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CHARACTERIZATION OF SNAP-21 AND SNAP-23A THERMOELECTRIC MATERIALS

Space and Defense Products
ELECTRICAL PRODUCTS GROUP
3-M CENTER, ST. PAUL, MINN. 55101, PH 633-9400

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Prepared by

Technical Staff

Space & Defense Product Dept.

Approved by

D. D. Schley, Manager
SNAP-23A Program

J. A. Brandt, Manager
SNAP-21 Program

Issued by

Space and Defense Products

MINNESOTA MINING AND MANUFACTURING COMPANY

ST. PAUL, MINNESOTA 55101

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SECTION I
SUMMARY

I. SUMMARY

A. INTRODUCTION

This report summarizes effort conducted to determine the thermoelectric characteristics of materials currently utilized in the SNAP-23A and SNAP-21 thermoelectric couples.

The thermoelectric properties of importance are the Seebeck coefficient (S), the electrical resistivity (ρ), and the thermal conductivity (K), all of which are temperature dependent. A thermoelectric leg operating in a temperature gradient will exhibit a Seebeck voltage (E) relative to a given reference material (i.e., iron), a resistance (R), and conduct heat at the rate of (Q) watts. The values observed depend upon the thermoelectric properties of the material and the junction temperatures. From a number of such observations made at a series of junction temperatures, it is possible to determine values for S , ρ , and K as point functions of temperature.

The characterization program described herein utilized basic equipment and measurement techniques developed for TELPS (Thermoelectric Leg Product Specification) on the SNAP-27 Program under AEC contract AT(30-1)-3535.*

B. OBJECTIVES

The primary objective of the material characterization effort was to obtain data on thermoelectric properties which could be factored into and upgrade the design data for the SNAP-23A converters, and SNAP-21 T/E generators.

*For a comprehensive review of the basic TELPS refer to General Electric document number 6300-262, titled "Thermoelectric Leg Product Specification (TELPS) final Technical Report" Volume 1 Part 1, Volume 1 Part 2; and Volume 2.

A secondary objective of this effort was to experimentally determine the characteristics of actual materials (assembled segmented T/E legs) used in devices which were being built to satisfy a two-fold purpose.

- To quantitatively establish the T/E leg manufacturing method (simultaneously pressed versus separately pressed and bonded), the latter of which provides the higher efficiency under operating conditions.
- To develop a strong degree of confidence in the ability to predict analytically device performance with the design data base.

C. STATUS OF TECHNOLOGY

At the start of the SNAP-23A Phase I program, thermoelectric property data available for converter design and analysis purposes was derived from 1964 characterization measurements. This data included Seebeck (S), resistivity (ρ), and thermal conductivity (K) as point functions of temperature. Subsequent to these 1964 determinations, revisions were made (in conjunction with the the SNAP-27 program) to upgrade the thermoelectric manufacturing process procedures and to establish Quality Control procedures compatible with NASA and AEC Quality Assurance requirements.

These revisions occurred during the time period after completion of the SNAP-23 initial program (3M) and prior to start up of the SNAP-23A Phase I program (3M/WANL). Because of the program discontinuity, the effect of the manufacturing revisions on the baseline SNAP-23 thermoelectric materials had not been established. Therefore, a program was required to recharacterize the specific materials used in the SNAP-23A converter design consistent with current (1967) manufacturing and quality standards.

The data from this effort establishes a current technological base from which Phase I thermopile designs, including the Experimental and Prototype Mockup Converters, can be designed and integrated into the system, and upon which future designs may be based.

Because of similarity in thermoelectric couple material configuration, the results of this characterization effort were considered to be directly applicable to SNAP-21.

D. SUMMARY OF RESULTS

1. Characterization of Bulk Thermoelectric Materials

Test measurements were made on three to six samples of each of five types of materials. Four types of materials samples for simultaneously pressed segmented legs were obtained as separate segments from the same batches, and received the same manufacturing processing (i. e., sintering) as those legs used in the first Experimental Mockup Converter. In addition, the fifth type of material tested is for the hot segments of separately pressed and bonded P-legs. Table I-1 illustrates the materials tested and their relationship to SNAP-23A and SNAP-21 devices.

The test data was analyzed with the aid of a digital computer to determine the material properties (S, K, ρ K) as functions of temperature in fifth-order polynomial form, e. g.,

$$S(\mu\text{V}/^\circ\text{K}) = S_0 + S_1 T + S_2 T^2 + S_3 T^3 + S_4 T^4 + S_5 T^5$$

$$K(\text{watts}/\text{cm}-^\circ\text{K}) = K_0 + K_1 T + K_2 T^2 + K_3 T^3 + K_4 T^4 + K_5 T^5$$

$$\begin{aligned} \rho K (\mu\Omega \text{ watts}/^\circ\text{K}) = & (\rho K)_0 + (\rho K)_1 T + (\rho K)_2 T^2 + (\rho K)_3 T^3 \\ & + (\rho K)_4 T^4 + (\rho K)_5 T^5 \end{aligned}$$

The material coefficients in this form are used in several digital computer programs employed in thermoelectric device design, such as the program described in SNAP-23A Quarterly Report No. 1 (MMM 3824-0006). Tabulated values of the material coefficients and graphs of the material properties S, K, ρ and ZT (dimensionless figure of merit) are included in Section III, Test Results.

2. Performance of Assembled Segmented Thermoelectric Legs

Test measurements were conducted on several assembled segmented legs of both manufacturing techniques (simultaneously pressed and separately pressed and bonded) of each N-type and P-type, using both SNAP-21 and SNAP-23A geometry samples.

Table I-1. Materials Used in the SNAP-21 and SNAP-23A Thermoelectric Couples

Program	Device Type	Model	Leg	Application		Manufacturing Method
				Cold Segment	Hot Segment	
SNAP-21	All 10-watt Generators	All	N	TPM 13 PbTe	TPM 223 PbTe	Separately Pressed and Bonded
			P	TPM 29 BiSbTe	TPM 222 PbSnTe	
SNAP-23A	60-watt Converters	All EMC PMC	N	TPM 13 PbTe	TPM 223 PbTe	Simultaneously Powder Pressed
		EMC-1 EMC-2	P	TPM 29 BiSbTe	TPM 76 PbSnTe	Simultaneously Powder Pressed
		EMC-3 PMC-1	P	TPM 29 BiSbTe	TPM 222 PbSnTe	Separately Pressed and Bonded

Measurements were made under open circuit conditions of the Seebeck voltage, thermal conductance and the ρK product, and their dependency upon hot and cold junction temperatures.

With the aid of a digital computer, an equivalent interpolation and normalization of each experiment to a consistent test condition was performed (by a least-squares multiple-regression surface-fitting technique). The following observations were made of the calculated results:

- P-legs made by the separately pressed and bonded technique are clearly superior in efficiency to those made by the simultaneous pressing technique, exhibiting an approximate 20 percent higher efficiency.
- N-leg measured data illustrates up to 7 percent higher efficiency for the simultaneously pressed leg, but the calculated data illustrates the opposite, with a 2 percent efficiency advantage for the separately pressed and bonded type. The magnitude of the differences is not considered sufficient to draw firm conclusions for the number of samples measured.

E. CONCLUSIONS AND RECOMMENDATIONS

The primary objective of the material characterization effort has been satisfied, that is, characterization has been completed for the thermoelectric properties of the bulk material and the upgrading of the design data base for converters and T/E generators.

In addition, the secondary objective of this effort – to quantitatively establish the T/E leg manufacturing method (simultaneously pressed versus separately pressed and bonded) the latter of which provides the higher efficiency under operating conditions – has been partially satisfied in that the P-leg has been shown to be of higher efficiency in the separately pressed and bonded form, however, the data for the N-leg is not sufficient to warrant similar conclusive statements.

Based on these conclusions, recommendations for additional effort of this nature should include additional N-leg testing and analysis. Furthermore, if additional work were to be contemplated, it would be desirable to include actual device hardware in this type of test, such as cold-end hot-end electrodes, to aid in the

determination of device "extraneous resistance" factors (by direct substitution). Such factors are a practical consideration in the design of T/E generators and converters.

Since the test program evaluated the composite thermoelectric legs without electrodes, the effort was not expected to allow valid direct comparisons to be made with other ongoing tests including SNAP-23A bell jars, ten-couple modules, 60-watt converters and SNAP-21 generators. Therefore, it should be observed that correlation with the other test data was not attempted as it would require extensive additional effort to modify the TELPS apparatus to include the required thermopile hardware, insulation and environmental conditions.

SECTION II

TECHNICAL APPROACH

II. TECHNICAL APPROACH

A. GENERAL DESCRIPTION OF TELPS APPARATUS AND PROCEDURES

New apparatus, test procedures, and numerical data reduction techniques, which were developed under the TELPS program, permit determination of values of the Seebeck coefficient, thermal conductivity, and resistivity of an individual test specimen as a function of temperature over the temperature range of room temperature to 1300° F. The method is a transient ingradient performance test in which a test leg is subjected to a series of increasing temperature gradients (the hot and cold junction temperatures) at each of which are measured the Seebeck voltage, ingradient resistance, and conducted heat. The test fixture consists of TELPS ingradient performance test fixtures (Figures II-1, II-2 and II-3 modified to include a thermal heat flux meter (Figure II-4).

The ingradient performance fixture is essentially a four probe (two current and two potential) resistivity measuring device of special design to permit measurements to be made under one dimensional temperature gradient condition. Two Inconel sheathed iron-constantan thermocouples are compressively loaded against opposite ends of the test specimen along its central axis. The iron wires of each thermocouple are used as potential probes. Flat graphite current electrodes are provided with an axial hole 0.090 inch in diameter through which 0.065 inch diameter thermocouples pass without touching. Insulating sleeves help ensure that the thermocouples (and thus, the potential probes) do not short out against the current electrode.

The current electrodes are attached to the thermoelectric legs in such a way that the current flows axially and radially in the cylindrical element, but no angular current flow exists. By defining the voltage distribution within the leg for a particular electrode and leg configuration, it is possible to devise a correction factor for the measured resistance. A resistance calculation based on the usual relation

Figure II-1. TELPS Laboratory

Figure II-2. Isothermal Furnace Used for Thermocouple Calibration

Figure II-3. Close-Up View of a TELPS Ingradient Performance Fixture Showing a Test Specimen in Position

Figure II-4. Assembly of Thermal Conductivity Insert

$R = (E - V)/I$ would be in error because of non-uniform potential distribution near the electrodes. If we assume perfect contact between the electrode and the element, the voltage distribution within the element may be calculated.

The element is assumed to consist of uniform toroidal segments. Under steady current flow in the element, the net amount of electrical current flowing into each toroidal element must be zero. Therefore, we may write a current balance for each segment of the element.

Equations may be written for each segment of the element including the boundaries. A series of simultaneous equations is obtained which may be solved by relaxation procedures or matrix inversion.

An alternate method of determining the voltage distribution in the element is to assume a voltage distribution at some initial time and then calculate the voltage change for each segment as a function of time using finite difference techniques. This calculation is performed for each segment until a steady state is reached.

This second method was used in calculating the voltage distribution for the thermoelectric elements. The equations are analogous to the equations for heat transfer in cylinders. Therefore, a computer program which had been used for the calculation of heat transfer in cylinders was used for these calculations.

In the actual calculations, the use of a calculation method for non-steady state would require a long time to reach steady-state conditions. However, it has been found in previous work that, for systems which are approaching steady state, when $\Delta E/\Delta t$ is plotted versus E and then extrapolated to $\Delta E/\Delta t = 0$, a good estimate of the steady-state value of E is obtained. With a computer, it is relatively easy to store values of $\Delta E/\Delta t$ and E at selected times and perform the linear extrapolation mathematically. After the extrapolation, the finite difference calculation may be continued for several more time increments to confirm that steady-state conditions have been determined. When the finite difference method, i. e., non-steady state technique, is used in conjunction with the extrapolation technique, the computer time required to calculate steady-state voltages is of the same order of magnitude as the time required for matrix inversion or relaxation methods.

The resistance correction factor was derived by obtaining an accurate potential map for an assumed potential difference of 1 volt. By finding the ratio of the measured voltage gradient $(E-V)/L$ to the average gradient near the center of the test specimen, we obtain the factor by which the measured voltage gradient gives too low an indication of the average voltage gradient in a region of the specimen where the current density is uniform. The resistance correction factor is then given by the ratio of the average gradient to the apparent gradient. It was found that the magnitude of this correction factor was not very sensitive to changes in leg diameter or small changes in length.

The ingradient performance fixture design provides a thermal environment which favors one dimensional heat flow in the test specimen as a consequence of the large temperature gradient and the large area isothermal hot block and cold block surfaces which tend to reduce lateral radiation heat loss. In addition, gas convection heat losses, as well as radiation loss through the quartz tube (which could produce sufficient change in the thermal gradient to cause a detectable change in resistance from that observed) are effectively eliminated by insertion of micro-quartz insulation into the vacant region surrounding the legs between the heater blocks.

B. THERMOCOUPLE CALIBRATION

The Inconel sheathed iron-constantan hot and cold junction thermocouples of the TELPS fixtures were calibrated against a calibrated standard thermocouple (Figure II-5) which, in turn, had been calibrated against a Bureau of Standards secondary standard.

All the thermocouples were fabricated from wires of the same spools and were found to be in close agreement with each other, but they averaged about 8-10° F too high an indicated temperature in the 1300° F range compared to tabulated values. Thus, to convert thermocouple readings in millivolts to accurate temperature readings in degrees Fahrenheit, a two-step procedure was adopted. First, a 5th order least squares polynomial curve fit expressing temperature as a function of millivolt readings (referring to 32° F) was established, and the six coefficients of the power series were stored in the appropriate data reduction programs.

Figure II-5. Standard Thermocouple

A second order polynomial correction curve was then derived to express the average temperature error curve versus millivolt output. The calculated error for a given millivolt reading was then algebraically added to handbook temperature values to give corrected values. Since all thermocouples were referenced to a 150° F controlled reference junction terminal box, it was necessary first to add 1.22 mv to all thermocouple readings for correction to a 32° F reference junction temperature prior to entering the curve fits. The temperature was then calculated by:

$$T = A_0 + A_1(mv) + A_2(mv)^2 + A_5(mv)^5$$

It is estimated that this procedure gives temperature values accurate to within +2° F or about 0.15 percent whereas, manufacturing J standards specify 3/4 percent accuracy.

SECTION III

TEST RESULTS

III. TEST RESULTS

A. MEASUREMENT OF THERMOELECTRIC CHARACTERISTICS OF BULK MATERIALS

Test measurements were made on 3 to 6 samples each of 5 types of materials. Four types of materials samples for simultaneously pressed segmented legs were obtained as separate segments from the same batches, and received the same manufacturing processing (i. e. , sintering) as those legs used in the first Experimental Mockup Converter. In addition, the fifth type of material tested is for the hot segment of separately pressed and bonded P-legs which have been undergoing test in bell jars and 10-couple modules, and have been used in Experimental Mock-up Converter No. 3 and included in the Prototype Mockup Converter design.

The test measurements covered the range of temperature from room ambient (70° F) up to 1200° F in various increments at approximately 18 measurements per sample.

The test data was analyzed with the aid of a digital computer to determine the material properties (S, K, ρK) as functions of temperature in fifth-order polynomial form, e. g. ,

$$S (\mu V/^{\circ}K) = S_0 + S_1 T + S_2 T^2 + S_3 T^3 + S_4 T^4 + S_5 T^5$$

$$K (\text{watts/cm-}^{\circ}K) = K_0 + K_1 T + K_2 T^2 + K_3 T^3 + K_4 T^4 + K_5 T^5$$

$$\begin{aligned} \rho K (\mu\Omega \text{ watts}/^{\circ}K) = & (\rho K)_0 + (\rho K)_1 T + (\rho K)_2 T^2 + (\rho K)_3 T^3 + (\rho K)_4 T^4 \\ & + (\rho K)_5 T^5 \end{aligned}$$

The material coefficients in this form are used in several digital computer programs employed in the SNAP-21 and SNAP-23A Programs, such as the program described in SNAP-23A Quarterly Report No. 1 (MMM 3824-0006).

Tables III-1, III-2 and III-3 list the values of the material coefficients determined for the five types of materials. Figures III-1 through III-16 are graphs of the material properties, S , K , ρ and the dimensionless figure of merit ($ZT = TS^2/K\rho$) versus temperature for the four materials of simultaneously pressed segmented legs for both the old SNAP-23 coefficients (dashed line), and the new coefficients (solid line). Figures III-17 through III-20 are similar graphs for the hot segment material of separately pressed and bonded P-legs for the new SNAP-23A coefficients-only no previous distinction had been made between the coefficients for hot segment material of the simultaneously pressed or separately pressed and bonded categories.

Validation of these material coefficients in computer programs for leg and couple design and parameteric studies has been conducted by analysis involving the comparison of theoretical values with experimental data obtained from 10-couple module and bell jar tests, from large-scale thermopiles such as the 264-couple Experimental Mockup Converters, and from several SNAP-21 48-couple generators (particularly from the data for separately pressed and bonded legs).

The best measure or criterion for validation of these coefficients is seen in the comparison of experimental Seebeck voltage with computer-calculated (theoretical) Seebeck voltage for a given temperature gradient. As an example, the Seebeck comparison from bell jar test data illustrates very close agreement of experimental versus theoretical values (in most cases, only 1 or 2 percent difference). A secondary "measure" is seen in the Resistance comparisons determined similarly. However, the theoretical resistance calculated does not include any allowance for extraneous resistance such as couple electrode resistance and contact resistance. Therefore, this measure for validation of material characterization coefficients will have larger variations than the Seebeck criterion; but with good Seebeck correlation, it can be used effectively to determine extraneous resistance data for design purposes and analysis of test data generated for larger-scale devices.

Table III-1. N-Leg Thermoelectric Material Coefficients for Simultaneously Pressed and Separately Pressed and Bonded Segmented Legs

Material Property Coefficient	Hot Segment	Cold Segment
<div> <div>S(0)</div> <div>S(1)</div> <div>S(2)</div> <div>S(3)</div> <div>S(4)</div> <div>S(5)</div> </div> <div> <div></div> <div></div> <div>Micro-Volts/°K</div> <div></div> <div></div> <div></div> </div>	<div>-246.686</div> <div>2.41069</div> <div>-6.70460E-3</div> <div>1.00199E-5</div> <div>-6.61775E-9</div> <div>1.29358E-12</div>	<div>59.0898</div> <div>0.987564</div> <div>-4.67608E-3</div> <div>1.43634E-5</div> <div>-1.83783E-8</div> <div>7.84170E-12</div>
<div> <div>K(0)</div> <div>K(1)</div> <div>K(2)</div> <div>K(3)</div> <div>K(4)</div> <div>K(5)</div> </div> <div> <div></div> <div></div> <div>Watts/cm-°K</div> <div></div> <div></div> <div></div> </div>	<div>0.104257</div> <div>-4.88731E-4</div> <div>1.10784E-6</div> <div>-1.23955E-9</div> <div>6.11540E-13</div> <div>-6.22918E-17</div>	<div>9.01458E-2</div> <div>-5.16967E-4</div> <div>1.40647E-6</div> <div>-1.91744E-9</div> <div>1.26591E-12</div> <div>-2.92224E-16</div>
<div> <div>ρK(0)</div> <div>ρK(1)</div> <div>ρK(2)</div> <div>ρK(3)</div> <div>ρK(4)</div> <div>ρK(5)</div> </div> <div> <div></div> <div></div> <div>Micro-Ohm-Watt/°K</div> <div></div> <div></div> <div></div> </div>	<div>28.5186</div> <div>-0.204087</div> <div>6.77201E-4</div> <div>-7.93314E-7</div> <div>2.03229E-10</div> <div>2.75771E-13</div>	<div>-81.4665</div> <div>1.34380</div> <div>-6.47748E-3</div> <div>1.40912E-5</div> <div>-1.30684E-8</div> <div>4.39302E-12</div>

Table III-2. P-Leg Thermoelectric Material Coefficients for Simultaneously Pressed Segmented Legs

Material Property Coefficient	Hot Segment	Cold Segment
<div> <div>S(0)</div> <div>S(1)</div> <div>S(2)</div> <div>S(3)</div> <div>S(4)</div> <div>S(5)</div> </div> <div> <div>Micro-Volts/°K</div> </div>	<div>-416.525</div> <div>3.78319</div> <div>-1.33208E-2</div> <div>2.51686E-5</div> <div>-2.23243E-8</div> <div>7.29535E-12</div>	<div>232.255</div> <div>-1.13113</div> <div>2.91156E-3</div> <div>1.76130E-6</div> <div>-1.07502E-8</div> <div>7.40293E-12</div>
<div> <div>K(0)</div> <div>K(1)</div> <div>K(2)</div> <div>K(3)</div> <div>K(4)</div> <div>K(5)</div> </div> <div> <div>Watts/cm-°K</div> </div>	<div>0.04248</div> <div>-2.13363E-4</div> <div>6.70986E-7</div> <div>-9.96224E-10</div> <div>6.31959E-13</div> <div>-1.01514E-16</div>	<div>4.51357E-2</div> <div>-2.55684E-4</div> <div>8.50050E-7</div> <div>-1.53148E-9</div> <div>1.43965E-12</div> <div>-4.73309E-16</div>
<div> <div>$\rho K(0)$</div> <div>$\rho K(1)$</div> <div>$\rho K(2)$</div> <div>$\rho K(3)$</div> <div>$\rho K(4)$</div> <div>$\rho K(5)$</div> </div> <div> <div>Micro-Ohm-Watt/°K</div> </div>	<div>-144.095</div> <div>1.25128</div> <div>-3.79086E-3</div> <div>5.57955E-6</div> <div>-3.80016E-9</div> <div>1.05895E-12</div>	<div>-119.562</div> <div>1.18363</div> <div>-4.21591E-3</div> <div>7.00537E-6</div> <div>-4.99433E-9</div> <div>1.26456E-12</div>

Table III-3. P-Leg Thermoelectric Material Coefficients for Separately Pressed and Bonded Segmented Legs

Material Property Coefficient		Hot Segment	Cold Segment
S(0)	Micro-Volts/°K	-811.495	232.255
S(1)		7.38649	-1.13113
S(2)		-2.58988E-2	2.91156E-3
S(3)		4.66543E-5	1.76130E-6
S(4)		-4.00778E-8	-1.07502E-8
S(5)		1.29656E-11	7.40293E-12
K(0)	Watts/cm-°K	5.71695E-2	4.51357E-2
K(1)		-3.30488E-4	-2.55684E-4
K(2)		9.98746E-7	8.50050E-7
K(3)		-1.45013E-9	-1.53148E-9
K(4)		9.66867E-13	1.43965E-12
K(5)		-2.10714E-16	-4.73309E-16
$\rho K(0)$	Micro-Ohm-Watt/°K	-73.0916	-119.562
$\rho K(1)$		7.77575E-1	1.18363
$\rho K(2)$		-2.76745E-3	-4.21591E-3
$\rho K(3)$		4.97147E-6	7.00537E-6
$\rho K(4)$		-4.31329E-9	-4.99433E-9
$\rho K(5)$		1.59399E-12	1.26456E-12

Figure III-1. Seebeck Coefficient (S)
(N Leg, Hot Segment
TPM-223, PbTe)

Figure III-2. Resistivity (ρ)
(N Leg, Hot Segment
TPM-223, PbTe)

Figure III-3. Thermal Conductivity (K)
(N Leg, Hot Segment
TPM-223, PbTe)

Figure III-4. Dimensionless Figure of Merit (ZT)
(N Leg, Hot Segment
TPM-223, PbTe)

Figure III-5. Seebeck Coefficient (S)
(N Leg, Cold Segment
TPM-13, PbTe)

Figure III-6. Resistivity (ρ)
(N Leg, Cold Segment
TPM-13, PbTe)

Figure III-7. Thermal Conductivity (K)
(N Leg, Cold Segment
TPM-13, PbTe)

Figure III-8. Dimensionless Figure of Merit (ZT)
(N Leg, Cold Segment
TPM-13, PbTe)

Figure III-9. Seebeck Coefficient (S)
(P Leg, Hot Segment
TPM-76, PbSnTe)

Figure III-10. Resistivity (ρ)
(P Leg, Hot Segment
TPM-76, PbSnTe)

Figure III-11. Thermal Conductivity (K)
(P Leg, Hot Segment
TPM-76, PbSnTe)

Figure III-12. Dimensionless Figure of Merit (ZT)
(P Leg, Hot Segment
TPM-76, PbSnTe)

Figure III-13. Seebeck Coefficient (S)
(P Leg, Cold Segment
TPM-29, BiSbTe)

Figure III-14. Resistivity (ρ)
(P Leg, Cold Segment
TPM-29, BiSbTe)

Figure III-15. Thermal Conductivity (K)
(P Leg, Cold Segment
TPM-29, BiSbTe)

Figure III-16. Dimensionless Figure of Merit (ZT)
(P Leg, Cold Segment
TPM-29, BiSbTe)

Figure III-17. Seebeck Coefficient (S) (P-Leg Hot Segment for Separately Pressed and Bonded TPM-222, PbSnTe)

Figure III-18. Resistivity (ρ) (P-Leg, Hot Segment For Separately Pressed and Bonded TPM-222, PbSnTe)

Figure III-19. Thermal Conductivity (K) (P-Leg, Hot Segment For Separately Pressed and Bonded TPM-222, PbSnTe)

Figure III-20. Dimensionless Figure of Merit (ZT) (P-Leg, Hot Segment For Separately Pressed and Bonded TPM-222, PbSnTe)

B. MEASUREMENT OF THERMOELECTRIC CHARACTERISTICS OF ASSEMBLED SEGMENTED LEGS

Several segmented legs of both manufacturing techniques – simultaneously pressed and separately pressed and bonded – of each N-type and P-type were tested in a TELPS performance fixture which was modified to provide water cooling of the cold junction block for proper control of the temperature gradient.

Measurements were made at open circuit conditions of the Seebeck voltage, thermal conductance and the ρK product as functions of the hot and cold junction temperatures.

Each of the performance parameters were expressed by equations of the following form:

$$X = A_0 + A_1(Th - Tc) + A_2 \left[\frac{Th^2 - Tc^2}{2} \right] + A_3 \left[\frac{Th^3 - Tc^3}{3} \right]$$

where the constants A_0 , A_1 , A_2 and A_3 were determined by a least-squares multiple-regression surface-fitting technique.

The performance of each test specimen was then calculated using the surface coefficients for each sample under specific SNAP-21 and SNAP-23A EOL conditions at maximum efficiency current loading. This is equivalent to an interpolation and normalization of each experiment to a consistent test condition. In addition, the expected performance of each test specimen under the prescribed temperature and loading condition was calculated. The experimental and calculated results are listed in Tables III-5 through III-8.

The data presented in those tables show that the separately pressed and bonded P-legs are clearly superior (in overall efficiency) to the simultaneously pressed P-leg. This relationship is consistent for both measured and calculated data, and under different ingradient temperatures.

Results for the N-legs are not as clearly defined. The data illustrates that the "measured" efficiency value for the simultaneously pressed N-leg is higher than that for the separately pressed and bonded N-leg, while the converse exists for the

Table III-4. Thermoelectric Leg Dimensions for SNAP-21 and SNAP-23A

Program	Parameter	P-Leg Assembly		N-Leg Assembly	Comments
		Simultaneously Pressed	Pressed and Bonded		
SNAP-23A	Total Length	$L_p = 0.327$ inches	$L_p = 0.327$ inches	$L_n = 0.479$ inches	N-Leg typical of EMC-1, EMC-2 and EMC-3 design. P-Leg simultaneously pressed typical of EMC-1 and EMC-2 design. P-Leg pressed and bonded typical of EMC-3 design.
	Hot Segment Length	$L_{hp} = 0.213$ inches	$L_{hp} = 0.213$ inches	$L_{hn} = 0.359$ inches	
	Cold Segment Length	$L_{cp} = 0.114$ inches	$L_{cp} = 0.114$ inches	$L_{cn} = 0.120$ inches	
	Diameter	$D_p = 0.187$ inches	$D_p = 0.187$ inches	$D_p = 0.187$ inches	
	Ratio of Cold Segment Length to Total Length	$\frac{L_{cp}}{L_p} = 0.350$	$\frac{L_{cp}}{L_p} = 0.350$	$\frac{L_{cn}}{L_n} = 0.250$	
SNAP-21	Total Length	Not Applicable	$L_p = 0.411$	$L_n = 0.571$	N and P-Legs typical of initial ball-and-socket (A10D1 through A10D4) and in-line (A10D5 through A10D7) generator designs.
	Hot Segment Length		$L_{hp} = 0.267$	$L_{hn} = 0.371$	
	Cold Segment Length		$L_{cp} = 0.144$	$L_{cn} = 0.200$	
	Diameter		$D_p = 0.187$	$D_n = 0.187$	
	Ratio of Cold Segment Length to Total Length		$\frac{L_{cp}}{L_p} = 0.350$	$\frac{L_{cn}}{L_n} = 0.350$	

Table III-5. Ingradient Performance Results for P-Leg Assemblies at
SNAP-23A Nominal EOL Temperatures
($T_c = 170^\circ\text{F}$ and $T_H = 900^\circ\text{F}$)

Type of Leg Assembly	E	V	$I \frac{L}{A}$	$R \frac{A}{L}$	$P \frac{L}{A}$	$Q_R \frac{L}{A}$	$Q_s \frac{L}{A}$	η
<u>SNAP-21⁽¹⁾</u>								
Separately	71.38	40.10	33.531	0.933	1.345	16.784	18.128	0.0742
Pressed and	70.87	39.46	32.048	0.980	1.265	17.409	18.647	0.0677
Bonded	72.02	40.40	33.377	0.947	1.348	17.032	18.381	0.0734
Average ⁽²⁾	71.42	39.99	32.985	0.953	1.319	17.075	18.385	0.0718
Calculated ⁽³⁾	75.10	42.60	35.51	0.915	1.512	17.215	17.728	0.0807
<u>SNAP-23A⁽¹⁾</u>								
Separately	67.72	38.05	36.417	0.815	1.386	17.100	18.485	0.0750
Pressed and	67.19	37.74	37.188	0.792	1.404	17.282	17.686	0.0751
Bonded	66.97	37.42	37.054	0.797	1.387	17.962	19.349	0.0717
Average ⁽²⁾	67.29	37.74	36.886	0.801	1.392	17.448	18.840	0.0739
Calculated ⁽³⁾	75.10	42.60	35.51	0.915	1.512	17.215	18.728	0.0807
<u>SNAP-23A⁽¹⁾</u>								
Simultaneously	64.35	35.34	30.055	0.965	1.062	16.143	17.205	0.0617
Pressed	60.82	33.13	27.871	0.994	0.923	15.513	16.436	0.0562
	64.59	35.56	29.162	0.995	1.037	15.595	16.632	0.0623
Average ⁽²⁾	63.25	34.68	29.029	0.984	1.007	15.750	16.758	0.0601
Calculated ⁽³⁾	69.90	38.90	34.32	0.903	1.336	17.233	18.569	0.0719

(1) Dimensions of Leg Assembly indicated in Table III-4.

(2) Based on measured composite leg characteristics.

(3) Computer calculations based on measured bulk material characteristics.

Table III-6. Ingradient Performance Results for P-Leg Assemblies at
SNAP-21 Nominal EOL Temperatures
($T_c = 105^\circ\text{F}$ and $T_H = 900^\circ\text{F}$)

Type of Leg Assembly	E	V	$I \frac{L}{A}$	$R \frac{A}{L}$	$P \frac{L}{A}$	$Q_R \frac{L}{A}$	$Q_s \frac{L}{A}$	η
<u>SNAP-21</u> ⁽¹⁾								
Separately	75.39	42.34	37.748	0.876	1.598	17.976	19.574	0.0817
Pressed and	74.85	41.80	35.850	0.922	1.498	18.206	19.705	0.0760
Bonded	76.15	42.81	37.529	0.888	1.607	17.798	19.405	0.0828
Average ⁽²⁾	75.46	42.32	37.042	0.895	1.568	17.993	19.561	0.0802
Calculated ⁽³⁾	79.40	45.00	39.58	0.869	1.779	18.574	20.353	0.0874
<u>SNAP-23A</u> ⁽¹⁾								
Separately	70.70	39.52	41.510	0.751	1.641	19.283	20.924	0.0784
Pressed and	70.21	39.23	42.206	0.734	1.656	19.454	21.110	0.0784
Bonded	69.96	39.04	42.084	0.735	1.643	19.563	21.206	0.0775
Average ⁽²⁾	70.29	39.26	41.930	0.740	1.647	19.433	21.080	0.0781
Calculated ⁽³⁾	79.40	45.00	39.58	0.869	1.779	18.574	20.353	0.0874
<u>SNAP-23A</u> ⁽¹⁾								
Simultaneously	67.56	37.15	33.858	0.898	1.256	17.032	18.290	0.0688
Pressed	63.97	34.82	31.600	0.922	1.100	16.777	17.877	0.0616
	67.89	37.33	32.939	0.928	1.230	16.953	18.183	0.0676
Average ⁽²⁾	66.47	36.43	32.799	0.916	1.195	16.921	18.167	0.0660
Calculated ⁽³⁾	74.00	41.10	38.280	0.859	1.573	18.635	20.207	0.0778

(1) Dimensions of Leg Assembly indicated in Table III-4.

(2) Based on measured composite leg characteristics.

(3) Computer calculations based on measured bulk material characteristics.

Table III-7. Ingradient Performance Results for N-Leg Assemblies at
 SNAP-23A Nominal EOL Temperatures
 ($T_c = 170^\circ\text{F}$ and $T_H = 900^\circ\text{F}$)

Type of Leg Assembly	E	V	$I \frac{L}{A}$	$R \frac{A}{L}$	$P \frac{L}{A}$	$Q_R \frac{L}{A}$	$Q_s \frac{L}{A}$	η
<u>SNAP-21⁽¹⁾</u>								
Separately	88.29	49.23	39.641	0.985	1.951	23.464	25.416	0.0768
Pressed and	88.46	49.51	41.241	0.944	2.042	23.620	25.662	0.0796
Bonded	88.49	49.91	40.687	0.948	2.031	21.879	23.910	0.0849
Average ⁽²⁾	88.41	49.55	40.523	0.959	2.008	22.988	24.996	0.0804
Calculated ⁽³⁾	88.20	50.70	44.94	0.834	2.276	20.595	22.871	0.0995
<u>SNAP-23A⁽¹⁾</u>								
Simultaneously	81.23	45.79	48.945	0.724	2.241	24.130	26.371	0.0850
Pressed	81.40	45.91	48.728	0.725	2.237	23.868	26.105	0.0857
	81.26	45.87	46.965	0.754	2.154	22.937	25.092	0.0859
Average ⁽²⁾	81.30	45.86	48.213	0.735	2.211	23.645	25.856	0.0855
Calculated ⁽³⁾	83.50	47.90	48.63	0.732	2.330	21.293	23.632	0.0986

(1) Dimensions of Leg Assembly indicated in Table III-4.

(2) Based on measured composite leg characteristics.

(3) Computer calculations based on measured bulk material characteristics.

Table III-8. Ingradient Performance Results for N-Leg Assemblies at
SNAP-21 Nominal EOL Temperatures
($T_C = 105^\circ\text{F}$ and $T_H = 900^\circ\text{F}$)

Type of Leg Assembly	E	V	$I \frac{L}{A}$	$R \frac{A}{L}$	$P \frac{L}{A}$	$Q_R \frac{L}{A}$	$Q_s \frac{L}{A}$	η
<u>SNAP-21</u> ⁽¹⁾								
Separately	92.85	52.09	47.129	0.865	2.455	25.217	27.671	0.0887
Pressed and	93.01	52.43	48.747	0.832	2.556	25.000	27.556	0.0927
Bonded	93.13	52.85	48.188	0.836	2.547	23.472	26.019	0.0979
Average ⁽²⁾	93.00	52.46	48.021	0.844	2.519	24.563	27.082	0.0931
Calculated ⁽³⁾	92.80	53.30	52.43	0.753	2.797	22.787	25.584	0.1093
<u>SNAP-23A</u> ⁽¹⁾								
Simultaneously	85.23	48.39	57.825	0.637	2.798	25.612	28.410	0.0985
Pressed	85.38	48.51	57.774	0.638	2.803	25.382	28.185	0.0994
	85.40	48.56	54.861	0.672	2.664	24.094	26.758	0.0996
Average ⁽²⁾	85.34	48.49	56.820	0.648	2.755	25.029	27.784	0.0991
Calculated ⁽³⁾	87.70	50.40	56.37	0.662	2.839	23.593	26.432	0.1074

(1) Dimensions of Leg Assembly indicated in Table III-4

(2) Based on measured composite leg characteristics.

(3) Computer calculations based on measured bulk material characteristics.

"calculated" efficiency value. Consequently, no significance can be placed upon these observed differences in performance for the N-leg.

Investigation to determine reasons for this discrepancy included Resistance-versus-Length traces of the separately pressed and bonded N-leg; however, there was no indication of any excessive segment interface resistance of the samples tested. But, post-test visual examination of these legs tested revealed a decided difference between the apparent area of contact at the hot junction for the two types of N-legs. The simultaneously pressed legs appeared to have made 100 percent contact with the test fixture hot electrode, but the separately pressed and bonded legs appeared to have been contacted over only 50 to 60 percent of the total area (near the center of the leg). There is no definitive explanation for this difference; all tests were conducted under the same environment and loading conditions (95 percent Argon, 5 percent Hydrogen atmosphere, 250 psi load). It may be speculated that a local density difference in the legs in the region of the hot junction could be responsible for the difference in contactability. However, that phenomena would require further extensive study.

It may be observed from Tables III-5 and III-6 that for the separately pressed and bonded P-legs, those legs of SNAP-21 geometry exhibit higher E and RA/L and lower $Q_s L/A$ values than those legs of SNAP-23A geometry, but that the efficiency values (η) for both are very comparable. The differences appear in all those tests and are most likely the result of normal manufacturing material tolerances.