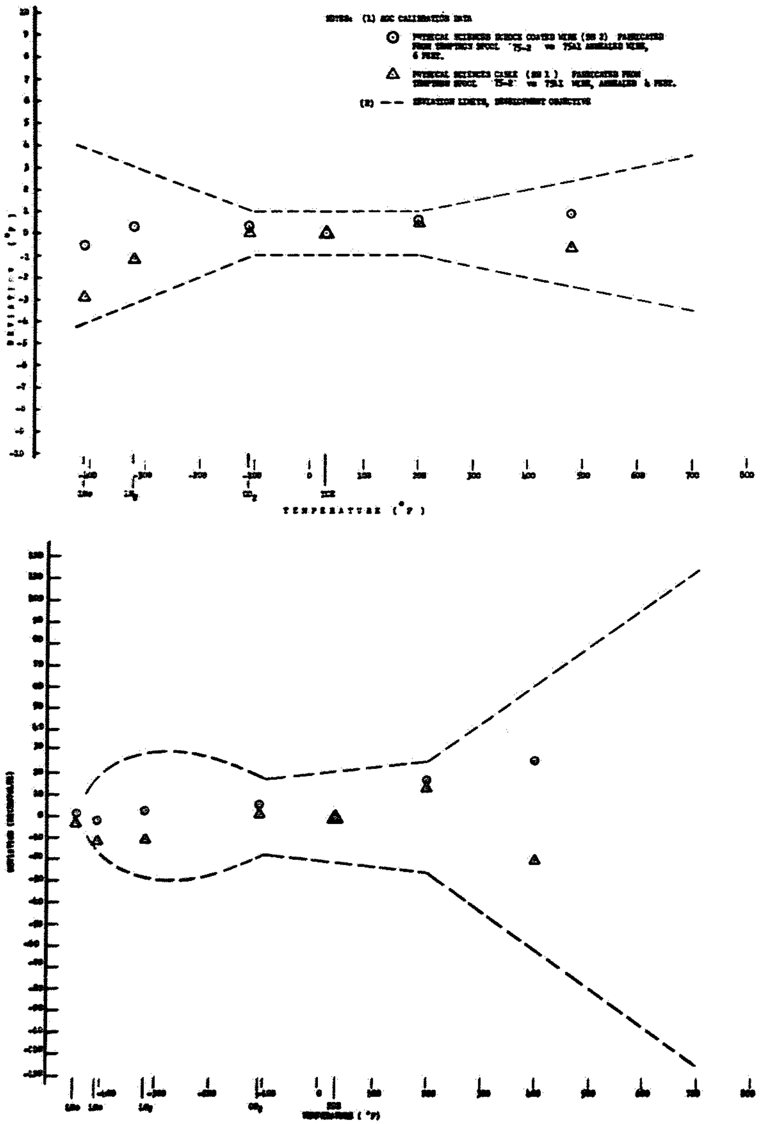

Figure 14
Test Items C/C-47 and -48 Test Results For Durock-Coated Wire and Cable

H. FABRICATION OF NRX-A2 THERMOCOUPLES

For diagnostic measurements on the NRX-A2 test, copper-constantan thermocouples have been developed in accordance with AGC-SCD 701530 through 701554. Temptron has been selected to manufacture thermocouples to these drawings.

The AGC-SCD 701530 through 701554 thermocouples are immersion type copper-constantan thermocouples with a shielded and grounded element with integral lead wires. They are designed to be attached to the pressure port of the engine with an AN929-4 coupling nut. The operating temperature range is -425 to +700°F. Each unit is constructed such that the copper and constantan wires are fully supported in the stem with tightly packed magnesium oxide insulation and in the housing with epoxy insulation. All joints are made by the TIG weld method. In compliance with the specification control drawing and as a result of this development program, the emf from each thermocouple is standardized or conforms to one master table. The required accuracy limits, when referenced to 32°F, are:

± 2% over the -425 to -300°F range

± 1% over the -300 to -100°F range

± 1°F over the -100 to +200°F range

± 0.5% over the +200 to + 700°F range.

Several immersion depths, ranging from 1.50 to 8.00 inches, are available on these drawings. Five immersion depths of 1.62, 2.00, 2.50, 3.50, and 3.75 inches have been tested and qualified for the NERVA program.

Stem and cable assemblies are fabricated from calibrated spools of 22 gage copper and constantan wire. The stem and leadwire assemblies for these thermocouples are constructed using the techniques developed and described in Sections F and G of this report. The stem and cable wire are from the same spool but are spliced together in the housing of each thermocouple. The junction on each stem is a reduced type for faster response.

AGC-SCD 701530 through 701554, Revision F, incorporates a dash number system so that different leadwire lengths may be purchased. The -19 drawing has a 30 foot leadwire and -29 has a 40 foot leadwire. Any additional leadwire length may be added to the drawing by the addition of the -39, -49, -59 series of numbers on a drawing change notice.

Three purchase orders were placed with Temptron for a total of 31 copper-constantan thermocouples fabricated in accordance with AGC-SCD 701530 through 701554 for evaluation purposes and use on NRX-A2. An illustration of this thermocouple is presented in Figure 15. All thermocouples have been acceptance tested and meet Aerojet requirements. A graphical presentation of calibration data for each shipment is illustrated in Figures 16 through 19, and the data are tabulated in Table VI (test items C/C-49 through 79). Although the Aerojet procurement specification requires that only one time constant be 0.5 sec maximum for a step from ambient air to water, all 31 thermocouples measured less than 0.2 seconds.

Three model 2925 thermocouples successfully passed environmental testing at United Aerotest Laboratory in Los Angeles, California. Each thermocouple was subjected to the following test series:

20 g sine wave vibration
32 g random vibration
38 g sine and random vibration
300°F high temperature vibration
-100°F low temperature vibration
-45°F frost with 38 g vibration
75% humidity

Details on this test series will be forthcoming.

Two immersion thermocouples made in accordance with AGC-SCD 701532 (immersion depth 2.00 inch) were modified and tested on GTR-14 during July-August. The modification consisted of reducing the leadwire to six inches and adding swaged

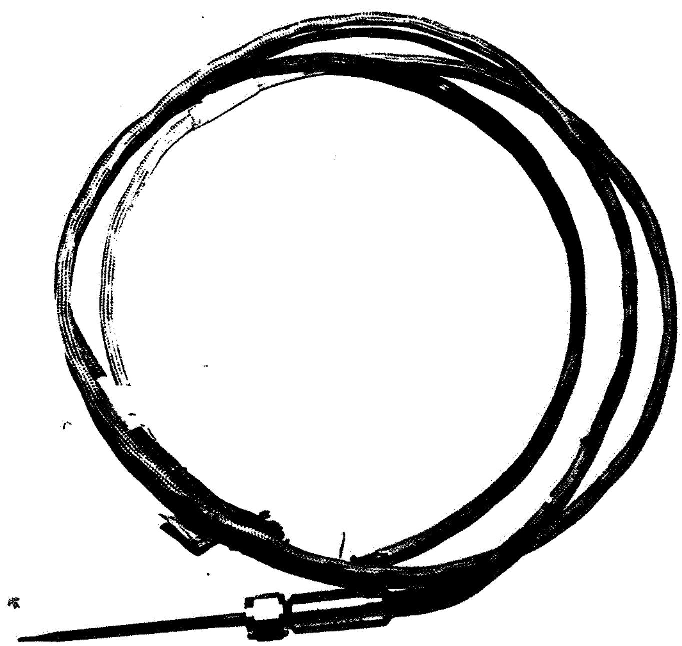

Figure 15
NRX-A2 Thermocouple With Durock Coated Wire and Cable

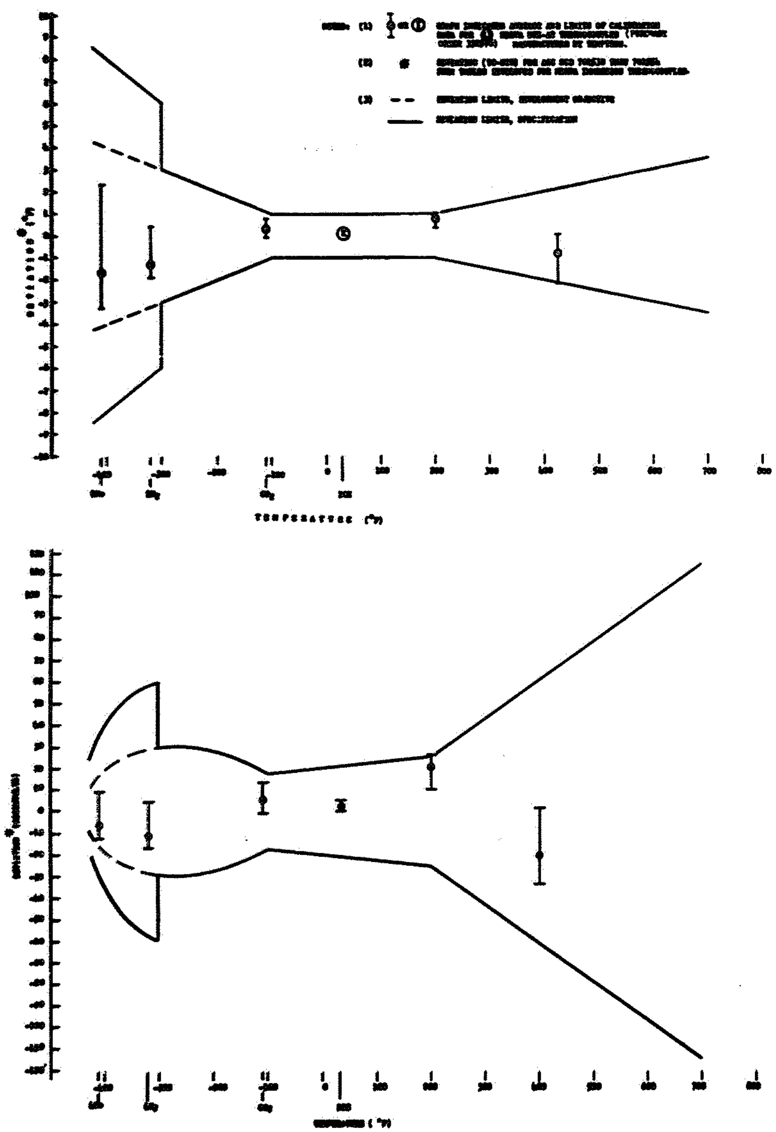

Figure 16
Test Items C/C-49 Through -61 Test Results For
NRX-A2 Thermocouples

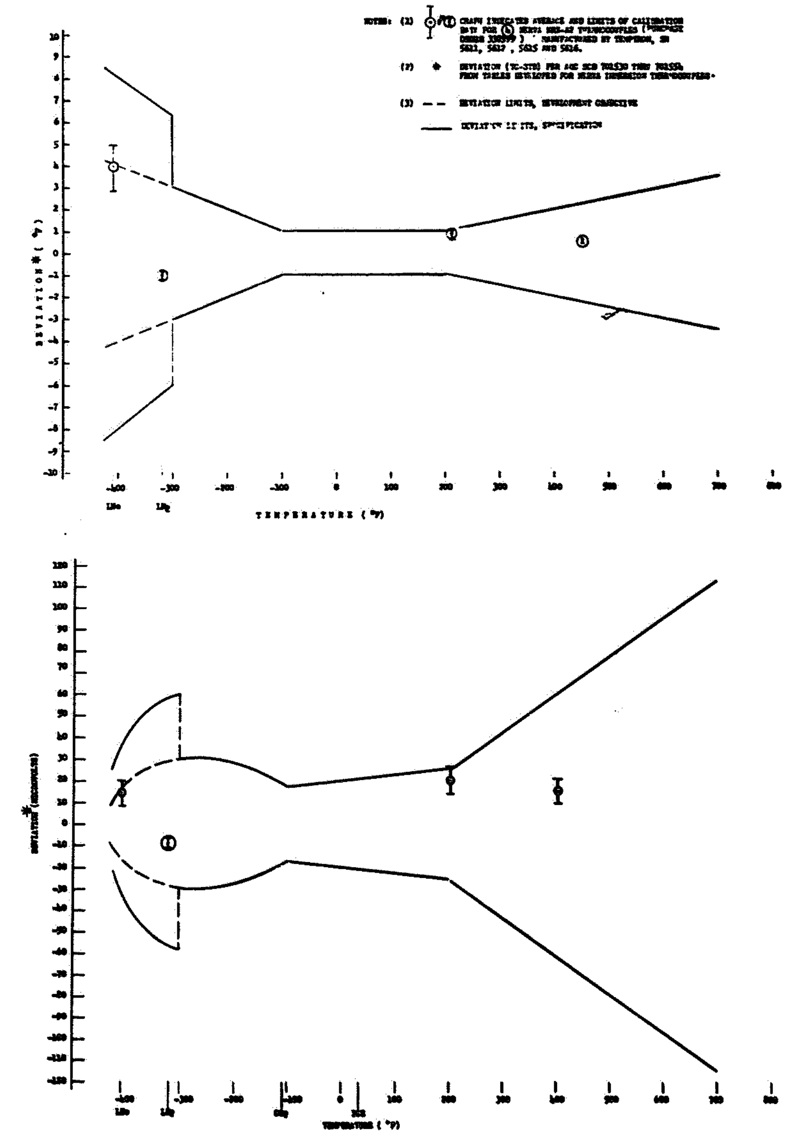

Figure 17
Test Items C/C-62, -63, -66, and -67 Test Results
For NRX-A2 Thermocouples

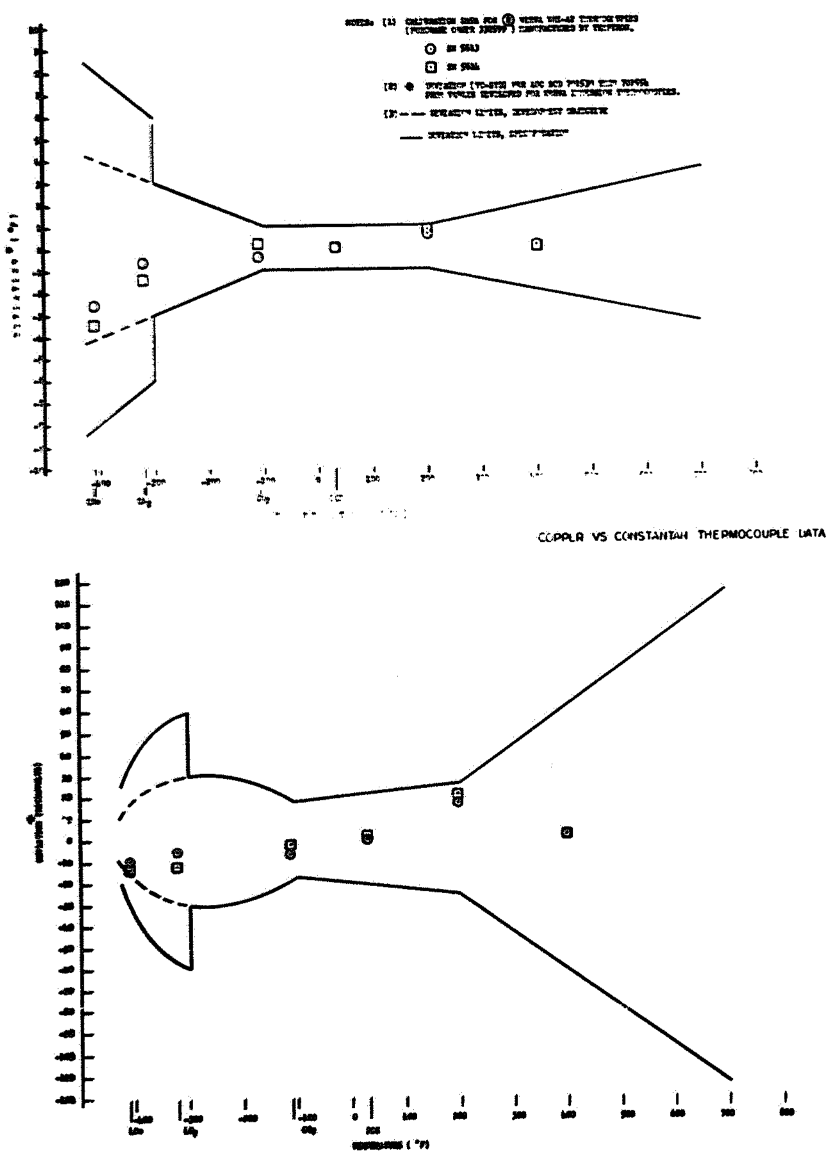

Figure 18
Test Items C/C-64 and -65 Test Results For NRX-A2 Thermocouples

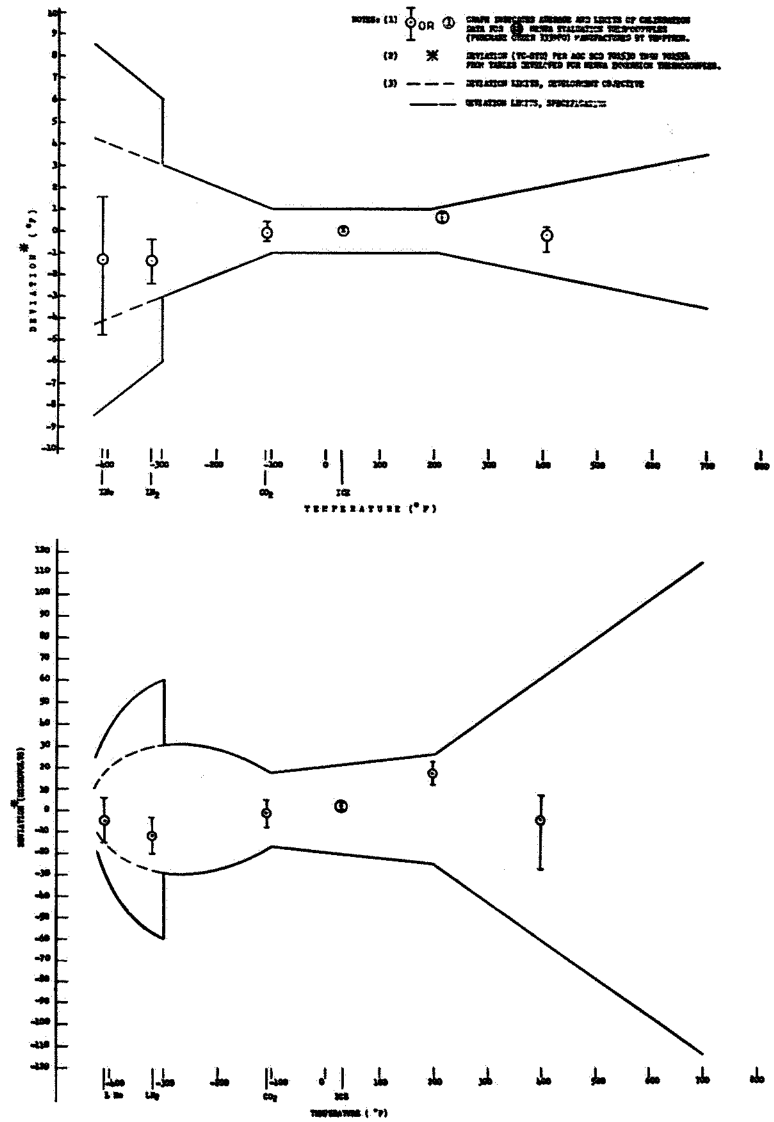

Figure 19
Test Items C/C-68 Through -79 Test Results For NRX-A2 Type Evaluation Thermocouples

leadwire and an extension. Using the calibrated spool wire, a 20 foot swaged leadwire was manufactured, attached to the thermocouple, and then silver-soldered into the dewar by General Dynamics personnel. A one-hundred foot extension was attached to the swaged leadwire to continue the circuit to the readout system.

A preliminary analysis of the data from GTR-14 has been completed but has not been reported for reference in this report.

The neutron damage to copper-constantan was calculated to be a 10 microvolt increase in output which is equivalent to 3°F when measuring liquid hydrogen under irradiation. Errors caused by gamma heating were negligible.

The test setup used in GTR-14 was very similar to the actual NRX-A2 test setup, however, it had a lower rate of neutron and gamma flux. Data obtained in this test will be beneficial to further thermocouple development.

I. WIRE CALIBRATION AND SELECTION

Six 22 gage wire thermocouples, one from each of six different spools of constantan wire, have been calibrated against copper for possible use in the fabrication of NRX thermocouples and/or cable. Four of the six spools were within the desirable tolerance for bare wire, thermal emf, output. The acceptable spools, 75A2, 75A3, 75A7, and 75A8, have a combined length of 17,620 feet. The other two spools, 75A4 and 75A6, fall outside the tolerance and are not recommended for NERVA application. When combined with the 75A1 spool, 21,400 feet of 22 AWG constantan wire are available which match with the existing 9,670 feet of copper wire.

Six 26 gage wire thermocouples for each combination, using three spools of constantan wire and two spools of copper wire, have also been calibrated. All spools are acceptable. Copper spools 77-1 and 77-2 have a combined length of 18,000 feet and constantan spools 77A1, 77A2, and 77A3 have a combined length of 9,078 feet.

The final selection was based on the calibration of a thermocouple made from each spool of wire. The thermal emf output had to be within 20 microvolts at liquid helium, 1% in the -425 to 100°F range, 1°F in the -100 to +200°F range, and 0.5% (of the point) in the +200 to +700°F range. All measurements were made in reference to a junction of the same material held at 32°F. The data were reduced by the standardized set of tables developed for NERVA immersion thermocouples.

A seven-point calibration was taken to evaluate and select this wire. All constantan wire was purchased from the Wilbur B. Driver Company by Temptron. Before calibration, the same thermocouples were annealed. The calibration data are tabulated in Table VI, test items C/C-80 through 91.

J. CALIBRATION TEST SETUP AND EQUIPMENT

All of the measurements were performed in the Aerojet Measurement Standards Laboratory except acceptance testing of four NRX-A2 thermocouples, Temptron Model 2925-200, S/N 5611, 5612, 5615, and 5616, which were completed at the Aerojet Transducer Laboratory, and response measurements which were made in the Aerojet Engineering Laboratory.

1. Emf Measurements

A Wenner potentiometer, Model 7559, was used to measure all thermocouple outputs. This potentiometer is manufactured by the Leeds and Northrup Company and measures emf in the 0.1 microvolt to 1.8 volt range with an accuracy of 0.01% ± 0.1 microvolts. A photograph of this bridge is presented in Figure 20. Since this potentiometer does not correct for thermocouple junctions, all measurements are in reference to a junction of like material at 32°F maintained by an ice bath.

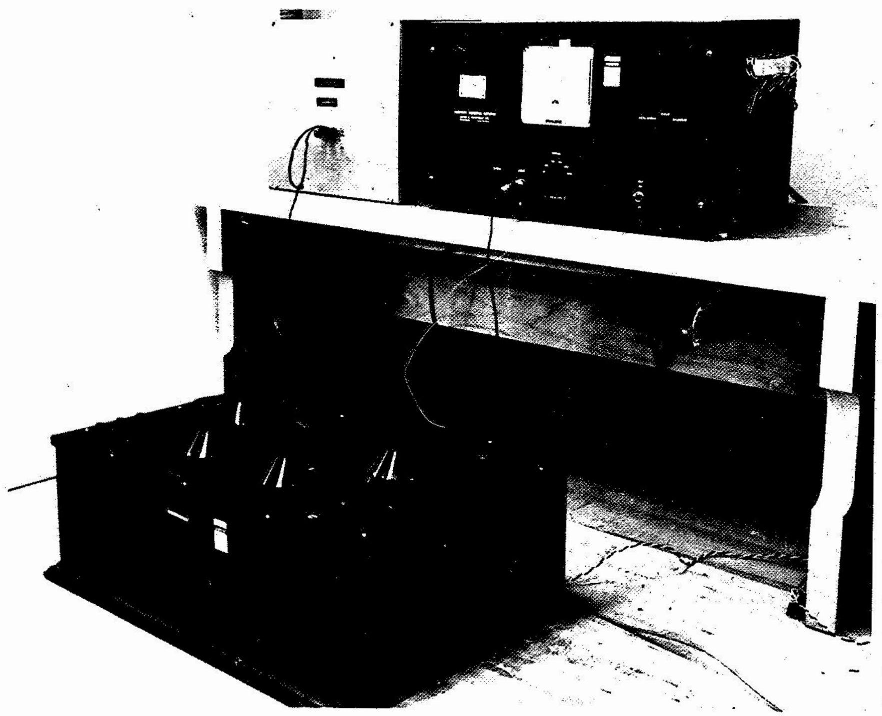

Figure 20
EMF Measurements

2. Temperature Measurements

A platinum resistance standard thermometer, manufactured by Leeds and Northrup and Rosemount Engineering, was used to measure all bath temperatures except the ice bath and the liquid helium temperature. A capsule type thermometer, Model 8164, or 162C (Rosemount Engineering), was used to measure temperatures below 32°F, and Model 8163 was used to measure temperatures above 32°F. A G-2 (Mueller type) bridge and Model 2284B reflecting galvanometer, manufactured by Leeds and Northrup, were used to measure the resistance of the standard thermometer, Figure 21.

3. Ice Bath

A model 910 ice bath, manufactured by Rosemount Engineering Company, was used for the reference junction and thermocouple calibration bath. When properly filled with crushed (distilled water) ice and distilled water, the ice bath will maintain a temperature of ± 0.002°F in the calibration zone. No standard thermometer is necessary for measuring the ice bath temperature. This bath is illustrated in Figure 22.

4. Carbon Dioxide Bath

Each test thermocouple and a standard thermometer were placed in a laboratory dewar in close proximity to each other, and packed with powdered dry ice. An insulating lid was then placed over the dewar. Approximately two hours is required to stabilize at the sublimation point of carbon dioxide. The bath temperature was determined by a standard thermometer. (See Figure 22.)

5. Liquid Nitrogen Bath

A laboratory vacuum dewar was filled with liquid nitrogen so that a standard thermometer and thermocouple could be located next to each other and be fully immersed in the liquid nitrogen. (See Figure 23.)

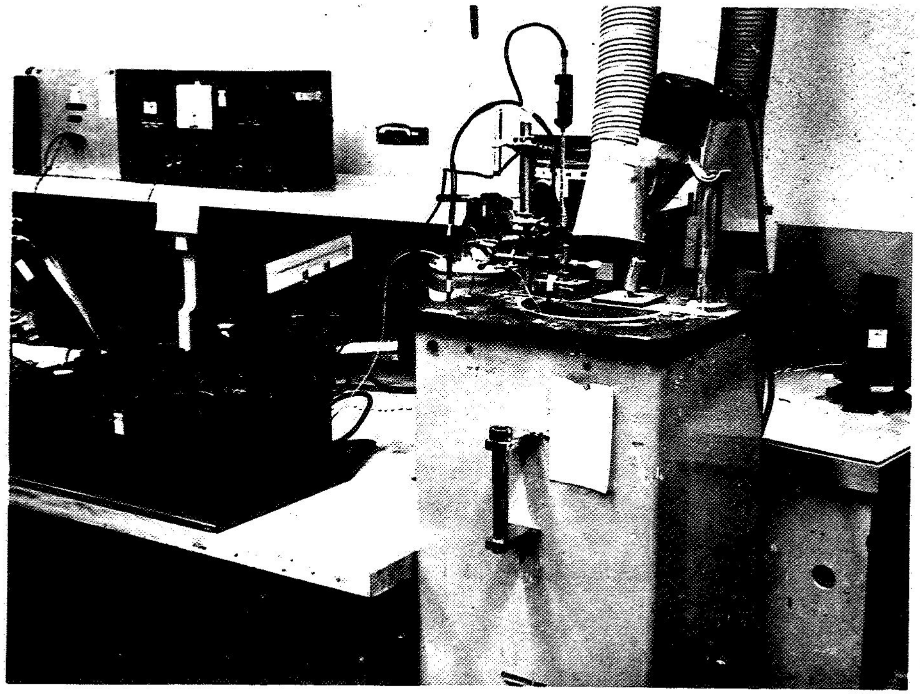

Figure 21
Temperature Measurement Bridge

Figure 22
Carbon Dioxide Bath And Ice Bath

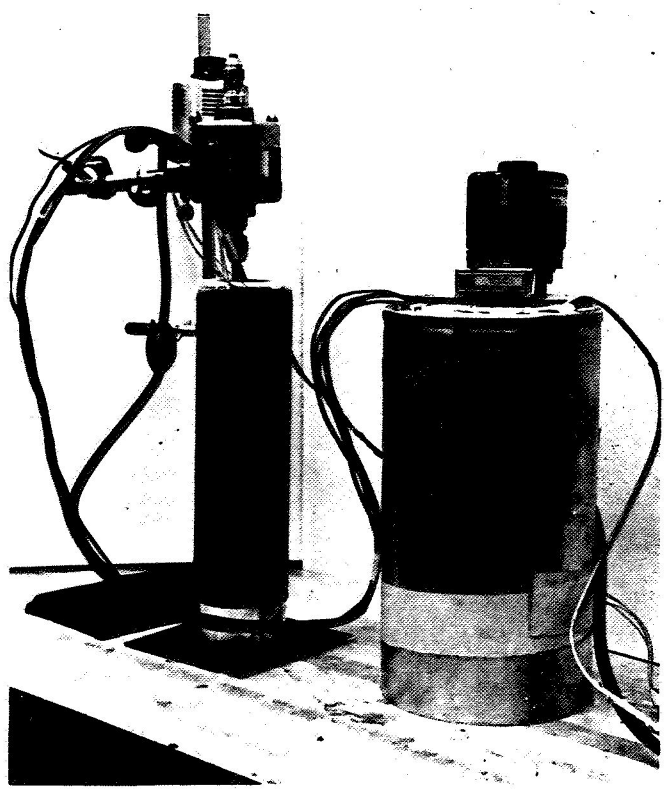

Figure 23
Liquid Nitrogen Bath And Ice Bath

6. Liquid Neon Bath

A special double-vacuum dewar arrangement was used for this bath. Liquid nitrogen was maintained between the two dewars to cool the center dewar where the liquid neon was located as a calibration fluid. Since liquid neon is very expensive, approximately $100.00 per liter, all parts were precooled in liquid nitrogen before being immersed into the calibration region. A pressure-tight cap was used on this setup such that the vapor was vented through a low range monostat to maintain a slight positive pressure. By varying the pressure it was possible to adjust to a precise temperature point if desired. This pressure cap also reduced the buildup of ice within the bath or on the surface of the liquid. This setup is free from temperature gradients and does not require agitation. During this development liquid neon has been extremely useful in providing a fixed point in the liquid hydrogen region which is easily and safely handled in the Measurement Standards Laboratory. This test setup is illustrated in Figure 24.

7. Oil Bath

A Model 1132A Hallikainen oil bath, manufactured by Hallikainen Instruments, Berkeley, California, was used to provide temperatures between +80 and +400°F. See Figure 25.

8. Salt Bath

A Model 1164D Hallikainen salt bath was used to provide temperatures between +400 and +1000°F. See Figure 26.

9. Liquid Helium Bath

All measurements taken at liquid helium temperature were made by inserting the thermocouple junctions directly into a shipping dewar. It was necessary to maintain a relatively high liquid level within the container to eliminate leadwire conduction. Temperature was calculated on the established vapor pressure-temperature relationship.

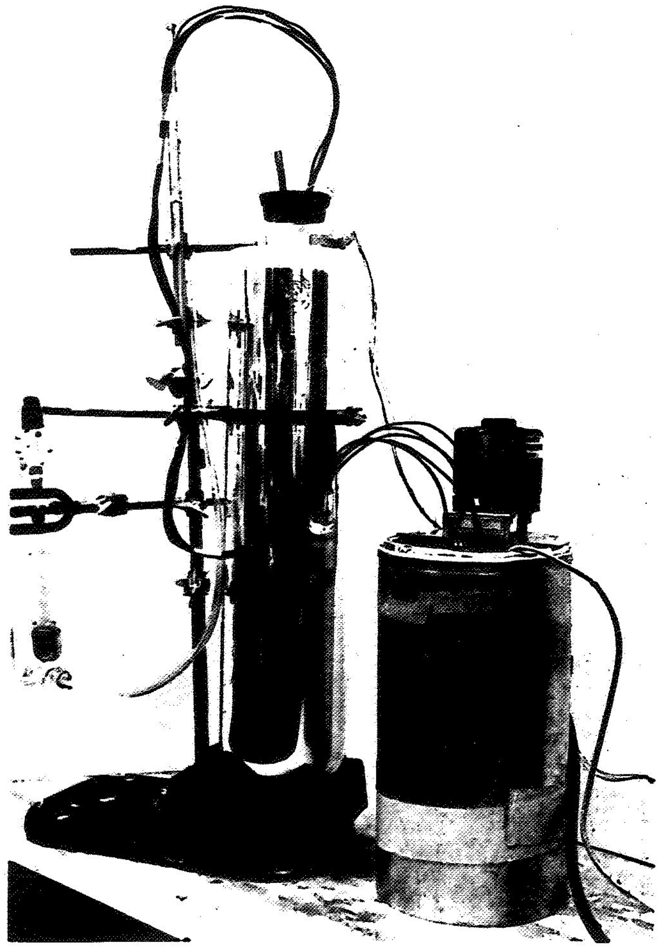

Figure 24
Liquid Neon Bath And Ice Bath

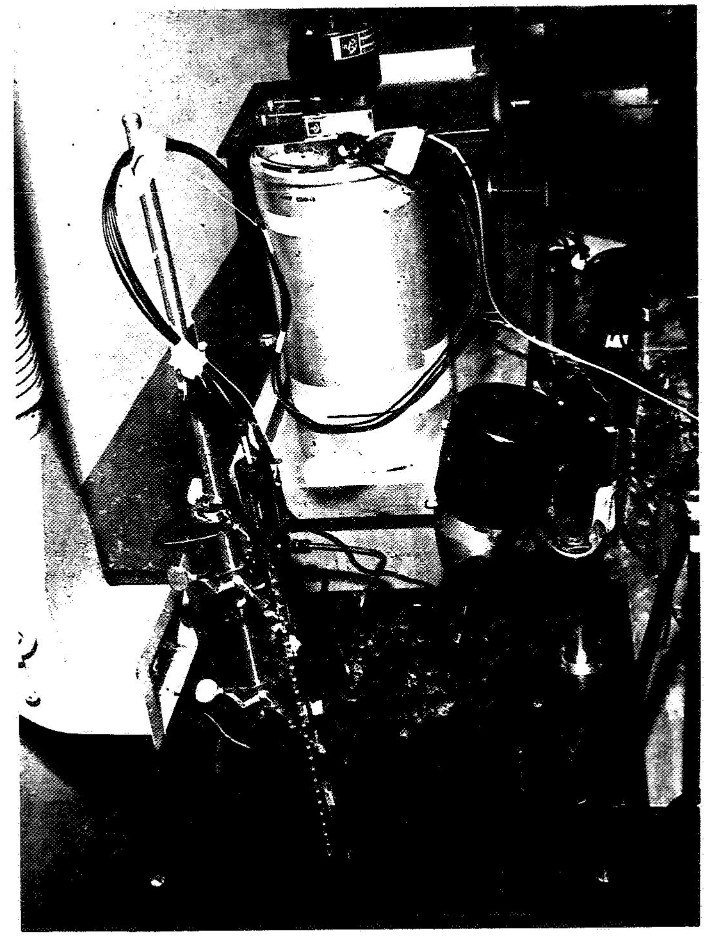

Figure 25
Oil Bath And Ice Bath

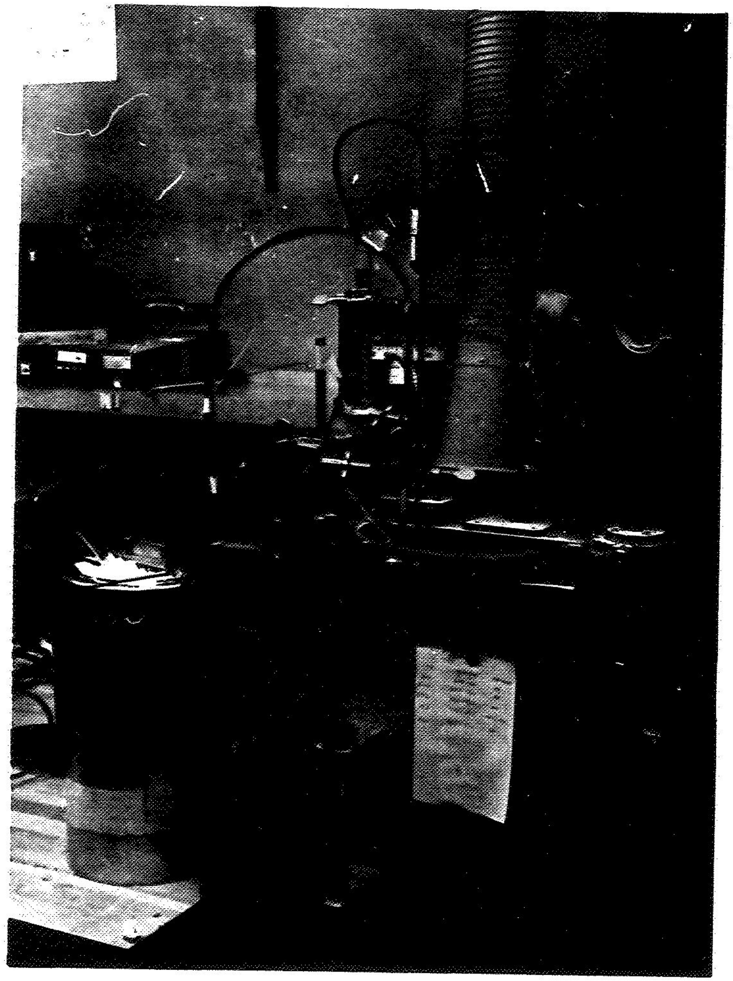

Figure 26
Salt Bath And Ice Bath

10. Gaseous Helium Cooled Cryostat

An Aerojet developed cryostat, manufactured by the Cryogenic Engineering Company, Denver, Colorado, was used for the multipoint calibration of samples of thermocouple bare wires. The cryostat is cooled by a shipping dewar of liquid helium placed below the cryostat chamber. Cold gaseous helium is boiled off by a heating element located within the dewar which passes up through (1) a series of heat shields, (2) a copper block surrounded by copper screen, (3) a second series of heat shields, and is then vented out the exhaust. The cryostat has a liquid nitrogen shield and a vacuum shield to reduce the gradients internally.

A large copper block, with two locations for a standard thermometer and a calibration hole, is located in the center of the cryostat. The block temperature may be varied by its own heater element or by varying the flow of gaseous helium through the copper-screen area.

The entire system has a large thermal mass which makes it rather slow to cool down to liquid hydrogen temperatures. However, a very high stability is attained with the large thermal mass. Cooling the leadwires is accomplished by inserting the test device down the exhaust. A cap is always maintained over the exhaust to prevent the buildup of solids within the copper block test hole.

For the multipoint calibration the thermocouples were all mounted in a common heat shield with a standard thermometer to provide the greatest accuracy. Measurements were taken on each thermocouple from -20°F down to -426°F. Each thermocouple was referenced to the Rosemount ice bath mounted directly on the cryostat.

Normally measurements are limited below liquid nitrogen temperatures for the greatest stability. The copper block has been cooled as low as -440°F, but was not for this test because it was below the necessary development objective of thermocouple measurements. For measurements below -426°F a germanium-resistance, standard, thermometer, manufactured by the Minneapolis-Honeywell Regulator Company, is used to measure the copper block temperature because the sensitivity of platinum is relatively flat below -426°F as compared with the sensitivity of germanium. This test setup is illustrated in Figure 27.

K. MEASUREMENT TECHNIQUES AND ANALYSIS

Seven recommendations for temperature measurements are listed in the Conclusion Section of this report. These recommendations are well founded and have been verified by laboratory tests at Aerojet.

Measurements made in the test area on the NERVA cold flow tests could be improved significantly. The thermocouple system should be modified to have the reference bath as close to the thermocouples as possible. More attention should be given to the thermocouple leadwire and test stand drop lines; they must be matched or local temperatures at the splice of joining points will introduce errors in measurement. On 15 September 1964 the data reduction equations were converted to the new data reducing equations (9) through (16). These new equations will be much closer to the true calibration curve for most thermocouples. It is recommended that all test area thermocouples for cryogenic service be calibrated at two additional temperatures, liquid neon or hydrogen and liquid nitrogen, by immersing only the tip in the calibration bath. Only thermocouples that are within the specification limits for NRX-A2 should be retained for cryogenic service. The limits are ± 2% for the -425 to -300°F range, ± 1% for the -300 to -100°F range ± 1°F for the -100 to +200°F range, and ± 0.5% for the +200 to +700°F range when calibrated in reference to a 32°F junction.

A memorandum was prepared for the M-1 liquid hydrogen and liquid oxygen engine development program (Reference 12) which provides an interesting discussion on basic principles of thermocouple measurements. Copies of this memorandum may be obtained through the office of Mr. A. R. Larson, Manager, Measurement Engineering, Department 9271, Liquid Rocket Operations, Aerojet-General Corp., Sacramento, California.

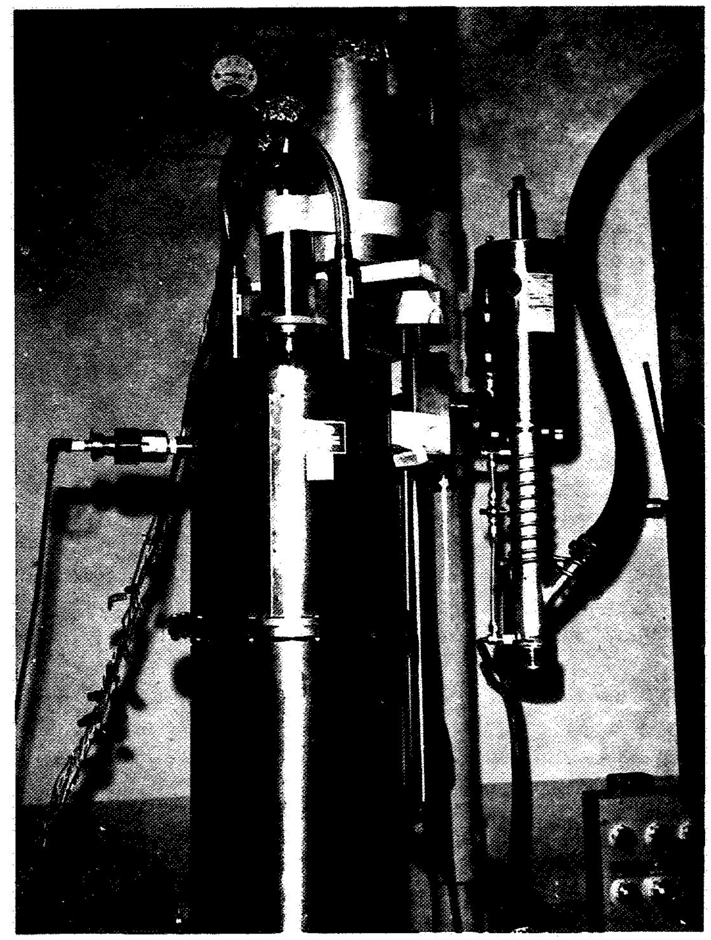

Figure 27
Cryostat And Ice Bath

Temperature measurements of the NERVA turbopump assembly bearings are discussed in Report 8771:2197, Reference 13. Three types of thermocouples (gold 2.11 atomic percent cobalt alloys vs copper, copper-constantan, and chromel-alumel) are described. Measurement of internal parts, such as bearings, can be improved by application of the data presented in this report. Copies of this report are also available from the above-mentioned office.

All new data reduction equations (9) through (16) may be easily converted for data measured in reference to a different temperature than 32°F. For example, to convert the equations to an equivalent set of equations for a 150°F hot block reference junction, let

$$°F = °F_{(150°F)}$$

and

$$(XN)_{(150°F)} = \frac{X - M - C}{D}$$

where C is 2.7114 (millivolt value from Table V for 150°F)

By substituting the new values in any one of equations (9) through (16), the resulting equation is valid over each specified temperature range.

NOTE: The millivolt output range will change for each reference junction temperature.

The solutions to equations (9) through (16) are in degrees Fahrenheit, however, by substituting the temperature conversion equations all the data reduction equations may be converted to any other unit. For example, to convert to degrees Rankine, use the following relationship:

$$°F = °R - 459.67 \qquad (17)$$

REFERENCES

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   b. Section 5, "Improved Reference Tables for Thermocouples, by Robert P. Benedict and Harold F. Ashby, Westinghouse Electric Corporation, Lester, Pennsylvania, pages 51 to 64.
3. ISA RP 1.3, "Thermocouples and Thermocouple Extension Wires - Terminology, Limits of Error, and Wire Sizes," Instrument Society of America, 22 August 1952.
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5. Component Specification AGC 42136, "General Specification for Thermocouples," Aerojet-General Corporation
   a. Original Issue - 4 August 1959
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   c. Revision B - 23 October 1962
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11. Bulletin C-1, "Multi-Conductor Cable," Physical Sciences Corporation, July 1962.
12. Discussion of Thermocouple Circuit Analysis, Memorandum 8771:2721, to P. L. Camerzell from V. A. De Vita, dated 13 July 1964.
13. Technical Report 8771:2197, "Instrumentation for Cryogenic Temperature Measurements of the NERVA Turbopump Assembly Bearings During Non-Nuclear Static Testing," by J. W. Farnham and H. C. Chandon, 19 November 1963.

APPENDIX A

TABLES

TEMPERATURE (DEGREE)		OUTPUT (MILLIVOLTS)	
(1) KELVIN T (°K)	(2) FAHRENHEIT T (°F)	(3) E (0°K)	(4) E (32°F)
1.0	-457.870	0.00017	-6.25853
2.0	-456.070	0.00066	-6.25804
3.0	-454.270	0.00148	-6.25722
4.0	-452.470	0.00262	-6.25608
5.0	-450.670	0.00407	-6.25463
6.0	-448.870	0.00583	-6.25287
7.0	-447.070	0.00790	-6.25080
8.0	-445.270	0.01026	-6.24844
9.0	-443.470	0.01292	-6.24578
10.0	-441.670	0.01588	-6.24282
11.0	-439.870	0.01912	-6.23958
12.0	-438.070	0.02264	-6.23606
13.0	-436.270	0.02643	-6.23227
14.0	-434.470	0.03050	-6.22820
15.0	-432.670	0.03484	-6.22386
16.0	-430.870	0.03943	-6.21927
17.0	-429.070	0.04429	-6.21441
18.0	-427.270	0.04940	-6.20930
19.0	-425.470	0.05478	-6.20392
20.0	-423.670	0.06040	-6.19830
21.0	-421.870	0.06628	-6.19242
22.0	-420.070	0.07242	-6.18628
23.0	-418.270	0.07880	-6.17990
24.0	-416.470	0.08543	-6.17327
25.0	-414.670	0.09231	-6.16639
26.0	-412.870	0.09943	-6.15927
27.0	-411.070	0.10680	-6.15190
28.0	-409.270	0.11440	-6.14430
29.0	-407.470	0.12220	-6.13650
30.0	-405.670	0.13030	-6.12840
31.0	-403.870	0.13860	-6.12010
32.0	-402.070	0.14710	-6.11160
33.0	-400.270	0.15580	-6.10290
34.0	-398.470	0.16470	-6.09400
35.0	-396.670	0.17390	-6.08480
36.0	-394.870	0.18330	-6.07540
37.0	-393.070	0.19290	-6.06580
38.0	-391.270	0.20270	-6.05600
39.0	-389.470	0.21270	-6.04600
40.0	-387.670	0.22290	-6.03580

Table I
NBS Boulder Copper vs Constantan Thermocouple Table
With 0°K and 32°F Reference
Sheet 1 of 8

TEMPERATURE (DEGREE)		OUTPUT (MILLIVOLTS)	
(1) KELVIN T (°K)	(2) FAHRENHEIT T (°F)	(3) E (0°K)	(4) E (32°F)
41.0	-385.870	0.23330	-6.02540
42.0	-384.070	0.24390	-6.01480
43.0	-382.270	0.25470	-6.00400
44.0	-380.470	0.26570	-5.99300
45.0	-378.670	0.27680	-5.98190
46.0	-376.870	0.28820	-5.97050
47.0	-375.070	0.29980	-5.95890
48.0	-373.270	0.31150	-5.94720
49.0	-371.470	0.32350	-5.93520
50.0	-369.670	0.33560	-5.92310
51.0	-367.870	0.34790	-5.91080
52.0	-366.070	0.36030	-5.89840
53.0	-364.270	0.37300	-5.88570
54.0	-362.470	0.38580	-5.87290
55.0	-360.670	0.39880	-5.85990
56.0	-358.870	0.41190	-5.84680
57.0	-357.070	0.42520	-5.83350
58.0	-355.270	0.43870	-5.82000
59.0	-353.470	0.45240	-5.80630
60.0	-351.670	0.46620	-5.79250
61.0	-349.870	0.48010	-5.77860
62.0	-348.070	0.49430	-5.76440
63.0	-346.270	0.50850	-5.75020
64.0	-344.470	0.52300	-5.73570
65.0	-342.670	0.53750	-5.72120
66.0	-340.870	0.55230	-5.70640
67.0	-339.070	0.56720	-5.69150
68.0	-337.270	0.58220	-5.67650
69.0	-335.470	0.59730	-5.66140
70.0	-333.670	0.61270	-5.64600
71.0	-331.870	0.62810	-5.63060
72.0	-330.070	0.64370	-5.61500
73.0	-328.270	0.65940	-5.59930
74.0	-326.470	0.67530	-5.58340
75.0	-324.670	0.69120	-5.56750
76.0	-322.870	0.70730	-5.55140
77.0	-321.070	0.72350	-5.53520
78.0	-319.270	0.73990	-5.51880
79.0	-317.470	0.75640	-5.50230
80.0	-315.670	0.77300	-5.48570

Table I
NBS Boulder Copper vs Constantan Thermocouple Table
With 0°K and 32°F Reference
Sheet 2 of 8

TEMPERATURE (DEGREE)		OUTPUT (MILLIVOLTS)	
(1) KELVIN T (°K)	(2) FAHRENHEIT T (°F)	(3) E (0°K)	(4) E (32°F)
81.0	-313.870	0.78980	-5.46890
82.0	-312.070	0.80660	-5.45210
83.0	-310.270	0.82370	-5.43500
84.0	-308.470	0.84080	-5.41790
85.0	-306.670	0.85810	-5.40060
86.0	-304.870	0.87560	-5.38310
87.0	-303.070	0.89310	-5.36560
88.0	-301.270	0.91090	-5.34780
89.0	-299.470	0.92870	-5.33000
90.0	-297.670	0.94670	-5.31200
91.0	-295.870	0.96480	-5.29390
92.0	-294.070	0.98300	-5.27570
93.0	-292.270	1.00140	-5.25730
94.0	-290.470	1.01990	-5.23880
95.0	-288.670	1.03850	-5.22020
96.0	-286.870	1.05730	-5.20140
97.0	-285.070	1.07620	-5.18250
98.0	-283.270	1.09520	-5.16350
99.0	-281.470	1.11440	-5.14430
100.0	-279.670	1.13370	-5.12500
101.0	-277.870	1.15310	-5.10560
102.0	-276.070	1.17270	-5.08600
103.0	-274.270	1.19240	-5.06630
104.0	-272.470	1.21220	-5.04650
105.0	-270.670	1.23210	-5.02660
106.0	-268.870	1.25220	-5.00650
107.0	-267.070	1.27240	-4.98630
108.0	-265.270	1.29270	-4.96600
109.0	-263.470	1.31310	-4.94560
110.0	-261.670	1.33370	-4.92500
111.0	-259.870	1.35440	-4.90430
112.0	-258.070	1.37520	-4.88350
113.0	-256.270	1.39620	-4.86250
114.0	-254.470	1.41730	-4.84140
115.0	-252.670	1.43850	-4.82020
116.0	-250.870	1.45980	-4.79890
117.0	-249.070	1.48130	-4.77740
118.0	-247.270	1.50290	-4.75580
119.0	-245.470	1.52460	-4.73410
120.0	-243.670	1.54640	-4.71230

Table I
NBS Boulder Copper vs Constantan Thermocouple Table
With 0°K and 32°F Reference
Sheet 3 of 8

TEMPERATURE (DEGREE)		OUTPUT (MILLIVOLTS)	
(1) KELVIN T (°K)	(2) FAHRENHEIT T (°F)	(3) E (0°K)	(4) E (32°F)
121.0	-241.870	1.56840	-4.69030
122.0	-240.070	1.59050	-4.66820
123.0	-238.270	1.61270	-4.64600
124.0	-236.470	1.63500	-4.62370
125.0	-234.670	1.65750	-4.60120
126.0	-232.870	1.68010	-4.57860
127.0	-231.070	1.70280	-4.55590
128.0	-229.270	1.72560	-4.53310
129.0	-227.470	1.74860	-4.51010
130.0	-225.670	1.77170	-4.48700
131.0	-223.870	1.79490	-4.46380
132.0	-222.070	1.81830	-4.44040
133.0	-220.270	1.84170	-4.41700
134.0	-218.470	1.86530	-4.39340
135.0	-216.670	1.88910	-4.36960
136.0	-214.870	1.91290	-4.34580
137.0	-213.070	1.93690	-4.32180
138.0	-211.270	1.96100	-4.29770
139.0	-209.470	1.98520	-4.27350
140.0	-207.670	2.00950	-4.24920
141.0	-205.870	2.03400	-4.22470
142.0	-204.070	2.05860	-4.20010
143.0	-202.270	2.08340	-4.17530
144.0	-200.470	2.10820	-4.15050
145.0	-198.670	2.13320	-4.12550
146.0	-196.870	2.15830	-4.10040
147.0	-195.070	2.18360	-4.07510
148.0	-193.270	2.20890	-4.04980
149.0	-191.470	2.23440	-4.02430
150.0	-189.670	2.26000	-3.99870
151.0	-187.870	2.28570	-3.97300
152.0	-186.070	2.31160	-3.94710
153.0	-184.270	2.33760	-3.92110
154.0	-182.470	2.36370	-3.89500
155.0	-180.670	2.38990	-3.86880
156.0	-178.870	2.41680	-3.84250
157.0	-177.070	2.44270	-3.81600
158.0	-175.270	2.46920	-3.78950
159.0	-173.470	2.49590	-3.76280
160.0	-171.670	2.52270	-3.73600

Table I
NBS Boulder Copper vs Constantan Thermocouple Table
With 0°K and 32°F Reference
Sheet 4 of 8

TEMPERATURE (DEGREE)		OUTPUT (MILLIVOLTS)	
(1) KELVIN T (°K)	(2) FAHRENHEIT T (°F)	(3) E (0°K)	(4) E (32°F)
161.0	-169.870	2.54960	-3.70910
162.0	-168.070	2.57670	-3.68200
163.0	-166.270	2.60380	-3.65490
164.0	-164.470	2.63110	-3.62760
165.0	-162.670	2.65850	-3.60020
166.0	-160.870	2.68600	-3.57270
167.0	-159.070	2.71360	-3.54510
168.0	-157.270	2.74130	-3.51740
169.0	-155.470	2.76920	-3.48950
170.0	-153.670	2.79710	-3.46160
171.0	-151.870	2.82520	-3.43350
172.0	-150.070	2.85340	-3.40530
173.0	-148.270	2.88170	-3.37700
174.0	-146.470	2.91010	-3.34860
175.0	-144.670	2.93870	-3.32000
176.0	-142.870	2.96730	-3.29140
177.0	-141.070	2.99610	-3.26260
178.0	-139.270	3.02500	-3.23370
179.0	-137.470	3.05400	-3.20470
180.0	-135.670	3.08310	-3.17560
181.0	-133.870	3.11230	-3.14640
182.0	-132.070	3.14160	-3.11710
183.0	-130.270	3.17110	-3.08760
184.0	-128.470	3.20060	-3.05810
185.0	-126.670	3.23030	-3.02840
186.0	-124.870	3.26010	-2.99860
187.0	-123.070	3.29000	-2.96870
188.0	-121.270	3.32000	-2.93870
189.0	-119.470	3.35010	-2.90860
190.0	-117.670	3.38030	-2.87840
191.0	-115.870	3.41060	-2.84810
192.0	-114.070	3.44210	-2.81760
193.0	-112.270	3.47160	-2.78710
194.0	-110.470	3.50230	-2.75640
195.0	-108.670	3.53310	-2.72560
196.0	-106.870	3.56390	-2.69480
197.0	-105.070	3.59490	-2.66380
198.0	-103.270	3.62600	-2.63270
199.0	-101.470	3.65730	-2.60140
200.0	-99.670	3.68860	-2.57010

Table I
NBS Boulder Copper vs Constantan Thermocouple Table
With 0°K and 32°F Reference
Sheet 5 of 8

TEMPERATURE (DEGREE)		OUTPUT (MILLIVOLTS)	
(1) KELVIN T (°K)	(2) FAHRENHEIT T (°F)	(3) E (0°K)	(4) E (32°F)
201.0	-97.870	3.72000	-2.53870
202.0	-96.070	3.75150	-2.50720
203.0	-94.270	3.78320	-2.47550
204.0	-92.470	3.81490	-2.44380
205.0	-90.670	3.84680	-2.41190
206.0	-88.870	3.87880	-2.37990
207.0	-87.070	3.91080	-2.34790
208.0	-85.270	3.94300	-2.31570
209.0	-83.470	3.97530	-2.28340
210.0	-81.670	4.00770	-2.25100
211.0	-79.870	4.04020	-2.21850
212.0	-78.070	4.07280	-2.18590
213.0	-76.270	4.10550	-2.15320
214.0	-74.470	4.13830	-2.12040
215.0	-72.670	4.17120	-2.08750
216.0	-70.870	4.20430	-2.05440
217.0	-69.070	4.23740	-2.02130
218.0	-67.270	4.27060	-1.98810
219.0	-65.470	4.30400	-1.95470
220.0	-63.670	4.33740	-1.92130
221.0	-61.870	4.37100	-1.88770
222.0	-60.070	4.40460	-1.85410
223.0	-58.270	4.43840	-1.82030
224.0	-56.470	4.47220	-1.78650
225.0	-54.670	4.50620	-1.75250
226.0	-52.870	4.54020	-1.71850
227.0	-51.070	4.57440	-1.68430
228.0	-49.270	4.60870	-1.65000
229.0	-47.470	4.64300	-1.61570
230.0	-45.670	4.67750	-1.58120
231.0	-43.870	4.71210	-1.54660
232.0	-42.070	4.74680	-1.51190
233.0	-40.270	4.78150	-1.47720
234.0	-38.470	4.81640	-1.44230
235.0	-36.670	4.85140	-1.40730
236.0	-34.870	4.88650	-1.37220
237.0	-33.070	4.92160	-1.33710
238.0	-31.270	4.95690	-1.30180
239.0	-29.470	4.99230	-1.26640
240.0	-27.670	5.02780	-1.23090

Table I
NBS Boulder Copper vs Constantan Thermocouple Table
With 0°K and 32°F Reference
Sheet 6 of 8

TEMPERATURE (DEGREE)		OUTPUT (MILLIVOLTS)	
(1) KELVIN T (°K)	(2) FAHRENHEIT T (°F)	(3) E (0°K)	(4) E (32°F)
241.0	-25.870	5.06340	-1.19530
242.0	-24.070	5.09900	-1.15970
243.0	-22.270	5.13480	-1.12390
244.0	-20.470	5.17070	-1.08800
245.0	-18.670	5.20670	-1.05200
246.0	-16.870	5.24270	-1.01600
247.0	-15.070	5.27890	-0.97980
248.0	-13.270	5.31520	-0.94350
249.0	-11.470	5.35150	-0.90720
250.0	-9.670	5.38800	-0.87070
251.0	-7.870	5.42450	-0.83420
252.0	-6.070	5.46120	-0.79750
253.0	-4.270	5.49790	-0.76080
254.0	-2.470	5.53480	-0.72390
255.0	-0.670	5.57170	-0.68700
256.0	1.130	5.60880	-0.64990
257.0	2.930	5.64590	-0.61280
258.0	4.730	5.68320	-0.57550
259.0	6.530	5.72050	-0.53820
260.0	8.330	5.75790	-0.50080
261.0	10.130	5.79540	-0.46330
262.0	11.930	5.83300	-0.42570
263.0	13.730	5.87070	-0.38800
264.0	15.530	5.90850	-0.35020
265.0	17.330	5.94640	-0.31230
266.0	19.130	5.98440	-0.27430
267.0	20.930	6.02250	-0.23620
268.0	22.730	6.06070	-0.19800
269.0	24.530	6.09890	-0.15980
270.0	26.330	6.13730	-0.12140
271.0	28.130	6.17580	-0.08290
272.0	29.930	6.21430	-0.04440
273.0	31.730	6.25290	-0.00580
274.0	33.530	6.29170	0.03300
275.0	35.330	6.33050	0.07180
276.0	37.130	6.36940	0.11070
277.0	38.930	6.40840	0.14970
278.0	40.730	6.44750	0.16880
279.0	42.530	6.48670	0.22800
280.0	44.330	6.52600	0.26730

Table I
NBS Boulder Copper vs Constantan Thermocouple Table
With 0°K and 32°F Reference
Sheet 7 of 8

TEMPERATURE (DEGREE)		OUTPUT (MILLIVOLTS)	
(1) KELVIN T (°K)	(2) FAHRENHEIT T (°F)	(3) E (0°K)	(4) E (32°F)
281.0	46.130	6.56530	0.30660
282.0	47.930	6.60480	0.34610
283.0	49.730	6.64430	0.38560
284.0	51.530	6.68400	0.42530
285.0	53.330	6.72370	0.46500
286.0	55.130	6.76350	0.50480
287.0	56.930	6.80340	0.54470
288.0	58.730	6.84340	0.58470
289.0	60.530	6.88350	0.62460
290.0	62.330	6.92370	0.66500
291.0	64.130	6.96390	0.70520
292.0	65.930	7.00430	0.74560
293.0	67.730	7.04470	0.78600
294.0	69.530	7.08520	0.82650
295.0	71.330	7.12580	0.86710
296.0	73.130	7.16650	0.90780
297.0	74.930	7.20730	0.94860
298.0	76.730	7.24820	0.98950
299.0	78.530	7.28920	1.03050
300.0	80.330	7.33020	1.07150

Table I
NBS Boulder Copper vs Constantan Thermocouple Table
With 0°K and 32°F Reference
Sheet 8 of 8

Reference Junction 32°F

Temp °F	0	1	2	3	4	5	6	7	8	9
	EMF (MILLIVOLTS)									
-420	-6.1859	-6.1894	-6.1928	-6.1961	-6.1993	-6.2025				
-410	-6.1474	-6.1516	-6.1558	-6.1598	-6.1638	-6.1677	-6.1715	-6.1752	-6.1789	-6.182
-400	-6.1016	-6.1064	-6.1112	-6.1160	-6.1206	-6.1253	-6.1298	-6.1343	-6.1388	-6.143
-390	-6.0490	-6.0546	-6.0601	-6.0655	-6.0708	-6.0761	-6.0813	-6.0864	-6.0915	-6.096
-380	-5.9900	-5.9962	-6.0023	-6.0084	-6.0144	-6.0203	-6.0262	-6.0320	-6.0377	-6.043
-370	-5.9251	-5.9319	-5.9386	-5.9452	-5.9518	-5.9584	-5.9649	-5.9712	-5.9775	-5.983
-360	-5.8548	-5.8621	-5.8693	-5.8765	-5.8836	-5.8907	-5.8977	-5.9046	-5.9115	-5.918
-350	-5.7794	-5.7871	-5.7949	-5.8025	-5.8101	-5.8177	-5.8253	-5.8327	-5.8401	-5.847
-340	-5.6991	-5.7074	-5.7155	-5.7237	-5.7318	-5.7399	-5.7478	-5.7558	-5.7637	-5.771
-330	-5.6144	-5.6231	-5.6317	-5.6403	-5.6488	-5.6573	-5.6658	-5.6742	-5.6825	-5.690
-320	-5.5256	-5.5347	-5.5437	-5.5527	-5.5616	-5.5705	-5.5794	-5.5882	-5.5970	-5.605
-310	-5.4325	-5.4420	-5.4515	-5.4609	-5.4702	-5.4796	-5.4889	-5.4981	-5.5073	-5.516
-300	-5.3353	-5.3452	-5.3550	-5.3649	-5.3747	-5.3844	-5.3941	-5.4038	-5.4134	-5.423
-290	-5.2339	-5.2442	-5.2545	-5.2647	-5.2749	-5.2851	-5.2952	-5.3053	-5.3153	-5.325
-280	-5.1285	-5.1392	-5.1499	-5.1606	-5.1712	-5.1817	-5.1922	-5.2027	-5.2132	-5.223
-270	-5.0192	-5.0303	-5.0413	-5.0524	-5.0634	-5.0743	-5.0852	-5.0961	-5.1070	-5.117
-260	-4.9058	-4.9173	-4.9288	-4.9402	-4.9516	-4.9630	-4.9743	-4.9856	-4.9968	-5.008
-250	-4.7886	-4.8005	-4.8124	-4.8242	-4.8360	-4.8477	-4.8594	-4.8711	-4.8827	-4.894
-240	-4.6674	-4.6797	-4.6919	-4.7042	-4.7163	-4.7285	-4.7406	-4.7526	-4.7647	-4.776
-230	-4.5423	-4.5550	-4.5676	-4.5802	-4.5928	-4.6053	-4.6178	-4.6303	-4.6427	-4.6551
-220	-4.4135	-4.4265	-4.4395	-4.4525	-4.4654	-4.4783	-4.4912	-4.5040	-4.5168	-4.529
-210	-4.2806	-4.2940	-4.3075	-4.3209	-4.3342	-4.3475	-4.3608	-4.3740	-4.3872	-4.400
-200	-4.1439	-4.1577	-4.1715	-4.1853	-4.1990	-4.2127	-4.2264	-4.2400	-4.2536	-4.2671
-190	-4.0034	-4.0176	-4.0318	-4.0459	-4.0600	-4.0741	-4.0881	-4.1021	-4.1161	-4.1300
-180	-3.8591	-3.8737	-3.8882	-3.9028	-3.9172	-3.9317	-3.9461	-3.9605	-3.9748	-3.9891
-170	-3.7111	-3.7261	-3.7410	-3.7559	-3.7707	-3.7856	-3.8003	-3.8151	-3.8298	-3.8445
-160	-3.5595	-3.5748	-3.5901	-3.6053	-3.6206	-3.6357	-3.6509	-3.6660	-3.6811	-3.6961
-150	-3.4042	-3.4199	-3.4356	-3.4512	-3.4668	-3.4823	-3.4978	-3.5133	-3.5287	-3.5441
-140	-3.2454	-3.2615	-3.2775	-3.2935	-3.3094	-3.3253	-3.3411	-3.3570	-3.3728	-3.3885
-130	-3.0832	-3.0996	-3.1159	-3.1322	-3.1485	-3.1647	-3.1810	-3.1971	-3.2133	-3.2294
-120	-2.9174	-2.9342	-2.9509	-2.9675	-2.9841	-3.0007	-3.0173	-3.0338	-3.0503	-3.0668
-110	-2.7483	-2.7654	-2.7824	-2.7994	-2.8164	-2.8333	-2.8502	-2.8671	-2.8839	-2.9007

Table II
NBS Boulder/Washington Copper vs Constantan Table
Sheet 1 of 4

Reference Junction 32°F

Temp °F	0	1	2	3	4	5	6	7	8	9
	EMF (MILLIVOLTS)									
-100	-2.5758	-2.5932	-2.6106	-2.6279	-2.6452	-2.6625	-2.6797	-2.6969	-2.7141	-2.7312
-90	-2.4000	-2.4177	-2.4354	-2.4531	-2.4707	-2.4883	-2.5059	-2.5234	-2.5409	-2.5584
-80	-2.2209	-2.2389	-2.2569	-2.2749	-2.2929	-2.3108	-2.3287	-2.3466	-2.3644	-2.3822
-70	-2.0385	-2.0568	-2.0752	-2.0935	-2.1118	-2.1301	-2.1483	-2.1665	-2.1846	-2.2028
-60	-1.8528	-1.8715	-1.8902	-1.9089	-1.9275	-1.9460	-1.9646	-1.9831	-2.0016	-2.0200
-50	-1.6640	-1.6830	-1.7020	-1.7210	-1.7399	-1.7588	-1.7777	-1.7965	-1.8153	-1.8341
-40	-1.4720	-1.4913	-1.5106	-1.5299	-1.5492	-1.5684	-1.5876	-1.6067	-1.6258	-1.6449
-30	-1.2769	-1.2965	-1.3161	-1.3357	-1.3553	-1.3748	-1.3943	-1.4138	-1.4332	-1.4526
-20	-1.0786	-1.0986	-1.1185	-1.1384	-1.1583	-1.1781	-1.1979	-1.2177	-1.2375	-1.2572
-10	-0.8774	-0.8977	-0.9179	-0.9381	-0.9583	-0.9784	-0.9985	-1.0186	-1.0386	-1.0587
-0	-0.6732	-0.6937	-0.7142	-0.7347	-0.7552	-0.7756	-0.7961	-0.8164	-0.8368	-0.8571
+0	-0.6732	-0.6526	-0.6319	-0.6113	-0.5906	-0.5699	-0.5492	-0.5284	-0.5076	-0.4868
+10	-0.4660	-0.4551	-0.4242	-0.4032	-0.3823	-0.3613	-0.3402	-0.3192	-0.2981	-0.2770
20	-0.2559	-0.2347	-0.2135	-0.1923	-0.1710	-0.1497	-0.1284	-0.1071	-0.0857	-0.0643
30	-0.0429	-0.0214	0.0000	0.0213	0.0427	0.0642	0.0856	0.1071	0.1286	0.1502
40	-0.1717	-0.1933	0.2150	0.2366	0.2583	0.2800	0.3018	0.3235	0.3453	0.3671
50	0.3890	0.4109	0.4328	0.4547	0.4767	0.4987	0.5207	0.5427	0.5648	0.5869
60	0.6090	0.6312	0.6534	0.6756	0.6978	0.7201	0.7424	0.7647	0.7871	0.8095
70	0.8319	0.8543	0.8768	0.8992	0.9218	0.9447	0.9673	0.9899	1.0125	1.0352
80	1.0578	1.0805	1.1033	1.1260	1.1488	1.1716	1.1945	1.2173	1.2402	1.2631
90	1.2861	1.3091	1.3321	1.3551	1.3781	1.4012	1.4243	1.4474	1.4706	1.4938
100	1.5170	1.5402	1.5635	1.5868	1.6101	1.6335	1.6568	1.6802	1.7036	1.7271
110	1.7506	1.7741	1.7976	1.8212	1.8447	1.8683	1.8920	1.9156	1.9393	1.9631
120	1.9868	2.0106	2.0344	2.0582	2.0820	2.1065	2.1304	2.1543	2.1783	2.2023
130	2.2263	2.2503	2.2743	2.2984	2.3225	2.3466	2.3708	2.3949	2.4191	2.4434
140	2.4676	2.4919	2.5162	2.5405	2.5648	2.5892	2.6136	2.6380	2.6624	2.6869
150	2.7114	2.7359	2.7605	2.7850	2.8096	2.8342	2.8589	2.8835	2.9082	2.9329
160	2.9577	2.9824	3.0072	3.0320	3.0569	3.0817	3.1066	3.1315	3.1564	3.1814
170	3.2064	3.2314	3.2564	3.2815	3.3066	3.3322	3.3573	3.3825	3.4077	3.4329
180	3.4581	3.4833	3.5086	3.5339	3.5592	3.5845	3.6099	3.6353	3.6607	3.6861
190	3.7115	3.7370	3.7625	3.7880	3.8136	3.8391	3.8647	3.8903	3.9160	3.9416

Table II
NBS Boulder/Washington Copper vs Constantan Table
Sheet 2 of 4

Reference Junction 32°F

Temp °F	0	1	2	3	4	5	6	7	8	9
	EMF (MILLIVOLTS)									
200	3.9673	3.9930	4.0187	4.0445	4.0702	4.0960	4.1219	4.1477	4.1736	4.1994
210	4.2253	4.2513	4.2772	4.3032	4.3292	4.3552	4.3813	4.4073	4.4334	4.4595
220	4.4857	4.5118	4.5380	4.5642	4.5904	4.6172	4.6435	4.6698	4.6961	4.7224
230	4.7488	4.7751	4.8015	4.8280	4.8544	4.8809	4.9074	4.9339	4.9604	4.9869
240	5.0135	5.0401	5.0667	5.0934	5.1200	5.1467	5.1734	5.2001	5.2269	5.2536
250	5.2804	5.3072	5.3340	5.3609	5.3878	5.4146	5.4416	5.4685	5.4954	5.5224
260	5.5494	5.5764	5.6035	5.6305	5.6576	5.6847	5.7118	5.7390	5.7662	5.7934
270	5.8206	5.8478	5.8750	5.9023	5.9296	5.9573	5.9847	6.0120	6.0394	6.0668
280	6.0942	6.1216	6.1491	6.1766	6.2041	6.2316	6.2591	6.2867	6.3143	6.3419
290	6.3695	6.3971	6.4248	6.4525	6.4802	6.5079	6.5356	6.5634	6.5912	6.6190
300	6.6468	6.6746	6.7025	6.7304	6.7583	6.7862	6.8141	6.8421	6.8701	6.8981
310	6.9261	6.9542	6.9822	7.0103	7.0384	7.0665	7.0947	7.1228	7.1510	7.1792
320	7.2074	7.2357	7.2640	7.2922	7.3205	7.3495	7.3779	7.4062	7.4346	7.4630
330	7.4914	7.5199	7.5483	7.5768	7.6053	7.6338	7.6623	7.6908	7.7194	7.7480
340	7.7766	7.8052	7.8338	7.8625	7.8911	7.9198	7.9485	7.9772	8.0060	8.0347
350	8.0635	8.0923	8.1211	8.1499	8.1788	8.2076	8.2365	8.2654	8.2943	8.3233
360	8.3522	8.3812	8.4102	8.4392	8.4682	8.4973	8.5263	8.5554	8.5845	8.6136
370	8.6428	8.6719	8.7011	8.7303	8.7595	8.7889	8.8182	8.8474	8.8767	8.9060
380	8.9353	8.9646	8.9940	9.0234	9.0527	9.0821	9.1115	9.1410	9.1704	9.1999
390	9.2294	9.2589	9.2884	9.3179	9.3475	9.3771	9.4067	9.4363	9.4659	9.4955
400	9.5252	9.5549	9.5846	9.6143	9.6440	9.6738	9.7035	9.7333	9.7631	9.7929
410	9.8227	9.8526	9.8825	9.9124	9.9423	9.9722	10.0021	10.0321	10.0620	10.0920
420	10.1220	10.1521	10.1821	10.2122	10.2422	10.2728	10.3029	10.3330	10.3632	10.3933
430	10.4235	10.4537	10.4839	10.5141	10.5444	10.5746	10.6049	10.6352	10.6655	10.6958
440	10.7261	10.7565	10.7868	10.8172	10.8476	10.8780	10.9084	10.9389	10.9693	10.9998
450	11.0303	11.0608	11.0913	11.1219	11.1524	11.1830	11.2136	11.2442	11.2748	11.3054
460	11.3361	11.3667	11.3974	11.4281	11.4588	11.4896	11.5203	11.5511	11.5818	11.6126
470	11.6434	11.6743	11.7051	11.7359	11.7668	11.7980	11.8289	11.8598	11.8907	11.9217
480	11.9527	11.9836	12.0146	12.0456	12.0766	12.1077	12.1387	12.1698	12.2009	12.2320
490	12.2631	12.2942	12.3253	12.3565	12.3877	12.4189	12.4501	12.4813	12.5125	12.5437

Table II
NBS Boulder/Washington Copper vs Constantan Table
Sheet 3 of 4

Reference Junction 32°F

Temp °F	0	1	2	3	4	5	6	7	8	9
	EMF (MILLIVOLTS)									
500	12.5750	12.6063	12.6376	12.6689	12.7002	12.7315	12.7629	12.7942	12.8256	12.8570
510	12.8884	12.9198	12.9513	12.9827	13.0142	13.0457	13.0772	13.1087	13.1402	13.1717
520	13.2033	13.2349	13.2665	13.2981	13.3297	13.3617	13.3933	13.4250	13.4567	13.4883
530	13.5200	13.5518	13.5835	13.6152	13.6470	13.6787	13.7105	13.7423	13.7741	13.8060
540	13.8378	13.8696	13.9015	13.9334	13.9653	13.9972	14.0291	14.0610	14.0930	14.1249
550	14.1569	14.1889	14.2209	14.2529	14.2849	14.3170	14.3490	14.3811	14.4132	14.4453
560	14.4774	14.5095	14.5416	14.5738	14.6059	14.6381	14.6703	14.7025	14.7347	14.7670
570	14.7992	14.8315	14.8637	14.8960	14.9283	14.9609	14.9932	15.0256	15.0579	15.0903
580	15.1226	15.1550	15.1874	15.2199	15.2523	15.2847	15.3172	15.3497	15.3821	15.4146
590	15.4471	15.4797	15.5122	15.5447	15.5773	15.6099	15.6424	15.6750	15.7076	15.7403
600	15.7729	15.8055	15.8382	15.8709	15.9036	15.9363	15.9690	16.0017	16.0344	16.0672
610	16.1000	16.1327	16.1655	16.1983	16.2311	16.2640	16.2968	16.3297	16.3625	16.3954
620	16.4283	16.4612	16.4941	16.5270	16.5600	16.5931	16.6261	16.6591	16.6921	16.7251
630	16.7581	16.7911	16.8242	16.8572	16.8903	16.9234	16.9564	16.9895	17.0227	17.0558
640	17.0889	17.1221	17.1552	17.1884	17.2216	17.2548	17.2880	17.3212	17.3545	17.3877
650	17.4210	17.4543	17.4876	17.5209	17.5542	17.5875	17.6208	17.6542	17.6875	17.7209
660	17.7543	17.7877	17.8211	17.8545	17.8880	17.9214	17.9549	17.9883	18.0218	18.0553
670	18.0888	18.1223	18.1559	18.1894	18.2230	18.2570	18.2906	18.3242	18.3578	18.3914
680	18.4250	18.4586	18.4923	18.5259	18.5596	18.5933	18.6270	18.6606	18.6944	18.7281
690	18.7618	18.7955	18.8293	18.8631	18.8968	18.9306	18.9644	18.9982	19.0320	19.0659
700	19.0997	19.1335	19.1674	19.2013	19.2352	19.2690	19.3030	19.3369	19.3708	19.4047
710	19.4387	19.4726	19.5066	19.5406	19.5746	19.6086	19.6426	19.6766	19.7106	19.7447
720	19.7787	19.8128	19.8468	19.8809	19.9150	19.9491	19.9833	20.0174	20.0515	20.0857
730	20.1198	20.1540	20.1882	20.2224	20.2566	20.2908	20.3250	20.3593	20.3935	20.4278
740	20.4620	20.4963	20.5306	20.5649	20.5992	20.6335	20.6679	20.7022	20.7366	20.7709

Table II
NBS Boulder/Washington Copper vs Constantan Table
Sheet 4 of 4

TEST ITEM	MANUFACTURER	DESCRIPTION	S/N	PURPOSE OF TEST	LIMITS	TEMPERATURE AND/OR OUTPUT DEVIATION (THERMOCOUPLE-STANDARD)							
						LHe BATH (-452°F)		LNe BATH (-411°F)		LN2 BATH (-320°F)		ICE BATH (32°F)	
						uv	°F	uv	°F	uv	°F	uv	°F
					DEVELOPMENTAL	None	None		±8.2		±6.4		±1.0
C/C-1	Nugget Mfg. Co.	Test Area open element thermocouple Model 105B65 per AGC SCD 267016	2N1784	Cryogenic Calibration		--	--	101.8	20.78	80.8	8.72	0	0
C/C-2			2N1785			--	--	111.9	22.56	75.8	8.19	0	0
C/C-3			2N1786			--	--	97.9	20.09	70.9	7.67	0	0
C/C-4			2N1788			--	--	72.8	15.42	45.8	4.98	0	0
C/C-5			2N1789			--	--	73.8	15.61	25.8	2.82	0	0
C/C-6		Test Area grounded element thermocouple Model 102B60 per AGC SCD 267115	2N1576			--	--	127.8	25.33	77.8	8.40	0	0
C/C-7			2N1581			--	--	97.8	20.07	81.8	8.82	0	0
C/C-8			2N1563			--	--	97.8	20.07	64.8	7.02	0	0
C/C-9			2N1568			--	--	97.8	20.09	81.9	8.83	0	0
C/C-10		Test Area grounded element thermocouple Model 102B60 per AGC SCD 248007	2N1098			--	--	61.8	13.28	41.8	4.55	0	0
C/C-11			2N1099			--	---	Invalid Data		40.8	4.45	0	0
C/C-12	J R C McIntosh Co.	Test Area grounded element thermocouple per AGC SCD 235486-64	T-40			--	--	168.8	32.07	96.8	10.40	0	0
C/C-13			T-86			--	--	36.8	8.22	--	--	0	0
C/C-14	Electrowest	Test Area grounded element Thermocouples	B-6309			--	--	60.8	13.10	--	--	0	0
C/C-15			B-6310			--	--	69.3	14.76	--	--	0	0
C/C-16			B-6399			--	--	55.8	12.10	--	--	0	0
C/C-1 thru C/C-16				Average		-- --	-- --	89.0	18.20	65.3	7.06	0	0
					DEVELOPMENTAL	±20	None		±4.1		±3.2		±1.0
C/C-17	Temptron Inc.	Unannealed 22 AWG Bare Wire 75-2VS75A1	1	Cryogenic Calibration		123.9*	45.6*	90.8	18.80	62.7	5.87	0	0
C/C-17			1	1st LHe Data Cycle		123.8	--	--	--	--	--	--	--
C/C-17			1	2nd LHe Data Cycle		123.8	--	--	--	--	--	--	--
C/C-17			1	3rd LHe Data Cycle		124.3	--	--	--	--	--	--	--
C/C-17			1	4th LHe Data Cycle		123.8	--	--	--	--	--	--	--
C/C-18			2	Cryogenic Calibration		121.0*	45.0*	92.3	19.09	54.2	4.50	0	0
C/C-18			2	1st LHe Data Cycle		120.8	--	--	--	--	--	--	--
C/C-18			2	2nd LHe Data Cycle		121.3	--	--	--	--	--	--	--
C/C-18			2	3rd LHe Data Cycle		120.6	--	--	--	--	--	--	--
C/C-18			2	4th LHe Data Cycle		121.1	--	--	--	--	--	--	--
C/C-19		Unannealed 22AWG Bare Wire 75-1VS75A3	1	Cryogenic Calibration		196.7*	60.3*	116.3	23.36	57.2	5.24	0	0
C/C-19			1	1st LHe Data Cycle		197.8	--	--	--	--	--	--	--
C/C-19			1	2nd LHe Data Cycle		196.3	--	--	--	--	--	--	--
C/C-19			1	3rd LHe Data Cycle		195.8	--	--	--	--	--	--	--
C/C-19			1	4th LHe Data Cycle		196.8	--	--	--	--	--	--	--
C/C-20			2	Cryogenic Calibration		199.3*	60.4*	117.8	23.78	47.2	4.15	0-	0
C/C-20			2	1st LHe Data Cycle		198.8	--	--	--	--	--	--	--
C/C-20			2	2nd LHe Data Cycle		199.3	--	--	--	--	--	--	--
C/C-20			2	3rd LHe Data Cycle		199.8	--	--	--	--	--	--	--
C/C-20			2	4th LHe Data Cycle		199.3	--	--	--	--	--	--	--

*AVERAGE OF 4 CYCLES
--NO MEASUREMENT TAKEN

Table III
Test Results - Aerojet Calibration Data Reduced per NBS Boulder/Washington and Aerojet Copper vs Constantan Thermocouple Table
Sheet 1 of 3

TEST ITEM	MANUFACTURER	DESCRIPTION	S/N	PURPOSE OF TEST	LIMITS	LHe BATH (-452°F) uv	LHe BATH (-452°F) °F	LH2 BATH (-411°F) uv	LH2 BATH (-411°F) °F	LN2 BATH (-320°F) uv	LN2 BATH (-320°F) °F	ICE BATH (32°F) uv	ICE BATH (32°F) °F
					DEVELOPMENTAL	±20	None		±4.1		±3.2		±1.0
C/C-21	Temptron Inc.	Unannealed 30 AWG Bare Wire 80VS80A1	1	Cryogenic Calibration		58.4*	27.7*	19.3	4.42	-4.6	-0.49	0	0
C/C-21			1	1st LHe Data Cycle		57.8	--	--	--	--	--	--	--
C/C-21			1	2nd LHe Data Cycle		58.3	--	--	--	--	--	--	--
C/C-21			1	3rd LHe Data Cycle		59.3	--	--	--	--	--	--	--
C/C-21			1	4th LHe Data Cycle		58.3	--	--	--	--	--	--	--
C/C-22		Unannealed 30 AWG Bare Wire 80 VS 80A2	1	Cryogenic Calibration		62.2*	29.8*	23.8	5.42	-7.0	-0.23	0	0
C/C-22			1	1st LHe Data Cycle		61.8	--	--	--	--	--	--	--
C/C-22			1	2nd LHe Data Cycle		62.8	--	--	--	--	--	--	--
C/C-22			1	3rd LHe Data Cycle		61.8	--	--	--	--	--	--	--
C/C-22			1	4th LHe Data Cycle		61.3	--	--	--	--	--	--	--
C/C-23		Unannealed 30 AWG Bare Wire 80 VS 80A3	1	Cryogenic Calibration		61.4*	29.6*	24.8	5.64	-4.0	-0.50	0	0
C/C-23			1	1st LHe Data Cycle		60.8	--	--	--	--	--	--	--
C/C-23			1	2nd LHe Data Cycle		60.8	--	--	--	--	--	--	--
C/C-23			1	3rd LHe Data Cycle		61.8	--	--	--	--	--	--	--
C/C-23			1	4th LHe Data Cycle		62.3	--	--	--	--	--	--	--
C/C-24		Unannealed 30 AWG Bare Wire 80 VS 80A4	1	Cryogenic Calibration		62.3*	29.9*	22.8	5.20	-6.7	-0.26	0	0
C/C-24			1	1st LHe Data Cycle		61.8	--	--	--	--	--	--	--
C/C-24			1	2nd LHe Data Cycle		62.3	--	--	--	--	--	--	--
C/C-24			1	3rd LHe Data Cycle		62.8	--	--	--	--	--	--	--
C/C-24			1	4th LHe Data Cycle		62.3	--	--	--	--	--	--	--
C/C-25		Unannealed 30 AWG Bare Wire 80 VS 80A5	1	Cryogenic Calibration		61.3*	29.6*	21.3	4.84	-6.5	-0.28	0	0
C/C-25			1	1st LHe Data Cycle		60.8	--	--	--	--	--	--	--
C/C-25			1	2nd LHe Data Cycle		60.8	--	--	--	--	--	--	--
C/C-25			1	3rd LHe Data Cycle		61.8	--	--	--	--	--	--	--
C/C-25			1	4th LHe Data Cycle		61.8	--	--	--	--	--	--	--
C/C-26		Annealed 22 AWG Bare Wire 75-2 VS 75A1	1	Cryogenic Calibration		52.2*	26.7*	34.8	7.75	26.0	1.86	0	0
C/C-26			1	1st LHe Data Cycle		51.8	--	--	--	--	--	--	--
C/C-26			1	2nd LHe Data Cycle		51.8	--	--	--	--	--	--	--
C/C-26			1	3rd LHe Data Cycle		52.8	--	--	--	--	--	--	--
C/C-26			1	4th LHe Data Cycle		52.3	--	--	--	--	--	--	--
C/C-27			2	Cryogenic Calibration		56.2*	28.0*	38.8	7.58	26.6	1.92	0	0
C/C-27			2	1st LHe Data Cycle		56.3	--	--	--	--	--	--	--
C/C-27			2	2nd LHe Data Cycle		55.8	--	--	--	--	--	--	--
C/C-27			2	3rd LHe Data Cycle		55.8	--	--	--	--	--	--	--
C/C-27			2	4th LHe Data Cycle		56.8	--	--	--	--	--	--	--

*AVERAGE OF 4 CYCLES
--NO MEASUREMENT TAKEN

Table III
Test Results - Aerojet Calibration Data Reduced per NBS Boulder/Washington and Aerojet Copper vs Constantan Thermocouple Table
Sheet 2 of 3

TEST ITEM	MANUFACTURER	DESCRIPTION	S/N	PURPOSE OF TEST	LIMITS	LHe BATH (-452°F) uv	LHe BATH (-452°F) °F	LH2 BATH (-411°F) uv	LH2 BATH (-411°F) °F	LN2 BATH (-320°F) uv	LN2 BATH (-320°F) °F	ICE BATH (32°F) uv	ICE BATH (32°F) °F
					DEVELOPMENTAL	±20	None		±4.1	-	±3.2		±1.0
C/C-28	Temptron Inc.	Annealed 22 AWG Bare Wire 75-1 VS 75A3	1	Cryogenic Calibration		110.6*	42.7*	64.1	13.74	35.1	2.84	0	0
C/C-28			1	1st LHe Data Cycle		108.8	--	--	--	--	--	--	--
C/C-28			1	2nd LHe Data Cycle		109.8	--	--	--	--	--	--	--
C/C-28			1	3rd LHe Data Cycle		112.8	--	--	--	--	--	--	--
C/C-28			1	4th LHe Data Cycle		110.8	--	--	--	--	--	--	--
C/C-29			2	Cryogenic Calibration		110.7*	42.6*	61.6	13.24	34.6	2.79	0	0
C/C-29			2	1st LHe Data Cycle		109.8	--	--	--	--	--	--	--
C/C-29			2	2nd LHe Data Cycle		111.3	--	--	--	--	--	--	--
C/C-29			2	3rd LHe Data Cycle		110.8	--	--	--	--	--	--	--
C/C-29			2	4th LHe Data Cycle		110.8	--	--	--	--	--	--	--
C/C-30		Annealed 30 AWG Bare Wire 80 VS 80A1	1	Cryogenic Calibration		134.3*	47.9*	89.8	20.58	55.5	5.05	0	0
C/C-30			1	1st LHe Data Cycle		132.8	--	--	--	--	--	--	--
C/C-30			1	2nd LHe Data Cycle		134.8	--	--	--	--	--	--	--
C/C-30			1	3rd LHe Data Cycle		134.8	--	--	--	--	--	--	--
C/C-30			1	4th LHe Data Cycle		134.8	--	--	--	--	--	--	--
C/C-31		Annealed 30 AWG Bare Wire 80 VS 80A2	1	Cryogenic Calibration		130.2*	47.0*	94.8	19.48	53.5	4.83	0	0
C/C-31			1	1st LHe Data Cycle		130.8	--	--	--	--	--	--	--
C/C-31			1	2nd LHe Data Cycle		129.8	--	--	--	--	--	--	--
C/C-31			1	3rd LHe Data Cycle		130.8	--	--	--	--	--	--	--
C/C-31			1	4th LHe Data Cycle		128.8	--	--	--	--	--	--	--
C/C-32		Annealed 30 AWG Bare Wire 80 VS 80A3	1	Cryogenic Calibration		137.4*	48.6*	98.8	20.26	66.0	6.16	0	0
C/C-32			1	1st LHe Data Cycle		135.8	--	--	--	--	--	--	--
C/C-32			1	2nd LHe Data Cycle		138.8	--	--	--	--	--	--	--
C/C-32			1	3rd LHe Data Cycle		138.3	--	--	--	--	--	--	--
C/C-32			1	4th LHe Data Cycle		137.8	--	--	--	--	--	--	--
C/C-33		Annealed 30 AWG Bare Wire 80 VS 80A4	1	Cryogenic Calibration		140.1*	49.2*	94.8	19.48	63.5	5.90	0	0
C/C-33			1	1st LHe Data Cycle		140.8	--	--	--	--	--	--	--
C/C-33			1	2nd LHe Data Cycle		139.8	--	--	--	--	--	--	--
C/C-33			1	3rd LHe Data Cycle		140.3	--	--	--	--	--	--	--
C/C-33			1	4th LHe Data Cycle		139.3	--	--	--	--	--	--	--
C/C-34		Annealed 30 AWG Bare Wire 80 VS 80A5	1	Cryogenic Calibration		139.6*	49.9*	98.3	20.18	64.0	5.95	0	0
C/C-34			1	1st LHe Data Cycle		136.8	--	--	--	--	--	--	--
C/C-34			1	2nd LHe Data Cycle		139.8	--	--	--	--	--	--	--
C/C-34			1	3rd LHe Data Cycle		140.8	--	--	--	--	--	--	--
C/C-34			1	4th LHe Data Cycle		140.8	--	--	--	--	--	--	--

*AVERAGE OF 4 CYCLES
--NO MEASUREMENT TAKEN

Table III
Test Results - Aerojet Calibration Data Reduced per NBS Boulder/Washington and Aerojet Copper vs Constantan Thermocouple Table
Sheet 3 of 3

TEST SETUP	BATH TEMP. (°F)	Output for Test Items: C/C-35	Output for Test Items: C/C-36	Output for Test Items: C/C-37	TEMPERATURE AND/OR OUTPUT DEVIATION (THERMOCOUPLE-STANDARD): Test Item C/C-35, Spool 75-2V875A1 (SN 3): Reduced per NBS Table		Reduced per Aerojet Table		Test Item C/C-36, Spool 75-1V875A3 (SN 3): Reduced per NBS Table		Reduced per Aerojet Table		Test Item C/C-37, Spool 80V880A1 (SN 2): Reduced per NBS Table		Reduced per Aerojet Table	
		mv	mv	mv	uv	°F	uv	°F	uv	°F	uv	°F	uv	°F	uv	°F
Ice Bath	32.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cryostat	-20.65	-1.0899	-1.0886	-1.0852	1.6		0.9	0.05	2.9		2.2		6.3		5.6	
	-27.60	-1.2268	-1.2261	-1.2220	2.8		1.4	0.07	3.5		2.1		7.6		6.2	
	-48.53	-1.6362	-1.6310	-1.6250	-0.2		-4.0	-0.21	5.0		1.2		11.0		7.2	
	-54.37	-1.7449	-1.7417	-1.7357	1.9		-2.1	-0.12	5.1		1.1		11.1		8.1	
	-63.13	-1.9036	-1.9038	-1.8988	7.7		3.0	0.17	7.5		2.8		12.5		7.8	
	-95.99	-2.5014	-2.4990	-2.4895	4.3		0.1	0.01	6.7		2.5		16.2		12.0	
	-99.49	-2.5622	-2.5599	-2.5499	4.7		0.6	0.03	7.0		2.9		17.0		12.9	
Cryostat	-100.64	-2.5823	-2.5799	-2.5701	4.7		0.5	0.03	7.1		2.9		16.9		12.7	
CO_2 Bath	-125.17	-2.9956	-2.9910	-2.9845	8.7	0.58	1.8	0.11	12.5	0.75	6.5	0.39	19.0	1.14	13.0	0.79
Cryostat	-137.49	-3.1963	-3.1942	-3.1832	8.7		0.1	0.01	10.8		2.2		21.8		13.2	
	-154.12	-3.4539	-3.4545	-3.4449*	14.8		1.5	0.10	14.2		0.9		25.1		10.5	
	-177.61	-3.8042	-3.8046	-3.7949*	19.9		0.8	0.06	19.5		-0.4		29.2		10.1	
	-207.15	-4.2251	-4.2224	-4.2093	16.9		-1.4	-0.11	19.6		1.3		32.7		14.4	
	-207.22	-4.2263	-4.2232	-4.2101	16.7		-1.7	-0.13	19.8		1.4		32.9		14.5	
	-207.68	-4.2319	-4.2292	-4.2160*	17.5		-1.1	-0.06	20.1		1.6		33.2		14.8	
	-207.69	-4.2320	-4.2293	-4.2161*	17.4		-1.1	-0.08	20.1		1.6		33.4		14.8	
	-229.90	-4.5166	-4.5159	-4.5005*	24.4		2.5	0.20	25.1		3.3		40.6		18.6	
	-230.32	-4.5205	-4.5195	-4.5081*	25.8		3.9	0.31	26.8		4.9		38.6		16.3	
	-241.46	-4.6657	-4.6621	-4.6469*	19.6		-3.3	-0.27	23.2		0.4		38.7		15.5	
	-250.16	-4.7679	-4.7640	-4.7476*	22.6		-0.9	-0.07	26.5		3.0		42.9		19.4	
	-262.05	-4.9054	-4.9019	-4.8831*	24.1		0.6	0.05	27.6		4.1		46.3		22.9	
	-267.19	-4.9658	-4.9614	-4.9443*	22.3		-0.8	-0.06	26.7		3.6		43.7		20.7	
	-276.88	-5.0757	-5.0702	-5.0484*	19.0		-0.7	-0.06	24.5		4.8		46.3		26.6	
	-318.14	-5.4855	-5.4780	-5.4542	23.1		1.7	0.16	30.6		9.2		54.4		33.0	
Cryostat	-318.30	-5.4867	-5.4791	-5.4547	23.4		1.9	0.21	31.0		9.5		55.4		33.9	
LN_2 BATH	-320.12	-5.5062	-5.4979	-5.4701	20.5	2.24	-1.2	-0.13	28.8	3.15	7.1	0.79	56.6	6.14	34.9	3.86
LN_2 BATH	-320.14	-5.5066	-5.4983	-5.4709	20.2	2.21	-1.4	-0.15	28.5	3.11	6.9	0.77	55.9	6.06	34.3	3.79
Cryostat	-322.69	-5.5280	-5.5199	-5.4959	21.9		0.1	0.01	30.0		8.2		54.0		34.3	
Cryostat	-327.17	-5.5679	-5.5594	-5.5349	21.8		0	0	30.3		8.5		55.8		32.2	

* Thermocouple output was corrected to the indicated bath temperature.

Table IV
Test Results - Aerojet Multipoint Calibration Data Reduced per NBS Boulder/Washington and Aerojet Copper vs Constantan Thermocouple Table
Sheet 1 of 2

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TEST SETUP	BATH TEMP. (°F)	Output for Test Items			*TEMPERATURE AND/OR OUTPUT DEVIATION (THERMOCOUPLE-STANDARD)											
					Test Item O/C-35, Spool 75-PV875A1 (SN 3)				Test Item O/C-36, Spool 75-1V875A3 (SN 3)				Test Item O/C-37, Spool 80V880A1 (SN 2)			
		O/C-35	O/C-36	O/C-37	Reduced per NBS Table		Reduced per Aerojet Table		Reduced per NBS Table		Reduced per Aerojet Table		Reduced per NBS Table		Reduced per Aerojet Table	
		mV	mV	mV	uV	°F	uV	°F	uV	°F	uV	°F	uV	°F	uV	°F
Cryostat	-332.66	-5.6171	-5.6071	-5.5831	20.3		-1.4	-0.16	30.3		8.6		54.3		33.0	
	-338.49	-5.6589	-5.6534	-5.6304	23.7		2.1	0.25	33.2		11.6		56.2		32.6	
	-347.92	-5.7402	-5.7287	-5.7047	22.8		0.1	0.02	35.2		12.6		58.3		35.6	
	-351.71	-5.7677	-5.7558	-5.7311	25.0		1.1	0.15	36.9		13.0		61.6		37.7	
	-358.10	-5.8159	-5.8029	-5.7789	25.0		-0.6	-0.08	38.0		12.4		62.0		36.4	
	-364.14	-5.8574	-5.8436	-5.8196	27.2		1.6	0.22	41.0		15.4		65.0		39.4	
	-368.62	-5.8919	-5.8748	-5.8527	25.3		-0.5	-0.08	42.4		16.6		64.5		36.7	
	-376.26	-5.9379	-5.9206	-5.8983	28.6		0.5	0.08	45.9		17.8		68.2		40.1	
	-390.82	-6.0174	-5.9979	-5.9689	36.2		1.6	0.31	55.7		21.1		84.5		50.1	
	-394.46	-6.0378	-6.0151	-5.9881	35.5		0.3	0.06	58.2		23.0		65.2		50.0	
	-399.82	-6.0648	-6.0383	-6.0136	35.9		0.1	0.02	62.4		26.6		87.1		51.3	
	-403.64	-6.0871	-6.0561	-6.0336	31.9		-5.0	-1.07	62.9		26.0		85.4		58.5	
	-406.17	-6.0908	-6.0622	-6.0361	39.8		2.0	0.47	68.4		30.6		94.5		56.7	
Cryostat LHe BATH	-410.77	-6.1098	-6.0789	-6.0504	40.8		0.9	0.25	71.7		31.8		100.2		60.3	
	-410.92	-6.1081	-6.0761	-6.0590	43.2	9.58	3.2	0.85	75.2	15.92	35.2	8.64	92.3	16.11	52.3	18.32
Cryostat	-413.06	-6.1170	-6.0840	-6.0583	43.0		2.0	0.56	76.0		5.0		101.7		60.7	
	-416.70	-6.1299	-6.0945	-6.0679	44.2		1.4	0.42	79.6		36.8		106.2		63.4	
	-419.72	-6.1426	-6.1034	-6.0790	42.3		-1.9	-0.62	81.5		37.3		105.9		61.7	
	-423.98	-6.1525	-6.1100	-6.0858	46.7		0.5	0.17	89.2		43.0		113.4		67.2	
Cryostat LHe BATH	-426.90	-6.1591	-6.1148	-6.0906	47.9	13.67	0.5	0.19	92.2	23.74	44.8	14.61	116.4	28.67	69.0	20.85
	-452.1	-6.1965	-6.1317	-6.1166	59.3	29.0	0.3	0.55	124.1	45.7	65.1	35.3	139.2	49.0	80.2	39.7

* Thermocouple output was corrected to the indicated bath temperature.

Table IV
Test Results - Aerojet Multipoint Calibration Data Reduced per NBS
Boulder/Washington and Aerojet Copper vs Constantan Thermocouple Table
Sheet 2 of 2

Degrees Fahrenheit — Reference Junction 32 °F

Temp °F	0	1	2	3	4	5	6	7	8	9
	EMF ~ MILLIVOLTS									
-450	-6.1956	-6.1962	-6.1967	-6.1972	-6.1975	-6.1978	-6.1980	-6.1982	-6.1983	-6.1984
-440	-6.1861	-6.1874	-6.1887	-6.1895	-6.1905	-6.1917	-6.1927	-6.1936	-6.1943	-6.1949
-430	-6.1679	-6.1701	-6.1722	-6.1742	-6.1761	-6.1780	-6.1798	-6.1815	-6.1831	-6.1846
-420	-6.1416	-6.1446	-6.1475	-6.1503	-6.1530	-6.1557	-6.1583	-6.1608	-6.1633	-6.1656
-410	-6.1078	-6.1116	-6.1152	-6.1188	-6.1223	-6.1257	-6.1290	-6.1322	-6.1354	-6.1386
-400	-6.0656	-6.0702	-6.0748	-6.0793	-6.0836	-6.0879	-6.0920	-6.0961	-6.1001	-6.1040
-390	-6.0147	-6.0200	-6.0252	-6.0305	-6.0357	-6.0409	-6.0460	-6.0511	-6.0560	-6.0610
-380	-5.9601	-5.9657	-5.9713	-5.9768	-5.9823	-5.9878	-5.9932	-5.9986	-6.0040	-6.0093
-370	-5.8992	-5.9057	-5.9121	-5.9185	-5.9247	-5.9308	-5.9368	-5.9427	-5.9486	-5.9544
-360	-5.8291	-5.8364	-5.8436	-5.8508	-5.8580	-5.8650	-5.8721	-5.8790	-5.8858	-5.8925
-350	-5.7561	-5.7635	-5.7709	-5.7782	-5.7855	-5.7928	-5.8000	-5.8073	-5.8146	-5.8218
-340	-5.6775	-5.6856	-5.6937	-5.7018	-5.7097	-5.7176	-5.7255	-5.7332	-5.7410	-5.7485
-330	-5.5927	-5.6014	-5.6100	-5.6186	-5.6272	-5.6357	-5.6442	-5.6526	-5.6609	-5.6692
-320	-5.5040	-5.5130	-5.5219	-5.5309	-5.5398	-5.5487	-5.5576	-5.5664	-5.5752	-5.5840
-310	-5.4125	-5.4218	-5.4310	-5.4402	-5.4494	-5.4586	-5.4677	-5.4768	-5.4859	-5.4949
-300	-5.3174	-5.3272	-5.3368	-5.3465	-5.3560	-5.3655	-5.3750	-5.3844	-5.3938	-5.4032
-290	-5.2167	-5.2271	-5.2374	-5.2476	-5.2578	-5.2679	-5.2779	-5.2879	-5.2978	-5.3077
-280	-5.1095	-5.1205	-5.1314	-5.1423	-5.1531	-5.1639	-5.1746	-5.1852	-5.1958	-5.2063
-270	-4.9971	-5.0085	-5.0198	-5.0312	-5.0425	-5.0540	-5.0652	-5.0764	-5.0875	-5.0985
-260	-4.8823	-4.8938	-4.9054	-4.9169	-4.9284	-4.9399	-4.9514	-4.9628	-4.9743	-4.9857
-250	-4.7651	-4.7770	-4.7888	-4.8006	-4.8123	-4.8241	-4.8358	-4.8474	-4.8591	-4.8707
-240	-4.6446	-4.6568	-4.6690	-4.6811	-4.6932	-4.7053	-4.7173	-4.7293	-4.7413	-4.7532
-230	-4.5203	-4.5329	-4.5455	-4.5580	-4.5705	-4.5829	-4.5953	-4.6077	-4.6200	-4.6323
-220	-4.3927	-4.4056	-4.4185	-4.4313	-4.4441	-4.4569	-4.4697	-4.4824	-4.4950	-4.5077
-210	-4.2618	-4.2750	-4.2883	-4.3014	-4.3146	-4.3277	-4.3408	-4.3538	-4.3668	-4.3798
-200	-4.1269	-4.1408	-4.1546	-4.1673	-4.1810	-4.1946	-4.2082	-4.2216	-4.2351	-4.2484
-190	-3.9841	-3.9984	-4.0127	-4.0271	-4.0414	-4.0557	-4.0700	-4.0843	-4.0986	-4.1129
-180	-3.8398	-3.8543	-3.8688	-3.8832	-3.8977	-3.9121	-3.9265	-3.9410	-3.9553	-3.9697
-170	-3.6935	-3.7083	-3.7230	-3.7377	-3.7523	-3.7670	-3.7816	-3.7962	-3.8107	-3.8253
-160	-3.5445	-3.5596	-3.5746	-3.5895	-3.6045	-3.6194	-3.6343	-3.6491	-3.6640	-3.6788
-150	-3.3922	-3.4076	-3.4230	-3.4383	-3.4536	-3.4688	-3.4840	-3.4992	-3.5143	-3.5294
-140	-3.2362	-3.2520	-3.2677	-3.2834	-3.2991	-3.3147	-3.3303	-3.3458	-3.3613	-3.3768
-130	-3.0762	-3.0924	-3.1085	-3.1246	-3.1407	-3.1567	-3.1727	-3.1886	-3.2045	-3.2204
-120	-2.9120	-2.9286	-2.9452	-2.9617	-2.9782	-2.9946	-3.0110	-3.0274	-3.0437	-3.0600
-110	-2.7438	-2.7608	-2.7778	-2.7947	-2.8116	-2.8284	-2.8452	-2.8620	-2.8787	-2.8954

Table V
Aerojet Copper vs Constantan Thermocouple Table
Sheet 1 of 4

Temp °F	0	1	2	3	4	5	6	7	8	9
	EMF ~ MILLIVOLTS									
-100	-2.5716	-2.5890	-2.6063	-2.6237	-2.6409	-2.6582	-2.6754	-2.6925	-2.7097	-2.7268
-90	-2.3956	-2.4134	-2.4311	-2.4489	-2.4664	-2.4841	-2.5016	-2.5192	-2.5367	-2.5542
-80	-2.2163	-2.2343	-2.2524	-2.2704	-2.2884	-2.3064	-2.3243	-2.3422	-2.3600	-2.3778
-70	-2.0337	-2.0521	-2.0705	-2.0888	-2.1071	-2.1254	-2.1436	-2.1618	-2.1800	-2.1981
-60	-1.8483	-1.8670	-1.8856	-1.9042	-1.9228	-1.9414	-1.9599	-1.9784	-1.9969	-2.0153
-50	-1.6601	-1.6790	-1.6979	-1.7168	-1.7357	-1.7545	-1.7733	-1.7921	-1.8109	-1.8296
-40	-1.4691	-1.4883	-1.5075	-1.5267	-1.5458	-1.5649	-1.5840	-1.6031	-1.6221	-1.6411
-30	-1.2751	-1.2946	-1.3141	-1.3336	-1.3531	-1.3725	-1.3918	-1.4112	-1.4305	-1.4498
-20	-1.0779	-1.0978	-1.1176	-1.1374	-1.1572	-1.1769	-1.1966	-1.2163	-1.2359	-1.2555
-10	-0.8772	-0.8974	-0.9176	-0.9378	-0.9579	-0.9780	-0.9980	-1.0181	-1.0380	-1.0580
-0	-0.6729	-0.6934	-0.7140	-0.7345	-0.7550	-0.7755	-0.7959	-0.8163	-0.8366	-0.8569
0	-0.6729	-0.6523	-0.6316	-0.6109	-0.5902	-0.5694	-0.5486	-0.5277	-0.5069	-0.4860
10	-0.4651	-0.4441	-0.4231	-0.4022	-0.3811	-0.3601	-0.3391	-0.3180	-0.2969	-0.2758
20	-0.2547	-0.2336	-0.2125	-0.1914	-0.1703	-0.1493	-0.1282	-0.1071	-0.0861	-0.0651
30	-0.0441	-0.0231	0.0000	0.0213	0.0427	0.0642	0.0856	0.1071	0.1286	0.1502
40	0.1717	0.1933	0.2150	0.2366	0.2583	0.2800	0.3018	0.3235	0.3453	0.3671
50	0.3890	0.4109	0.4328	0.4547	0.4767	0.4987	0.5207	0.5427	0.5648	0.5869
60	0.6090	0.6312	0.6534	0.6756	0.6978	0.7201	0.7424	0.7647	0.7871	0.8095
70	0.8319	0.8543	0.8768	0.8992	0.9218	0.9447	0.9673	0.9899	1.0125	1.0352
80	1.0578	1.0805	1.1033	1.1260	1.1488	1.1716	1.1945	1.2173	1.2402	1.2631
90	1.2861	1.3091	1.3321	1.3551	1.3781	1.4012	1.4243	1.4474	1.4706	1.4938
100	1.5170	1.5402	1.5635	1.5868	1.6101	1.6335	1.6568	1.6802	1.7036	1.7271
110	1.7506	1.7741	1.7976	1.8212	1.8447	1.8683	1.8920	1.9156	1.9393	1.9631
120	1.9868	2.0106	2.0344	2.0582	2.0820	2.1065	2.1304	2.1543	2.1783	2.2023
130	2.2263	2.2503	2.2743	2.2984	2.3225	2.3466	2.3708	2.3949	2.4191	2.4434
140	2.4676	2.4919	2.5162	2.5405	2.5648	2.5892	2.6136	2.6380	2.6624	2.6869
150	2.7114	2.7359	2.7605	2.7850	2.8096	2.8342	2.8589	2.8835	2.9082	2.9329
160	2.9577	2.9824	3.0072	3.0320	3.0569	3.0817	3.1066	3.1315	3.1564	3.1814
170	3.2064	3.2314	3.2564	3.2815	3.3066	3.3322	3.3573	3.3825	3.4077	3.4329
180	3.4581	3.4833	3.5086	3.5339	3.5592	3.5845	3.6099	3.6353	3.6607	3.6861
190	3.7115	3.7370	3.7625	3.7880	3.8136	3.8391	3.8647	3.8903	3.9160	3.9416
200	3.9673	3.9930	4.0187	4.0445	4.0702	4.0960	4.1219	4.1477	4.1736	4.1994
210	4.2253	4.2513	4.2772	4.3032	4.3292	4.3552	4.3813	4.4073	4.4334	4.4595
220	4.4857	4.5118	4.5380	4.5642	4.5904	4.6172	4.6435	4.6698	4.6961	4.7224
230	4.7488	4.7751	4.8015	4.8280	4.8544	4.8809	4.9074	4.9339	4.9604	4.9869
240	5.0135	5.0401	5.0667	5.0934	5.1200	5.1467	5.1734	5.2001	5.2269	5.2536

Table V
Aerojet Copper vs Constantan Thermocouple Table
Sheet 2 of 4

Temp °F	0	1	2	3	4	5	6	7	8	9
	EMF ~ MILLIVOLTS									
250	5.2804	5.3072	5.3340	5.3609	5.3878	5.4146	5.4416	5.4685	5.4954	5.5224
260	5.5494	5.5764	5.6035	5.6305	5.6576	5.6847	5.7118	5.7390	5.7662	5.7934
270	5.8206	5.8478	5.8750	5.9023	5.9296	5.9573	5.9847	6.0120	6.0394	6.0668
280	6.0942	6.1216	6.1491	6.1766	6.2041	6.2316	6.2591	6.2867	6.3143	6.3419
290	6.3695	6.3971	6.4248	6.4525	6.4802	6.5079	6.5356	6.5634	6.5912	6.6190
300	6.6468	6.6746	6.7025	6.7304	6.7583	6.7862	6.8141	6.8421	6.8701	6.8981
310	6.9261	6.9542	6.9822	7.0103	7.0384	7.0665	7.0947	7.1228	7.1510	7.1792
320	7.2074	7.2357	7.2640	7.2922	7.3205	7.3495	7.3779	7.4062	7.4346	7.4630
330	7.4914	7.5199	7.5483	7.5768	7.6053	7.6338	7.6623	7.6908	7.7194	7.7480
340	7.7766	7.8052	7.8338	7.8625	7.8911	7.9198	7.9485	7.9772	8.0060	8.0347
350	8.0635	8.0923	8.1211	8.1499	8.1788	8.2076	8.2365	8.2654	8.2943	8.3233
360	8.3522	8.3812	8.4102	8.4392	8.4682	8.4973	8.5263	8.5554	8.5845	8.6136
370	8.6428	8.6719	8.7011	8.7303	8.7595	8.7889	8.8182	8.8474	8.8767	8.9060
380	8.9353	8.9646	8.9940	9.0234	9.0527	9.0821	9.1115	9.1410	9.1704	9.1999
390	9.2294	9.2589	9.2884	9.3179	9.3475	9.3771	9.4067	9.4363	9.4659	9.4955
400	9.5252	9.5549	9.5846	9.6143	9.6440	9.6738	9.7035	9.7333	9.7631	9.7929
410	9.8227	9.8526	9.8825	9.9124	9.9423	9.9722	10.0021	10.0321	10.0620	10.0920
420	10.1220	10.1521	10.1821	10.2122	10.2422	10.2728	10.3029	10.3330	10.3632	10.3933
430	10.4235	10.4537	10.4839	10.5141	10.5444	10.5746	10.6049	10.6352	10.6655	10.6958
440	10.7261	10.7565	10.7868	10.8172	10.8476	10.8780	10.9084	10.9389	10.9693	10.9998
450	11.0303	11.0608	11.0913	11.1219	11.1524	11.1830	11.2136	11.2442	11.2748	11.3054
460	11.3361	11.3667	11.3974	11.4281	11.4588	11.4896	11.5203	11.5511	11.5818	11.6126
470	11.6434	11.6743	11.7051	11.7359	11.7668	11.7980	11.8289	11.8598	11.8907	11.9217
480	11.9527	11.9836	12.0146	12.0456	12.0766	12.1077	12.1387	12.1698	12.2009	12.2320
490	12.2631	12.2942	12.3253	12.3565	12.3877	12.4189	12.4501	12.4813	12.5125	12.5437
500	12.5750	12.6063	12.6376	12.6689	12.7002	12.7315	12.7629	12.7942	12.8256	12.8570
510	12.8884	12.9198	12.9513	12.9827	13.0142	13.0457	13.0772	13.1087	13.1402	13.1717
520	13.2033	13.2349	13.2665	13.2981	13.3297	13.3617	13.3933	13.4250	13.4567	13.4883
530	13.5200	13.5518	13.5835	13.6152	13.6470	13.6787	13.7105	13.7423	13.7741	13.8060
540	13.8378	13.8696	13.9015	13.9334	13.9653	13.9972	14.0291	14.0610	14.0930	14.1249
550	14.1569	14.1889	14.2209	14.2529	14.2849	14.3170	14.3490	14.3811	14.4132	14.4453
560	14.4774	14.5095	14.5416	14.5738	14.6059	14.6381	14.6703	14.7025	14.7347	14.7670
570	14.7992	14.8315	14.8637	14.8960	14.9283	14.9609	14.9932	15.0256	15.0579	15.0903
580	15.1226	15.1550	15.1874	15.2199	15.2523	15.2847	15.3172	15.3497	15.3821	15.4146
590	15.4471	15.4797	15.5122	15.5447	15.5773	15.6099	15.6424	15.6750	15.7076	15.7403
600	15.7729	15.8055	15.8382	15.8709	15.9036	15.9363	15.9690	16.0017	16.0344	16.0672
610	16.1000	16.1327	16.1655	16.1983	16.2311	16.2640	16.2968	16.3297	16.3625	16.3954
620	16.4283	16.4612	16.4941	16.5270	16.5600	16.5931	16.6261	16.6591	16.6921	16.7251
630	16.7581	16.7911	16.8242	16.8572	16.8903	16.9234	16.9564	16.9895	17.0227	17.0558
640	17.0889	17.1221	17.1552	17.1884	17.2216	17.2548	17.2880	17.3212	17.3545	17.3877

Table V
Aerojet Copper vs Constantan Thermocouple Table
Sheet 3 of 4

Eff. 15 Sept 1964

Temp °F	0	1	2	3	4	5	6	7	8	9
	EMF ~ MILLIVOLTS									
650	17.4210	17.4543	17.4876	17.5209	17.5542	17.5875	17.6208	17.6542	17.6875	17.7209
660	17.7543	17.7877	17.8211	17.8545	17.8880	17.9214	17.9549	17.9883	18.0218	18.0553
670	18.0888	18.1223	18.1559	18.1894	18.2230	18.2570	18.2906	18.3242	18.3578	18.3914
680	18.4250	18.4586	18.4923	18.5259	18.5596	18.5933	18.6270	18.6606	18.6944	18.7281
690	18.7618	18.7955	18.8293	18.8631	18.8968	18.9306	18.9644	18.9982	19.0320	19.0659
700	19.0997	19.1335	19.1674	19.2013	19.2352	19.2690	19.3030	19.3369	19.3708	19.4047
710	19.4387	19.4726	19.5066	19.5406	19.5746	19.6086	19.6426	19.6766	19.7106	19.7447
720	19.7787	19.8128	19.8468	19.8809	19.9150	19.9491	19.9833	20.0174	20.0515	20.0857
730	20.1198	20.1540	20.1882	20.2224	20.2566	20.2908	20.3250	20.3593	20.3935	20.4278
740	20.4620	20.4963	20.5306	20.5649	20.5992	20.6335	20.6679	20.7022	20.7366	20.7709

Table V
Aerojet Copper vs Constantan Thermocouple Table
Sheet 4 of 4

TEST ITEM	MANUFACTURER	DESCRIPTION	S/N	PURPOSE OF TEST	LIMITS	LHe BATH (-452°F) uv	LHe BATH (-452°F) °F	LNe BATH (-411 °F) uv	LNe BATH (-411 °F) °F	LN_2 BATH (-320°F) uv	LN_2 BATH (-320°F) °F	CO_2 BATH (-110.5 °F) uv	CO_2 BATH (-110.5 °F) °F	ICE BATH (32°F) uv	ICE BATH (32°F) °F	OIL BATH (+200°F) uv	OIL BATH (+200°F) °F	SALT BATH (+400°F) uv	SALT BATH (+400°F) °F
					DEVELOPMENTAL	±70	NONE	±31.2	±4.1	±57.0	±6.4	±18.7	±1.1	±23.1	±1.0	±25.9	±1.0	±60.6	±2.0
C/C-26	Temptron Inc.	Annealed 22 AWG Bare Wire 75-2VR75A1	1	Cryogenic Calibration		-6.9*		-5.9	-1.56	-4.7	-0.53	--	--	0	0	--	--	--	--
C/C-26			1	1st LHe Data Cycle		-7.3		--	--	--	--	--	--	--	--	--	--	--	--
C/C-26			1	2nd LHe Data Cycle		-7.3		--	--	--	--	--	--	--	--	--	--	--	--
C/C-26			1	3rd LHe Data Cycle		-6.3		--	--	--	--	--	--	--	--	--	--	--	--
C/C-26			1	4th LHe Data Cycle		-6.8		--	--	--	--	--	--	--	--	--	--	--	--
C/C-27			2	Cryogenic Calibration		-2.9*		-1.8	-0.47	-4.2	-0.47	--	--	0	0	--	--	--	--
C/C-27			2	1st LHe Data Cycle		-2.8		--	--	--	--	--	--	--	--	--	--	--	--
C/C-27			2	2nd LHe Data Cycle		-3.3		--	--	--	--	--	--	--	--	--	--	--	--
C/C-27			2	3rd LHe Data Cycle		-3.3		--	--	--	--	--	--	--	--	--	--	--	--
C/C-27			2	4th LHe Data Cycle		-2.3		--	--	--	--	--	--	--	--	--	--	--	--
C/C-35			3	Cryogenic Calibration		0.2	0.5	2.8	0.74	-1.2	-0.13	2.4	0.15	0	0	--	--	--	--
C/C-35			3	1st Repeatability Cycle		2.2		--	--	-1.4	-0.15	2.4	0.15	-0.5	-0.02	--	--	--	--
C/C-35			3	2nd Repeatability Cycle		4.9		--	--	0.5	0.06	INVALID DATA		0	0	--	--	--	--
C/C-35			3	3rd Repeatability Cycle		4.1		--	--	0.8	0.09	2.5	0.15	0	0	--	--	--	--
C/C-17		Unannealed 22 AWG Bare Wire 75-2VR 75A1.	1	Cryogenic Calibration		64.8*	35.1*	45.2	11.90	31.5	3.54	17.5	1.03	0	0	-6.0	-0.23	-70.2	-2.32
C/C-17			1	1st LHe Data Cycle		64.7		--	--	--	--	--	--	--	--	--	--	--	--
C/C-17			1	2nd LHe Data Cycle		64.7		--	--	--	--	--	--	--	--	--	--	--	--
C/C-17			1	3rd LHe Data Cycle		65.2		--	--	--	--	--	--	--	--	--	--	--	--
C/C-17			1	4th LHe Data Cycle		64.7		--	--	--	--	--	--	--	--	--	--	--	--
C/C-18			2	Cryogenic Calibration		61.9*	34.2*	46.4	12.21	31.5	3.54	21.1	1.24	0	0	-6.5	-0.25	-33.0	-1.09
C/C-18			2	1st LHe Data Cycle		62.2		--	--	--	--	--	--	--	--	--	--	--	--
C/C-18			2	2nd LHe Data Cycle		61.7		--	--	--	--	--	--	--	--	--	--	--	--
C/C-18			2	3rd LHe Data Cycle		62.0		--	--	--	--	--	--	--	--	--	--	--	--
C/C-18			2	4th LHe Data Cycle		61.7		--	--	--	--	--	--	--	--	--	--	--	--
C/C-36		Annealed 22 AWG Bare Wire 75-1VR 75A3	3	Cryogenic Calibration		65.1	35.3	35.2	8.64	6.9	0.77	6.5	0.39	0	0	--	--	--	--
C/C-36			3	1st Repeatability Cycle		65.4	35.4	--	--	9.3	1.03	6.5	0.39	-0.5	-0.02	--	--	--	--
C/C-36			3	2nd Repeatability Cycle		65.4	35.4	--	--	9.6	1.17	INVALID DATA		0	0	--	--	--	--
C/C-36			3	3rd Repeatability Cycle		66.3	35.7	--	--	9.3	1.03	2.0	0.12	0	0	--	--	--	--
C/C-37		Annealed 30 AWG Bare Wire 80 vs 80A1	2	Cryogenic Calibration		60.2	39.7	52.3	12.32	34.3	3.79	13.0	0.79	0	0	--	--	--	--
C/C-37			2	1st Repeatability Cycle		71.7	37.3	--	--	34.7	3.83	13.0	0.79	0.7	0.03	--	--	--	--
C/C-37			2	2nd Repeatability Cycle		73.5	38.8	--	--	32.9	3.53	INVALID DATA		0	0	--	--	--	--
C/C-37			2	3rd Repeatability Cycle		76.0	36.5	--	--	33.2	3.66	10.7	0.65	0	0	--	--	--	--
C/C-38		Stem Assemblies fabricated with spool 75-2VR 75A1 Wire.	1	Initial Calibration		-5.4		-1.2	-0.31	2.1	0.24	--	--	0	0	--	--	2.6	0.08
C/C-39			2			-7.4		-1.9	-0.51	-1.1	-0.12	--	--	0	0	--	--	7.9	0.26
C/C-40			3			-6.7		0.9	0.24	1.2	0.12	--	--	0	0	--	--	1.3	0.04
C/C-41			4			-5.3		1.9	0.51	2.9	0.33	--	--	0	0	--	--	-0.3	-0.01
C/C-42			5			-3.0		-0.9	-0.23	1.6	0.18	--	--	0	0	--	--	4.3	0.14
C/C-43			6			-11.9		0.7	0.19	-2.0	-0.23	--	--	0	0	--	--	-1.3	-0.04
C/C-44			7			-6.7		-3.8	-1.01	[illegible]	-0.04	3.7	0.22	0	0	5.7	0.22	-7.0	-0.23
C/C-45			8			-12.6		[illegible]	-1.76	-4.1	-0.46	0.2	0.01	0	0	6.2	0.24	-1.8	-0.06
C/C-46	Physical Sciences Corp.	Barwck Coated Wire	1	Initial Calibration		--		--	--	-6.2	-0.69	--	--	0.4	0.02	--	--	--	--
C/C-47		Burock Coated Wire	2			0.9	--	[illegible]	-0.52	2.8	0.31	6.0	0.35	0	0	16.6	0.64	26.4	0.87
C/C-48		Cable Assembly	1					-11.0	-2.89	-10.7	-1.20	1.7	0.06	0	0	14.8	0.57	19.1	0.63

*AVERAGE OF 4 CYCLES
- -NO MEASUREMENT TAKEN

Table VI
Test Results - Aerojet Calibration Data Reduced per Aerojet
Copper vs Constantan Thermocouple Table
Sheet 1 of 3

TEST ITEM	MANUFACTURER	DESCRIPTION	S/N	PURPOSE OF TEST	LIMITS	LHe BATH (-452°F) mV	LHe BATH (-452°F) °F	LHe BATH (-411°F) mV	LHe BATH (-411°F) °F	LN_2 BATH (-320°F) mV	LN_2 BATH (-320°F) °F	CO_2 BATH (-110.5°F) mV	CO_2 BATH (-110.5°F) °F	ICE BATH (32°F) mV	ICE BATH (32°F) °F	OIL BATH (300°F) mV	OIL BATH (300°F) °F	SALT BATH (400°F) mV	SALT BATH (400°F) °F
					SPECIFICATION	NONE	NONE	±31.2	±8.2	±57.0	±6.4	±18.7	±1.1	±23.1	±1.0	±25.9	±1.0	±60.6	±2.0
C/C-49	Temptron Inc.	MKI-A2 Kit Immersion Thermocouples Model 2925 per AOC-SCD 701530-701554 (PO 332599)	5221	Receiving Calibration		- -	- -		1.19		-0.66	13.3	0.78		0.05		0.78		-0.88
C/C-50			5222			- -	- -		-2.59		-1.42		0.09	0	0		0.85		-1.11
C/C-51			5223			- -	- -		-3.34		-1.56		0.36		0.09		0.79		-0.48
C/C-52			5224			- -	- -	8.9	7.33	4.3	0.48		0.41		0.09		0.53		-1.11
C/C-53			5225			- -	- -		-1.50		-1.08		-0.09		0.05	26.2	1.01	-33.6	-0.69
C/C-54			5226			- -	- -		-3.29		-1.66		0.19		0		0.88		-0.16
C/C-55			5227			- -	- -		-1.47		-1.00		0.54		0.09		0.86		-0.60
C/C-56			5228			- -	- -		-2.32		-1.48		0.22		0.05		0.97		-0.04
C/C-57			5229			- -	- -		-2.04		-1.59		0.69	5.0	0.24	9.8	0.38		-1.10
C/C-58			52210			- -	- -		-1.62		-1.43		-0.11		0.24		0.67	1.8	0.04
C/C-59			52211			- -	- -		-2.35		-1.50		-0.04		0.09		0.80		-0.57
C/C-60			52212			- -	- -	-12.5	-3.28		-1.70	-0.7	0.54		0		0.82		-0.42
C/C-61			52213			- -	- -		-1.70	-16.8	-1.89		0.36		0		0.98		-0.61
C/C-49 thru C/C-61				Average		- -	- -	-6.43	-1.69	-11.3	-1.27	5.1	0.30	2.0	0.08	20.5	0.79	-24.6	-0.82
C/C-62		MKI-A2 Kit Immersion Thermocouples Model 2925 per AOC-SCD 701530-701554 (PO 332599)	5611	Receiving Calibration		- -	- -	10.6	2.8	-7.1	-0.8	- -	- -	- -	- -	25.9	1.0	18.2	0.6
C/C-63			5612			- -	- -	15.2	4.0	-8.9	-1.0	- -	- -	- -	- -	20.7	0.8	12.1	0.4
C/C-64			5613			- -	- -	-9.7	-2.54	-5.5	-0.62	-6.3	-0.37	0	0	16.3	0.63	1.8	0.06
C/C-65			5614			- -	- -	-12.8	-3.37	-12.0	-1.35	-3.1	-0.18	1.2	0.05	20.0	0.77	1.8	0.06
C/C-66			5615			- -	- -	18.6	4.9	-10.7	-1.2	- -	- -	- -	- -	15.6	0.6	15.2	0.5
C/C-67			5616			- -	- -	15.2	4.0	-8.9	-1.0	- -	- -	- -	- -	20.0	0.8	18.2	0.6
C/C-62 thru C/C-67				Average		- -	- -	6.2	1.63	-8.8	-0.99	-4.7	-0.28	0.6	0.02	19.9	0.77	11.2	0.37
C/C-68		MKI-A2 Evaluation Immersion Thermocouples Model 2925 per AOC-SCD 701530-701554 (PO 333980)	6121	Receiving Calibration		- -	- -		-0.46		-1.56		-0.39	2.2	0.09		0.62		-0.34
C/C-69			6122			- -	- -		-3.04		-1.83	-7.6	-0.45	0	0		0.64		0.02
C/C-70			6123			- -	- -		-0.84		-0.43		0.11		0	12.7	0.48	6.4	0.21
C/C-71			6124			- -	- -		-0.72		-1.54		-0.37		0		0.65		-0.27
C/C-72			6125			- -	- -		-1.39		-1.41		0.33		0.05		0.67		0.11
C/C-73			6127			- -	- -		-0.86		-0.52		-0.22		0.09		0.76		-0.31
C/C-74			6128			- -	- -		-0.70		-1.16		-0.13		0		0.61		0.04
C/C-75			61210			- -	- -	5.8	1.54	-3.4	-0.38	6.8	0.40		0.05		0.56		0.07
C/C-76			61211			- -	- -		-1.45		-1.40		-0.23		0.05	20.5	0.79		-0.31
C/C-77			61212			- -	- -		-2.11	-21.3	-2.39		-0.09		0		0.75		-0.21
C/C-78			61216			- -	- -	-18.0	-4.75		-1.09		0.02		0.09		0.71	-28.2	-0.93
C/C-79			61217			- -	- -		-0.82		-3.27		0.05		0		0.56		-0.26
C/C-68 thru C/C-79				Average		- -	- -	-4.9	-1.30	-12.2	-1.37	-1.4	-0.08	0.9	0.04	16.8	0.65	-5.8	-0.19

*Average of 4 Cycles
--No Measurement Taken

Table VI
Test Results - Aerojet Calibration Data Reduced per Aerojet
Copper vs Constantan Thermocouple Table
Sheet 2 of 3

TEST ITEM	MANUFACTURER	DESCRIPTION	S/N	PURPOSE OF TEST	LIMITS	LHe BATH (-452°F) mV	LHe BATH (-452°F) °F	LHe BATH (-411°F) mV	LHe BATH (-411°F) °F	LN_2 BATH (-320°F) mV	LN_2 BATH (-320°F) °F	CO_2 BATH (-110°F) mV	CO_2 BATH (-110°F) °F	ICE BATH (32°F) mV	ICE BATH (32°F) °F	OIL BATH (-200°F) mV	OIL BATH (-200°F) °F	SALT BATH (-400°F) mV	SALT BATH (-400°F) °F
					CONT.	±4	[illegible]		±4.2		±6.8		±1.1		±1.0		±1.0		±2.0
C/C-70	Temptron Inc.	MKI-A2 Evaluation Immersion Thermocouples Model 2925 per AOC-SCD 701530-701554 (PO 333980) Continued	6123	Tip Immersed to mounting nut only.	SPECIFICATION	- -	- -		2.88		0.82	- -	- -		0	- -	- -	- -	- -
C/C-74			6126			- -	- -		0.60		0.18	- -	- -		0	- -	- -	- -	- -
C/C-76			61211			- -	- -		0.20		0.28	- -	- -		0	- -	- -	- -	- -
C/C-77			61212			- -	- -		-1.53		0.14	- -	- -		0	- -	- -	- -	- -
C/C-79			61217			- -	- -		1.40		-0.25	- -	- -		0	- -	- -	- -	- -
C/C-69			6122	Post Calibration data-environmental qualification tests.		- -	- -		-3.00		-1.52	- -	- -		0	- -	- -	11.9	0.46
C/C-73			6127			- -	- -		-1.03		-1.14	- -	- -		0.05	- -	- -	10.6	0.35
C/C-78			61216			- -	- -		-4.79		-1.18	- -	- -		0.09	- -	- -	5.2	0.17
					ACCEPTANCE	±20		±15.6	±4.1	±28.5	±3.2	±18.7	±1.1	±23.1	±1.0	±25.9	±1.0	±60.6	±2.0
C/C-80		Annealed spool samples of 22 AWG wire from copper 75-2 and constantan as noted under SN column.	75A2	Spool Calibration		-6.7		-5.9	-1.56	-10.7	-1.20		0	0	0	2.1	0.08	-1.5	-0.05
C/C-81			75A3			-5.3		-5.9	-1.56	-10.7	-1.20		3.53	0	0	-7.8	-0.30	-18.8	-0.62
C/C-82			75A4			-5.6		-1.8	-0.46	-1.8	-0.20		1.46	0	0	-34.7	-1.34	-30.5	-1.04
C/C-83			75A6			-1.3		3.3	0.86	0.7	0.08		0.98	0	0	*76.1	-2.94	-116.0	-3.69
C/C-84			75A7			-7.3		-1.2	-0.32	-5.7	-0.64		0.43	0	0	*3.9	-0.15	-19.7	-0.65
C/C-85			75A8			-5.4		-7.4	-0.62	-3.[illegible]	-0.36		0.55	0	0	0	0	*15.1	-0.50
C/C-86		Annealed 26 AWG wire, copper 77-1 vs constantan wire as noted.	77A1	Spool Calibration		-16.3		+14.3	3.76	9.7	1.09	- -	- -	0	0	1.4	0.05	17.1	*0.56
C/C-87			77A2			15.4		6.1	5.61	14.9	1.66	- -	- -	0	0	10.4	0.40	-23.9	*0.78
C/C-88			77A3			16.9		15.3	4.03	4.6	0.97	- -	- -	0	0	-1.1	-0.04	5.4	0.18
C/C-89		Annealed 26 AWG wire, copper 77-2 vs constantan wire as noted.	77A2	Spool Calibration		14.9		9.3	2.45	3.1	0.35	- -	- -	0	0	6.9	0.27	-27.6	-0.91
C/C-90			77A8			16.6		9.1	2.40	10.6	1.19	- -	- -	0	0	10.5	0.41	16.4	0.54
C/C-91			77A3			13.5		12.8	3.77	10.7	1.20	- -	- -	0	0	-0.6	-0.02	14.2	0.47
					ENVIRONMENTAL	NONE	NONE		±8.2		±6.2		±1.1		±1.0		±1.0		±2.0
C/C-92	Nugget Manufacturing Inc.	MKI-A1 Kit Immersion Thermocouples Model [illegible] per AOC-SCD 267010	2N1727	Post Calibration (Stem Immersed)		- -	- -	8.0	2.09	3.2	0.34	19.4	1.14	0	0	-2.3	-0.09	- -	- -
C/C-93			2N1729			- -	- -	9.7	2.55	22.9	2.57	20.4	1.79	0	0	-3.9	-0.15	- -	- -
C/C-94			2N1745			- -	- -	5.7	1.50	15.9	1.79	29.[illegible]	1.72	[illegible]	0	5.7	0.22	- -	- -
C/C-95			2N1747			- -	- -	5.4	1.43	12.0	1.35	49.1	2.89	0	0	5.7	0.22	- -	- -
C/C-92			2N1727	Experimental Calibration (Fully immersed)		- -	- -	32.5	6.54	62.9	7.0[illegible]	- -	- -	- -	- -	-19.7	-0.76	- -	- -
C/C-93			2N1729			- -	- -	27.8	7.30	61.3	6.6[illegible]	- -	- -	- -	- -	-16.8	-0.65	- -	- -
C/C-94			2N1745			- -	- -	35.6	9.43	32.0	3.60	- -	- -	- -	- -	-9.3	-0.36	- -	- -
C/C-95			2N1747			- -	- -	32.4	8.52	40.6	4.56	- -	- -	- -	- -	-11.9	-0.46	- -	- -
C/C-96	Physical Sciences Corp.	MKI-A2 Cable Samples, Surface Thermocouples	1	Initial Calibration		265.9		- -	- -	Invalid Data 222.8		Invalid Data 123.5		-1.3		- -	- -	- -	- -
C/C-97			2			266.3		260.2						-1.0		-153.7			

Table VI
Test Results - Aerojet Calibration Data Reduced per Aerojet
Copper vs Constantan Thermocouple Table
Sheet 3 of 3