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**SNAP-23A PROGRAM, PHASE 1
THERMOELECTRIC CONVERTER
DEVELOPMENT PROGRAM**

QUARTERLY REPORT NO. 6

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

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Space and Defense Products
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TID-4500

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with the U.S. Atomic Energy Commission

SNAP-23A PROGRAM PHASE I

THERMOELECTRIC CONVERTER DEVELOPMENT PROGRAM

QUARTERLY REPORT NO. 6

April 1, 1968 through June 30, 1968

Prepared by

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FOREWORD

The Minnesota Mining and Manufacturing Company (3M Company), as prime contractor to the United States Atomic Energy Commission under contract AT(30-1)-3418, designed, developed, fabricated and tested the SNAP-23 60-watt mockup radioisotope power supply system. The basic SNAP-23 Program was directed toward the development of high performance, reliable thermoelectric converter modules, using segmented thermoelectric legs, having a five-year design life.

As a result of the advancements made in the application of segmented thermoelectric legs during the preliminary SNAP-23 effort, the AEC initiated a follow-on development program designed to advance the SNAP-23 technology into a series of technically improved and economically competitive radioisotope power systems in the 25- and 100-watt power ranges with a ten-year design life objective.

The SNAP-23A development effort is directed toward the design, fabrication, and test of a thermoelectric converter design to be used as a component in the 60-watt SNAP-23A Terrestrial Radioisotope Power Supply System. This document reports progress for this effort from the period 1 April 1968 through 30 June 1968.

The 3M Company Converter Development Program is being performed under AEC contract AT(30-1)-3824, in conjunction with the SNAP-23A system contractor, Westinghouse Astronuclear Laboratory (WANL). While the converter development program is directed toward the development of a 60-watt converter and conceptual designs for 25- and 100-watt converters, major emphasis will be concentrated on development of a design for thermoelectric couples which will perform reliably over a ten-year design life.

The specific requirements of the Phase I SNAP-23A development effort are:

- Design, develop, fabricate and test 60-watt(e) converters
- Prepare conceptual designs for 25- and 100-watt(e) converters

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SNAP-23A 60-WATT THERMOELECTRIC CONVERTER

1.0 SUMMARY

During this quarter approval of the Prototype Mockup Converter (PMC) design was received from the AEC; fabrication and processing of PMC-1 was completed; Converter EMC-2 was placed back on long-term test after repairs were completed to the heat source assembly of the process and test station; and EMC-3 was placed on long-term test.

The Prototype Mockup Converter (PMC) contains several design changes with respect to the Experimental Mockup Converter (EMC) design; they are:

1. The thermoelectric couple configuration was optimized.
2. The follower material was changed from aluminum hard-coated to beryllium oxide.
3. The interface dimensions were redefined which subsequently required additional measurement detail and variable data documentation.

It is anticipated that the T/E optimization will provide a converter efficiency greater than that which has been demonstrated previously in the EMC devices.

Long-term testing of 10-couple modules 1 through 12 was continued, with statistical analysis made every 1000 hours on the data from modules 5 through 12.

2.0 TASK I-PROGRAM MANAGEMENT

2.1 GENERAL

The development activities during this quarter were influenced by the program status at the outset. Late in the preceding quarter, efforts for the Prototype Mockup Converter (PMC) were in a decelerated state as compared to the original plan. This was caused by several factors:

- Delayed availability of test data from the first Experimental Mockup System pending resolution of heat source technical problems. This system incorporated the first Experimental Mockup Converter, EMC-1. System test data was a prerequisite to final release of the PMC converter design.
- A decision to use T/E test results from converter EMC-3 to establish the design base for the first Prototype Mockup Converter, PMC-1. Converter EMC-3 incorporated improved thermoelectric technology consisting of the bonded P-leg.
- Outstanding interface drawing details.
- System operation limitations resulting from EMC-1 cold end heat transfer anomalies.

Early in this quarter, the program development schedule and rationale were mutually reviewed by the AEC, Westinghouse, and 3M. As a result of this review a tentative plan was made and agreement was reached on guidelines to be followed for the subsequent Phase I activity relating to design, fabrication, assembly,

testing, delivery and integration of 60-watt converters. Significant aspects of these guidelines were

- Complete fabrication of PMC-1 converters and delivery to Westinghouse for integration with the rebuilt Experimental Mockup System
- Design, fabricate, assemble and deliver a Prototype Mockup Converter of final design configuration (PMC-2) to be integrated with the Westinghouse Prototype Mockup System. In addition to thermoelectric couple optimization, limited redesign is to be conducted in the hot side thermal-mechanical interface zone. This design is to be based upon test results from the detailed manufacturing experience documented during fabrication, assembly, delivery of PMC-1 and its integration into the system.
- Consideration of final assembly of a second PMC-1 converter, which would utilize residual piece-parts not applicable for the PMC-2 converter. This converter would be used for performance mapping activities and determination of long-term stability characteristics. This data will be considered in the design of the PMC-2.

2.2 LIAISON

Coordination and liaison activities were performed throughout the reporting period with Westinghouse Astronuclear Laboratory, 3M and Westinghouse liaison activities during the quarter were concerned with the following activities:

- Activities leading toward final resolution of the 60-watt converter-system interface drawing. This drawing, when issued would be effective for PMC-1.
- Westinghouse concurrence with the 252-couple PMC-1 design. The 3M thermoelectric characteristics, parameters, and performance predictions would form the basis for system performance predictions.

- 3M accepted as an objective, the achievement of a surface element straightness of 0.002 inch, for the PMC-1 hot frame and outer case interface zones. Agreement was reached on a 3M developed inspection program capable of documenting the critical interface parameters on PMC-1.
- Transmittal and action was completed relative to various detailed measurement data items during the fabrication and final assembly of PMC-1 converter. This activity consisted of interface inspection data relative to interface deviation and variable data recording.

2.3 DOCUMENTATION AND REPORTS

The following SNAP-23A reports were completed and transmitted to the Commission during this quarter.

- Design Review Presentation, dated 27 February 1968.
- April 1968 Monthly Report, No. MMM 3824-0021.
- PMC-1 Flow Plan and Design Engineering Drawings.
- May 1968 Monthly Report, No. MMM 3824-0022.

2.4 EFFORT PLANNED FOR NEXT QUARTER

- Initial Performance Verification of PMC-1 converter.
- Shipment of PMC-1 to Westinghouse for test integration.
- Assembly and processing of an additional PMC converter of the same design as PMC-1.
- Continuation testing and evaluation of devices on long-term test.

3.0 TASK II-CONVERTER DEVELOPMENT-60-WATT

3.1 EXPERIMENTAL MOCKUP CONVERTERS

Three Experimental Mockup Converters were completed under this program; one unit (EMC-1) was delivered to Westinghouse on January 9, 1968 for system integration, and two units (EMC-2 and EMC-3) remained at 3M for dynamic and long-term testing.

Dynamic testing of EMC-2 was successfully completed in the prior quarter. The only problem encountered was related to the heat source assembly of the test fixture (see paragraph 3.1.3.2 of Quarterly #5 - MMM 3824-0020). During this quarter the heat source was repaired by replacement of electrical heaters and converter EMC-2 was placed back in operation for long-term testing.

Prior to establishing the long-term test environment, EMC-2 was re-evaluated at EOL reference design conditions. The results of this and prior EOL design evaluations are listed in Table 3-1. The converter was then restabilized at BOL conditions for long-term testing; its BOL performance to date is presented in Table 3-2 and shown graphically in Figure 3-1. Initial and present EMC-2 experimental-to-theoretical performance ratios are presented in Table 3-3. Analysis of the EMC-2 data collected thus far indicates that:

- The thermoelectric components incurred no significant change in performance as a result of exposure to the dynamic test sequence. (See Table 3-2.)
- The pressure transducer appears to have suffered a loss of accuracy subsequent to dynamic testing, since during and immediately after dynamic testing it appeared to be indicating accurately.

Table 3-1. SNAP-23A EMC-2 Performance Data (End-of-Life Conditions)

Parameter	Units	Value		
		Initial Data	Re-evaluated at 508 hours Pre-dynamic test	Re-evaluated at 628 hours (Post-dynamic test)
Temperature -- Hot Junction	°F	901	898	904
Cold Junction	°F	173	172	176
Hot Frame	°F	931	926	934
Outer Case	°F	128	129	125
Open Circuit Voltage	Volts	41.1	42.4	42.9
Load Voltage	Volts	23.0	23.0	24.0
Load Current	Amps	2.50	2.50	2.38
Total Internal Resistance	Ohms	7.23	7.76	7.94
Power Output	Watts	57.6	57.6	57.1
Gross Power Input	Watts	860	880	888
Test Station Losses	Watts	32	32	32
Net Power Input	Watts	828	848	856
Efficiency	Percent	6.96	6.79	6.67
Internal Gas Pressure	PSIG	8.5	10.3	7.7

Table 3-2. SNAP-23A Converter EMC-2 Performance History (Beginning-of-Life Conditions)

Date	Test Hours	E, Volts	R _g , Ohms	P, Watts (e)	P _T , Watts (t)	T _c , °F	T _h , °F	P _g , psig
1-26-68	75.5	53.7	9.03	79.5	1104	191	1084	11.0
1-28-68	124.0	53.8	9.14	78.8	1108	191	1083	11.3
1-30-68	170.0	54.2	9.24	79.0	1112	191	1084	11.5
2-1-68	218.5	54.1	9.28	78.5	1112	191	1082	11.6
2-4-68	288.5	54.3	9.30	78.8	1116	191	1084	11.6
2-7-68	362.0	54.5	9.28	79.5	1116	190	1083	11.6
2-10-68	434	54.6	9.31	79.5	1120	189	1081	11.6
2-12-68	483	54.5	9.26	79.7	1120	190	1081	11.6
dynamic test and repair of heat source								
6-28-68	820	54.1	9.30	78.3	1132	189	1076	9.5

Key:

- E Instantaneous open circuit voltage
- R_g Internal resistance
- P Output power
- P_T Gross input power
- T_c Average cold electrode temperature
- T_h Average hot electrode temperature
- P_g Internal gas pressure

Figure 3-1. SNAP-23A Converter EMC-2 Beginning-of-Life Performance

Table 3-3. SNAP-23A Converter EMC-2 Performance Data
(Ratio of Experimental-to-Theoretical Values)

	Seebeck Ratio			Resistance Ratio*		
	EOL	BOL	Design	EOL	BOL	Design
Thermopile — Initial	1.02	1.01	1.00	1.16	1.10	1.068
— Re-evaluated	(1.06)	(1.03)		(1.28)	(1.17)	
Typical N-leg — Initial	1.00	0.99	1.00	0.97	0.93	1.068
— Re-evaluated	(1.02)	(1.00)		(0.95)	(0.91)	
Typical P-leg — Initial	1.04	1.03	1.00	1.34	1.28	1.068
— Re-evaluated	(1.12)	(1.06)		(1.61)	(1.45)	

*Theoretical resistance includes no extraneous resistance allowance.
() EOL re-evaluation at 628 test hours; BOL re-evaluation at 820 test hours.

Although the pressure reading has shifted, no continuous decrease in indicated pressure has occurred, hence no loss of hermetic seal is suspected.

- Recent electrical performance appears to be relatively stable (see Figure 3-1). However, P-leg resistance and Seebeck voltage have increased from their initial values (see Table 3-1).
- The primary cause of the slight decrease in converter efficiency with time appears to be the slight increase with time in the thermal input required by the converter, since the output power has remained relatively constant.

Long-term testing of converter EMC-3 was continued during the quarter. Converter performance at EOL reference design conditions was re-evaluated twice during the quarter. The results of these re-evaluations are presented in Table 3-4. EMC-3 BOL performance data is presented in Table 3-5 and shown graphically in Figure 3-2. Initial and present experimental-to-theoretical performance ratios are presented in Table 3-6. Analysis of the EMC-3 data collected thus far indicates that:

- Recent electrical performance appears to be relatively stable (see Figure 3-2), however, thermopile resistance has decreased significantly from its initial value with a resultant increase in output power.
- Converter efficiency has increased with time because the increase in output power has been proportionally larger than the increase in required thermal input.

Table 3-4. SNAP-23A Converter EMC-3 Performance Data (End-of-Life Conditions)

Parameter	Units	Value		
		Initial at 11.5 Hours	Re-evaluated at 1203 Hours	Re-evaluated at 2783 Hours
Temperature — Hot Junction	°F	900	903	899
Cold Junction	°F	172	172	174
Hot Frame	°F	928	931	925
Outer Case	°F	151	150	151
Open Circuit Voltage	Volts	40.7	41.5	41.3
Load Voltage	Volts	23.0	24.0	24.0
Load Current	Amps	2.66	2.72	2.77
Total Internal Resistance	Ohms	6.65	6.43	6.25
Power Output	Watts	61.2	65.3	66.5
Gross Power Input	Watts	852	888.0	892
Internal Gas Pressure	Psig	8.4	9.4	9.6
Net Power Input	Watts	820	895.5	863.5
Efficiency	Percent	7.46	7.60	7.70

Table 3.5 SNAP-23A Converter EMC-3 Performance History
(Beginning-of-Life Conditions)

Date	Test Hours	E, Volts	R _g , Ohms	P, Watts (e)	P _t Watts (t)	T _c , °F	T _h , °F	P _g , psig
2-20-68	123	54.1	8.27	88.0	1096	189	1080	10.4
2-23-68	198	53.9	8.17	88.3	1096	188	1075	10.6
2-27-68	296	53.6	8.10	88.3	1096	187	1070	10.8
3-2-68	392	53.6	8.15	87.8	1100	195	1074	10.9
3-6-68	489	53.4	8.00	88.8	1100	190	1067	11.0
3-10-68	585	53.8	8.05	89.5	1104	191	1073	11.0
3-14-68	681	53.7	8.04	89.3	1108	193	1074	11.2
3-19-68	804	54.0	7.92	91.5	1116	188	1073	11.0
3-26-68	968	54.2	8.01	91.2	1120	194	1079	11.1
4-1-68	1107	54.1	7.99	91.0	1120	195	1080	11.1
4-8-68	1276	54.1	8.06	90.3	1116	191	1078	11.1
4-19-68	1545	54.1	7.91	92.0	1120	192	1076	11.3
4-30-68	1800	53.9	7.90	91.5	1124	191	1074	11.0
5-15-68	2164	53.8	7.85	91.8	1124	190	1071	11.2
5-29-68	2497	53.7	7.79	92.1	1128	191	1070	10.9
6-13-68	2863	54.2	7.93	92.0	1128	190	1075	11.0
6-27-68	3190	54.1	7.91	92.0	1136	185	1070	10.9

Key:	E	Instantaneous open circuit voltage	T _c	Average cold electrode temperature
	R _g	Internal resistance	T _h	Average hot electrode temperature
	P	Output power	P _g	Internal gas pressure
	P _T	Gross input power		

Table 3-6. SNAP-23A Converter EMC-3 Performance Data
(Ratio of Experimental-to-Theoretical Values)

	Seebeck Ratio			Resistance Ratio*		
	EOL	BOL	Design	EOL	BOL	Design
Thermopile — Initial	0.98	0.98	1.00	1.09	1.07	1.068
— Re-evaluated	(0.99)			(1.03)		
Typical N-leg — Initial	1.01	1.00	1.00	1.05	1.01	1.068
— Re-evaluated	(1.01)			(1.00)		
Typical P-leg — Initial	0.96	0.97	1.00	1.13	1.13	1.068
— Re-evaluated	(0.96)			(1.05)		

() *Theoretical resistance includes no extraneous resistance allowance.
Re-evaluation after 2783 test hours.

Figure 3-2. SNAP-23A Converter EMC-3 Beginning-of-Life Performance versus Time

3.2 PROTOTYPE MOCKUP CONVERTER

3.2.1 DESIGN

3.2.1.1 Drawings and Bill of Materials

The balance of assembly and subassembly drawings for SNAP-23A Converter PMC-1 were released this quarter. The bill of materials for PMC-1 was also finalized with the approval of the 252-couple design. Along with the bill of materials, the thermopile product definition list was issued. With the release of these drawings and documents, all engineering documents were completed and submitted to the Commission.

Assembly drawings were revised from those of the EMC series for the following reasons (1) changes due to couple number revision from 264 to 252; (2) changes occurring by the establishment of new temperature sensing points and thermocouple routing, and (3) changes taking place as a result of the experience on the first three EMC converters.

Changes resulting from experience on the first three EMC's are:

- a. The removal of the pressure transducer, its receptacle, and tubing. In its place is an enlarged tubulation and a pressure gauge. This design provides a rugged, more reliable and less costly sensing device.
- b. The power output wire stress relief junction has been revised to incorporate provisions for potting the junction terminal in the event the system assembly and tests to be conducted by Westinghouse should require protection of the terminals. This change should improve the system reliability.
- c. The support wires which retain the leg compression springs of the thermopile assembly are of simplified design, reducing component complexity, assembly time, and yet maintaining the same degree of inherent reliability as the previous design.

- d. The routing of instrumentation wires to the headers and receptacles was changed to keep lead lengths to a minimum, thus reducing the complexity of the wire cable.
- e. The temperature sensing points inside the thermopile were changed to improve measurement of the temperature profile.
- f. A number of exterior thermocouples were removed or relocated by mutual agreement between 3M and Westinghouse.
- g. The procedure for attaching the exterior thermocouples to the converter was improved.
- h. Additional instructions pertaining to routing of instrumentation wires were specified on the applicable drawings.

3.2.1.2 Interface Drawing

Component drawings were originally released and parts fabricated on the basis of the 3M/Westinghouse interface drawing of 11 January 1968. At a subsequent interface meeting with Westinghouse on 3 April 1968, the interface dimensions were critically reviewed. This meeting resulted in a redefinition and revision of the dimensions on the interface drawing.

As a result of this revised interface drawing, a review of the prior released converter drawings and finished parts in stock, which were fabricated from these drawings, was conducted to determine their usability with the new interface. On the basis of this review, a report was submitted to Westinghouse giving data on the dimensions analyzed, location on the interface drawing, recommended change, and on alternate proposal were appropriate. Agreement was reached and a revised interface drawing was issued by Westinghouse. This drawing date of 22 May 1968, plus several additions received by TWX, identified the interface drawing for converter PMC-1.

Dimensions of piece parts affecting the interface of the converter with respect to the heat rejection system and the heat source were reinspected if: 1) additional variable data was required, 2) measurement of additional dimensions was required,

or 3) the dimension tolerance was decreased. Prior to this time fewer dimensions and lesser amount of variable data was specified on the interface drawing and a part was rejected or accepted based on the part tolerance, with no selection required on acceptable parts. Because of the revised interface drawing, the additional variable data and additional required dimensional measurements were evaluated by 3M, and a selection made of the most suitable hot frame, cold frame, and outer case to be used on PMC-1. This converter will be integrated with the SNAP-23A system. After completing this evaluation, all measurements on piece parts that would cause a deviation to the interface drawing were submitted to Westinghouse with a recommendation for disposition. Westinghouse concurred with all the recommendations and the parts were "used as deviated."

3.2.1.3 Interface Measurement Procedure

A Quality Control Measurement Procedure for variable data on the thermal-mechanical interface surfaces on sub and final assemblies for PMC-1 was prepared this quarter. This procedure was written to assure that adequate methods have been provided for taking thermal-mechanical interface dimensions called out on the interface drawing, and for the reporting of variable data to Westinghouse. These measurements will be taken and interpreted by 3M at various stages of assembly; if deviations are noted from the interface drawing, Westinghouse concurrence will be attained before fabrication continuation. Variable data will be forwarded to Westinghouse at the end of each inspection stage.

3.2.1.3.1 Shrink Fit Assembly

After completing the thermopile assembly, the outer case was shrunk fit over the thermopile assembly. After this operation, as an interface requirement, the thermal-mechanical interface data was taken according to the procedure by Quality Control and was forwarded to Engineering for interpretation. All interface thermal mechanical dimensions were met except for minor deviations in the outer case O.D. and the hot frame taper.

3.2.1.3.2 Hermetic Welding

After insulation packing, the support cone and lower cover were welded to the outer case. The thermal-mechanical interface data was again measured and

forwarded to Engineering for interpretation. Minor deviations were noted in the outer case O. D. and the hot frame taper and I. D. ; furthermore, it was noted that the hot frame dimensions that were out of tolerance after shrink fit were in tolerance, as expected, after hermetic welding.

3.2.1.3.3 Data

The variable raw data for measurements of interface dimensions after shrink fit and hermetic welding were submitted to Westinghouse. In addition any of the raw data dimensions that were out of tolerance were submitted to Westinghouse with a recommendation. In all cases the recommendation was to "use as deviated" to which Westinghouse concurred. This recommendation was made because the deviations are minor and may not exist after completion of processing and testing operations.

3.2.1.3.4 Additional Measurements

Additional measurements of the thermal-mechanical interface dimensions, and an evaluation and comparison of the variable raw data will be made at the end of the test cycle. This data likewise will be submitted to Westinghouse.

3.2.1.4 Design Analysis

Performance predictions for the prototype mockup converter PMC-1 were made and tabulated (see Table 3-7). These predictions are based on the following considerations:

a. Thermoelectric Material Characteristics:

Current material characteristics of S, K and P for separately pressed and bonded P legs and simultaneously pressed N legs as determined during the SNAP-23A Program.

b. Converter Shunt Heat Loss:

Converter shunt heat loss was calculated from K values determined by 3M for Min-K 1301 (powdered) compacted to specified density and backfilled with xenon gas. Close agreement between theoretical

and experimental values of total heat to the converter was obtained for EMC-1, EMC-2 and EMC-3. Although this does not directly verify 3M's K values for Min-K 1301, it does tend to confirm the predicted value for total heat to the converter which includes K for the thermoelectric legs and insulation.

c. Seebeck Voltage and Resistance Ratios

Nominal Seebeck voltage and resistance ratios were used to adjust Seebeck voltage and resistance calculated directly from material characteristics. The ratios were determined from an evaluation of SNAP-21 and SNAP-23A devices with simultaneously pressed N legs and/or bonded P legs. Quarterly Report No. 5 presents detailed information on derivation and application of the Seebeck voltage and resistance ratios.

Table 3-7. Performance Predictions for PMC-1

		<u>Units</u>
Seebeck Voltage	41.9 $\frac{+0.2}{-0.4}$	Volts
Load Voltage	24.4 $\frac{+0.2}{-0.4}$	Volts
Current	2.67 $\frac{+0.13}{-0.16}$	Amperes
Power Output	64.8 $\frac{+3.70}{-4.34}$	Watts (e)
Q input, total	819 $\frac{+11}{-12}$	Watts (th)
Q TE Legs	745	Watts (th)
Q Loss - Conv.	74	Watts (th)
Efficiency	7.91 $\frac{+0.34}{-0.42}$	Percent

3.2.1.5 Parametric Studies

Parametric studies were made to evaluate the thermoelectric performance of several SNAP-23A PMC designs for several conditions of junction temperature and for a range of normalized thermoelectric performance. The studies included an evaluation of the effects of hot junction temperature at end-of-life to allow an assessment of the overall SNAP-23A system efficiency. The performance improvement resulting from a possibly lower ΔT between the cold junction and the outer case through the use of BeO followers was studied. In addition the expected range in normalized thermoelectric performance as measured by Seebeck voltage and resistance ratio (*) observed in SNAP-21 and SNAP-23A units with simultaneously pressed N legs and separately pressed and bonded P legs included in SNAP-23A PMC evaluation.

Three thermopiles have been designed at end-of-life hot junction temperatures of 920, 900 and 880°F. The 920°F design (see paragraph 3.2.1.5.3 of Quarterly No. 5) was previously adopted as the SNAP-23A PMC design since it offers the highest thermopile efficiency and still meets the maximum BOL average temperature of 1080°F. The number of couples and leg geometries for the three designs are listed in Table 3-8.

Each of the three designs was required to produce a minimum of 60.25 watts under worst case Seebeck voltage and resistance conditions. In designing the thermopiles, the leg geometry was optimized for maximum efficiency under worst case normalized thermopile performance conditions and a load voltage of 24 volts. This design philosophy has the advantage of maximizing thermopile efficiency when it is most needed.

The performance of the 920°F design was evaluated at the extreme conditions of normalized thermopile performance (worst case and best case) and at the nominal condition. The results, Table 3-9, show the thermopile efficiency, power output

(*) The experimental Seebeck voltage and resistances were normalized by comparison to calculated values as determined from TELPS measured characterization data for the same junction temperatures. The calculated value for resistance did not include resistance extraneous to the thermoelectric legs.

Table 3-8. SNAP-23A PMC General Design Data Summary

				<u>Units</u>
T_h -	880	900	920	°F
T_c -	178	177	177	°F
Couples	270	260	252	
Diameter (N and P)	0.1875	0.1875	0.1875	inch
N Total Length	0.454	0.458	0.460	inch
N Cold Segment Length	0.159	0.160	0.161	inch
P Total Length	0.319	0.322	0.325	inch
P Cold Segment Length	0.137	0.132	0.127	inch

and load voltage at maximum efficiency under fixed hot and cold junction temperature. (*) Figure 3-3 shows the power output and thermopile efficiency variation with load voltage. The results illustrate that the load voltage at maximum efficiency remains within the PMC operating band of 24 ± 1 volt over the full range of expected Seebeck voltage and resistance ratios. Also shown is that the required heat input to maintain the 920°F hot junction temperature increases with improved T/E material performance. This means that with a constant power input, as is the case with an isotope fueled unit, the hot junction temperature would decrease at nominal and best case conditions and would not, therefore, exceed the BOL maximum of 1080°F.

(*) The cold junction temperature is such that the heat rejected is matched to the fin capability when the ΔT between the cold junction and the fin base is 30°F and when the Seebeck and resistance ratios are worst case.

Table 3-9. SNAP-23A PMC 920°F, 177°F EOL (Fixed Design at Worst Case)

MAXIMUM EFFICIENCY				
	<u>Worst</u>	<u>Nominal</u>	<u>Best</u>	<u>Unit</u>
Seebeck	41.5	41.9	42.1	Volts
Load Voltage	24	24.4	24.6	Volts
Load Current	2.51	2.67	2.80	Amps
Power Output	60.46	64.8	68.5	Watts
Q Input	807	819	830	Watts
Q Loss	74	74	74	Watts
Efficiency	7.49	7.91	8.25	Percent

BOL CONDITION

	<u>Worst</u>	
T_h	1080	°F
T_c	192	°F
Seebeck	52.4	Volts
Load Voltage	24	Volts
Power Output	78.5	Watts
Q Input	1032	Watts
Q Loss	100	Watts
Efficiency	7.59	Percent

The performance of the 900°F design was also evaluated for the range in expected Seebeck voltage and resistance ratios versus load voltage. The results, presented in Table 3-10 and Figure 3-4 show a slightly lower converter efficiency than for the 920°F design as would be expected for the lower ΔT . The load voltage at maximum efficiency, Table 3-10, remains in the 24 ± 1 volt operating band, and the heat required to maintain the hot junction temperature increases with improved T/E material performance.

The performance of the 880°F design for the same range in condition is shown in Table 3-11 and Figure 3-5. The comments made on the 900°F design apply.

The influence of various combinations of Seebeck voltage and resistance ratios was evaluated on the 920°F design. The performance results when nominal and best case Seebeck voltage combine with worst case resistance and when nominal and best case resistance combine with worst Seebeck voltage are presented in Table 3-12. The results show load voltage at maximum efficiency remain within 24 ± 1 volt for all conditions.

Table 3-13 illustrates how thermopile performance can be expected to react to a lower cold end ΔT . The condition selected was an assumed ΔT between the cold junction and fin base of 20°F rather than the present design value of 30°F. The thermopile performance results show that both hot and cold junction temperatures would decrease by 10°F and the power output and thermopile efficiency would increase.

3.2.2 FABRICATION AND ASSEMBLY

3.2.2.1 Summary

Thermoelectric couple drawings for the PMC-1 Converter were released to manufacturing on April 8, 1968, following AEC review and Westinghouse concurrence on the design.

The thermoelectric couple for PMC-1 consists of separately segmented and bonded P-legs and simultaneously pressed N-legs, which are similar to EMC-3 couples.

Table 3-10. SNAP-23A PMC 900°F, 177°F EOL
(Fixed Design at Worst Case)

MAXIMUM EFFICIENCY				
	<u>Worst</u>	<u>Nominal</u>	<u>Best</u>	<u>Units</u>
Seebeck	41.3	41.7	41.9	Volts
Maximum Load Voltage	24	24.4	24.5	Volts
Load Current	2.51	2.66	2.80	Amps
Power Output	60.3	64.6	68.4	Watts
Q Inputs	811.6	823	835	Watts
Q Loss	70.6	70.6	70.6	Watts
Efficiency	7.43	7.84	8.19	Percent

<u>BOL CONDITION</u>		
	<u>Worst</u>	<u>Units</u>
T_h	1055	°F
T_c	192	°F
Seebeck	52.3	Volts
Load Voltage	24	Volts
Power Output	78.7	Watts
Q Input	1038	Watts
Q Loss	95	Watts
Efficiency	7.58	Percent

Table 3-11. SNAP-23A PMC 880°F, 178°F EOL
(Fixed Design at Worst Case)

MAXIMUM EFFICIENCY				
	<u>Worst</u>	<u>Nominal</u>	<u>Best</u>	<u>Units</u>
Seebeck	41.39	41.80	42.0	Volts
Maximum Load Voltage	24	24.36	24.6	Volts
Load Current	2.53	2.67	2.79	Amps
Power Output	60.4	64.7	68.4	Watts
Q Input	821	833.8	844	Watts
Q Loss	67	67	67	Watts
Efficiency	7.35	7.76	8.10	Percent

BOL CONDITION

	<u>Worst</u>	<u>Units</u>
T_h	1030	°F
T_c	192	°F
Seebeck	52.4	Volts
Load Voltage	24	Volts
Power Output	79	Watts
Q Input	1050	Watts
Q Loss	91	Watts
Efficiency	7.52	Percent

Table 3-12. Effect of Influence Factors 177°F, 920°F
(Fixed Design at Worst Case)

SEEBECK VOLTAGE

<u>Condition</u>	<u>Worst Seebeck Worst Resistance</u>	<u>Nominal Seebeck Worst Resistance</u>	<u>Best Seebeck Worst Resistance</u>	<u>Units</u>
T_h	920	920	920	°F
T_c	177	177	177	°F
Seebeck	41. 5	41. 9	42. 1	Volts
Max. η Load Voltage	24	24 3	24. 4	Volts
Load Current	2. 51	2. 54	2. 55	Amps
Power Output	60. 46	61. 6	62. 1	Watts
Q Input	807	810	812	Watts
Q Loss	74	74	74	Watts
Efficiency	7. 49	7. 60	7. 65	Percent

RESISTANCE

<u>Condition</u>	<u>Worst Seebeck Worst Resistance</u>	<u>Worst Seebeck Nominal Resistance</u>	<u>Worst Seebeck Best Resistance</u>	<u>Units</u>
T_h	920	920	920	°F
T_c	177	177	177	°F
Seebeck	41. 5	41. 5	41. 5	Volts
Max. η Load Voltage	24	24. 1	24. 2	Volts
Load Current	2. 51	2. 65	2. 77	Amps
Power Output	60. 46	63. 7	66. 7	Watts
Q Input	807	817	825	Watts
Q Loss	74	74	74	Watts
Efficiency	7. 49	7. 80	8. 08	Percent

Table 3-13. Influence of Cold End ΔT Between Cold Junction and Fin Base
(Fixed Design at Worst Case)

<u>Condition</u>	<u>$\Delta T - 30^{\circ} F$</u>	<u>$\Delta T - 20^{\circ} F$</u>	<u>Units</u>
T_h	920	910	$^{\circ}F$
T_c	177	167	$^{\circ}F$
Seebeck	41.5	41.1	Volts
Max. η Load Voltage	24	23.8	Volts
Load Current	2.51	2.58	Amps
Power Output	60.46	61.0	Watts
Q Input	807	808	Watts
Q Loss	74	74	Watts
Efficiency	7.49	7.55	Percent

An acceptance yield of greater than 90% was achieved in fabrication and couple subassembly.

The converter was completed through assembly. Final processing with initial performance verification will occur early in the next quarter.

3.2.2.2 Weld Development

A weld development program was initiated late in the prior quarter. The purpose of this program was to:

- Improve the closure welds with respect to: design requirements, establishment of process controls (weld schedules) to obtain reproducibility, and quality assurance considerations.
- Provide a means of controlling the dimensional characteristics of the finished weld. These dimensions are critical relative to the converter-system interface, especially with respect to tolerances on the hot frame inside diameter.

Figure 3-3. SNAP-23A PMC Mapping $T_c = 177^\circ\text{F}$, $T_h = 920^\circ\text{F}$

Figure 3-4. SNAP-23A PMC Mapping $T_c = 177^\circ\text{F}$, $T_h = 900^\circ\text{F}$

Figure 3-5. SNAP-23A PMC Mapping $T_c = 178^\circ\text{F}$, $T_h = 880^\circ\text{F}$

This program was initially reported in Quarterly Report No. 5.

Hot frame weld samples were fabricated (see Figure 3-6) to simulate converter piece parts at the immediate weld zone with respect to material and dimensional configuration. These parts were welded together by utilizing a chill block (see Figure 3-6) to minimize shrinkage and weld "roll over." The copper chill block was fabricated with a 2° taper that would rest on the hot frame weld area. The largest diameter of the chill block was such that, with the nominal diameter of the hot frame, the chill block top edge would be approximately 1/8" above the hot frame lip. The minimum height that the top edge would be above the weld edge is 1/16" with the tolerances of the diameter of the hot frame at the lower end. A hole was drilled in the chill block to allow it to slip over the mandrel of the assembly fixture.

Figure 3-6. Weld Sample Assembly with Chill Block

It was observed that a minor reduction in diameter (roll-over) occurred in the weld plane, and that some distortion occurred due to internal stresses which were induced during the weld process.

Subsequent to this observation the weld samples were subjected to 1350°F for one hour using a simulated heat stud. This condition which simulates the operating temperature of the hot frame welds, may result in a dimensional change (stress relieving). Inspection after soaking for one hour at 1350°F indicated a minor change in dimension. Analysis of the inspection data for the hot frame weld indicates that this process will provide adequate control over the weld so that the revised interface tolerance of 0.025" can be satisfied.

The PMC-1 converter welds were made using the techniques and procedures established in the weld development program. Satisfactory welds were achieved, and final dimensions were within the tolerances.

3.2.2.3 Followers

Followers fabricated from beryllium oxide (BeO) material are used in PMC-1. This material is a replacement for hardcoated aluminum and was selected for several reasons:

- a) Superior electrical insulation characteristics to improve device reliability.
- b) Superior thermal characteristics
- c) Simplicity and potential advantages.

The use of BeO followers resulted in certain manufacturing procedural changes which are as follows:

- a) Cleaning and baking-out operations were required prior to use to remove moisture and contaminants.
- b) The elimination of heat transfer grease on the follower surfaces.

3.2.2.4 Converter Assembly

Manufacturing and inspection of all piece parts required for subassemblies were completed prior to 20 May 1968 at which date subassembly work began. This work consisted of fabricating the following assemblies; gas sampling, tubulation, tubulation filter, output couple, and instrumented hot junction button. After completion of these subassemblies the thermopile was assembled using BeO followers. The thermopile was assembled without incident and was completed by 6 June 1968, after which the outer case was "shrunk fit" over it. Min-K 1301 was packed into the converter, and the covers were welded to the outer case/hot frame (see Figures 3-7 and 3-8). The welding operation was successful, and all weld dimensional tolerance remained within specification. An acceptable hermetic seal was achieved. After completion of the welding operations the converter was prepared for processing.

3.2.2.5 Converter Processing

The PMC-1 converter was mounted on the Leak Detector Station (see Figure 3-9) subsequent to processing which began on 24 June 1968. During initial heat-up, it was necessary to make minor modification to the Process and Test Station (previously used for the EMC converters) in order to make it compatible to PMC-1. Processing continued without further incident.

3.3 TEST

The rough draft of the PMC-1 Test Plan and Procedure was completed. At the end of the period, the document was still undergoing final review.

Test personnel maintained close liaison with manufacturing during the processing of PMC-1 so that the transfer of the converter could be easily accomplished with respect to the reviewing of data and circuitry for associated test equipment.

3.4 PROCESS AND TEST STATION

The Process and Test Station design was reviewed and several minor changes were made to its assembly.

Figure 3-7. Welding Set-Up

Figure 3-8. Top View of Assembled Converter Showing Support Cone Weld

Figure 3-9. Assembled PMC-1 Converter on Leak Detector Station

3. 4. 1 TERMINAL BLOCK

The terminal block on the EMC-2 Process and Test Station overheated during operation. Consequently this block was relocated further away from the heat source, and additional thermal insulation was provided between it and the heat source. This was done on the EMC-2 and PMC-1 Process and Test Stations and will be effective for all subsequent units.

3. 4. 2 HEAT SIMULATOR

The design of the nickel bus bar and the boron nitride insulators was changed. The one piece bus bar was changed to two sections to reduce the I^2R heating effects, while the boron nitride insulators were subjected to a "bake out" process prior to use. The "bake out" process is expected to remove the majority of the moisture in the insulator. This will minimize the oxidation in this area.

These changes were made to reduce the localized over-temperature problems and oxidation that takes place at the heater terminals. These problems are most critical during the converter processing when the heat simulator is required to deliver its maximum power. The effectivity of these changes was the EMC-2 and subsequent Process and Test Stations.

3. 4. 3 INSTRUMENTATION

The thermocouple instrumentation arrangement for the PMC-1 converter was revised to reflect the change in the number of couples and in the temperature monitoring points. This change in the converter instrumentation arrangement required a corresponding change in the thermocouple readout panel. This effort was completed on the Process and Test Station for PMC-1.

3.5 QUALITY ASSURANCE

3. 5. 1 QUALITY CONTROL

The quality control effort for this quarter was devoted to thermoelectric couple inspection, development of a thermal-mechanical Interface Measurement Procedure, and inspection monitoring of the PMC-1 assembly and process operations.

3.5.1.1 Thermoelectric Couples

Inspection of all thermoelectric couples (instrumental and non-instrumental) for PMC-1 was completed during this quarter.

3.5.1.2 Thermal-Mechanical Interface Measurement

A quality control measurement procedure, for measuring the thermal-mechanical interface dimension on the converter was prepared and submitted to Westinghouse for concurrence. This procedure delineates the method both for measuring data, and the time during the assembly cycle when data should be recorded. Concurrence has been received from Westinghouse. As a result of this measurement procedure, a special mounting fixture was designed and fabricated. This fixture was designed to hold the converter after shrink fit and final welding of the outer case (see Figure 3-10).

The thermal-mechanical interface has been inspected and measured at three times in accordance with the procedure specified. These measurements occurred after:

- a) piece-part fabrication
- b) shrink fit of the outer case over the cold frame
- c) welding of the support cone and lower cover.

After each inspection and recording of the required variable data, Quality Control and Design analyzed the data for concurrence with the interface drawing. Any measurement found outside the dimensions specified on the interface drawing for PMC-1 received material Review Board action. These deviated measurements along with a recommendation were submitted to Westinghouse for concurrence. Concurrence and a recommendation from Westinghouse has been received for all deviations submitted on PMC-1.

The measurement data for each of the performed inspections was prepared and submitted to Westinghouse.

Figure 3-10. Inspection Set-Up for Thermal-Mechanical Interface Measurements

3.5.1.3 Inspection Monitoring

Inspection monitoring of the PMC-1 assembly and process was performed to assure high quality workmanship, and maintain up-to-date traceability of components.

3.5.2 RELIABILITY

The reliability effort for this period consisted of monitoring the PMC-1 assembly and inspection to assure that the inherent reliability was not compromised.

4.0 TASK III—THERMOELECTRIC COUPLE DEVELOPMENT

4.1 INTRODUCTION

The major objective of the thermoelectric couple development program is to identify and provide solutions for problem areas related to 10-year life thermoelectric leg stability. This effort is being conducted concurrently with the 60-watt converter development program through the three distinct approaches listed below.

- Post-test analysis of SNAP-23 converter and module.
- Bell jar testing to verify ingradient thermoelectric performance with respect to design objectives and specifications, and to qualify new concepts for long-term performance evaluation.
- 10-couple module testing for long-term performance evaluation of promising variables investigated in the bell jar tests.

The post-test analysis effort was concluded and reported in prior reports. All test effort conducted this quarter is reported in paragraph 4. 2.

4.2 TEST

4.2.1 BELL JAR TESTS

Bell jar test 5-19 was completed during the quarter. This test was an engineering evaluation to determine initial performance characteristics of Prototype Mockup Converter No. 1 couples. Performance results are summarized in Table 4-1. These results compare favorably with previous bell-jar evaluations of individually

segmented and bonded couples (refer to Quarterly Report No. 4), and they indicate improved performance characteristics when compared to bell-jar test 5-17 which evaluated EMC No. 3 couples (refer to Quarterly Report No. 5)

4.2.2 TEN-COUPLE MODULES TESTS

Long-term test of Modules 1 through 12 continued during the quarter.

Table 4-1. Bell Jar Test 5-19 Data

Operating Conditions	T_h °F	T_c °F	P-Leg		N-Leg	
			E_x/E_c	R_x/R_c	E_x/E_c	R_x/R_c^*
EOL	920	174	0.95	0.97	0.98	0.95
BOL	1080	185	0.96	0.96	0.97	0.96

Key:

T_h average hot junction temperature

T_c average cold junction temperature

E_x experimental Seebeck voltage

E_c theoretical Seebeck voltage

R_x experimental resistance

R_c theoretical resistance

* Theoretical resistance includes no allowance for extraneous resistance.

4.2.2.1 Modules 1 through 4

Plots of average performance ratios (experimental-to-theoretical values for Modules 1 through 4) are shown in Figures 4-1 through 4-12.

Analysis of the data for Modules 1 through 4 is summarized in Table 4-2.

To summarize the results very simply, use of bonded P-legs and Min-K 1301 thermal insulation yields significantly higher power output than their respective alternates (simultaneously pressed legs and microquartz insulation), with the difference between them becoming larger with time.

Table 4-2. SNAP-23A Ten-Couple Module Performance Analysis
(Modules 1 through 4)

Module	Legs	Comments
1	N	No significant degradation
	P	Power ratio up slightly on simultaneous pressed, down slightly on bonded (both due to resistance changes)
2	N	No significant degradation
	P	Considerable degradation on both types of P-leg with Min-K 1999 environment
3	N	Resistance up slightly, hence power down. Probable cause is lower contact pressure.
	P	Degradation is considerable and slight on simultaneous pressed and bonded respectively with microquartz environment.
4	N	Same as Mod 3 N-legs
	P	Same as Mod 2 P-legs except bonded leg degradation is not quite as advanced.

4.2.2.2 Modules 5 through 12

Statistical analyses of the data taken on 10-couple Modules 5 through 12 at their respective 1500-, 2000-, 2500-, and 3000-hour points were completed during the quarter. A general discussion of the test design and Yates analysis technique was presented in Quarterly Report No. 5; hence in this and subsequent reports the discussion will be concerned primarily with the results. Tables 4-3 through 4-8 present summaries of the N- and P-leg statistical analyses completed thus far.

Table 4-3. SNAP-23A N-Leg Statistical Analysis Summary – Seebeck Ratio

Effect	Effect Description	(+) Level	(-) Level
A	Leg Segmenting Technique	Simultaneous Press	Bonded
B	Hot Contact Material	Iron	Molybdenum
C	Hot Junction Temperature	1100° F	1000° F
D	Hot Contact Pressure	250 PSI	150 PSI
E	Thermal Insulation	Min-K 1301	Microquartz

Effect	Mean Effect and Test Hours							
	225	550	1000	1500	2000	2500	3000	3500
Average	1.01068	1.00739	1.01463	1.01709	1.01146	1.01343	1.01494	
A	0.00594	0.00271	0.00448	0.00375	-0.00208	0.00104	-0.00032	
B	0.00032	0.00271	-0.00239	-0.00125	0.00292	0.00104	0.00030	
C	0.00738	0.01250	0.00407	0.00291	0.00459	0.00209	0.00261	
D	-0.00032	-0.00625	0.00302	0.00625	-0.00126	0.00980	0.00448	
E	-0.01364	-0.01937	-0.00343	-0.00730	0.00771	-0.00250	-0.00406	
AB	0.00073	0.00229	0.00363	0.00417	0.00292	0.00436	0.00176	
AC	-0.00218	-0.00085	-0.00198	-0.00294	-0.00291	-0.00584	-0.00677	
AD	-0.00781	-0.00375	-0.00136	-0.00250	-0.00083	-0.00105	-0.00364	
AE	0.00219	-0.00020	0.00177	0.00188	0.00313	-0.00000	0.00115	
BC	-0.00656	-0.00710	-0.00011	0.00044	-0.00041	0.00291	0.00260	
BD	0.00407	0.00250	-0.00073	0.00000	-0.00083	-0.00105	-0.00051	
BE	0.00157	0.00520	0.00114	0.00313	-0.00062	0.00125	0.00052	
CD	0.00323	0.00646	0.00531	0.00291	0.00542	0.00375	0.00470	
CE	0.00906	0.01541	0.00343	0.00729	0.00603	0.01063	0.00824	
DE	-0.00197	-0.00334	0.00052	-0.00812	-0.00312	-0.00291	-0.00323	
ABC	-0.00199	-0.00125	-0.00031	-0.00209	0.00209	0.00584	0.00324	
ABD	0.00406	0.00000	0.00239	-0.00125	0.00124	0.00230	0.00135	
ABE	-0.00177	-0.00187	-0.00281	-0.00355	-0.00354	-0.00375	-0.00094	
ACD	0.00239	0.00354	0.00136	0.00209	-0.00001	0.00250	-0.00094	
ACE	0.00239	0.00041	0.00156	0.00104	-0.00019	-0.00228	-0.00072	
ADE	-0.00906	-0.00834	-0.00407	-0.00312	-0.01062	-0.01209	-0.00676	
BCD	0.00052	-0.00646	0.00073	-0.00041	0.00249	-0.00125	0.00094	
BCE	-0.00198	-0.00334	-0.00282	-0.00521	-0.00144	0.00022	-0.00010	
BDE	0.00282	0.00541	-0.00219	-0.00188	0.00563	0.00416	0.00261	
CDE	-0.00759	-0.00270	-0.00698	-0.00396	-0.00979	-0.01271	-0.01177	
ABCD	-0.00114	-0.00104	-0.00407	-0.00209	0.00042	-0.00000	0.00032	
ABCE	-0.00282	0.00166	-0.00219	0.00104	0.00228	-0.00187	0.00261	
ABDE	0.00491	0.00041	0.00511	0.00562	0.00313	0.00584	0.00740	
ACDE	0.00032	0.00187	-0.00261	-0.00104	-0.00229	-0.00229	-0.00114	
BCDE	-0.00156	-0.00812	-0.00052	0.00021	0.00146	0.00271	-0.00051	
ABCDE	0.00053	-0.00020	-0.00261	-0.00271	-0.00104	0.00229	0.00010	

Table 4-4. SNAP-23A N-Leg Statistical Analysis Summary – Resistance Ratio

Effect	Effect Description		Level	
			(+) Level	(-) Level
A	Leg Segmenting Technique		Simultaneous Press	Bonded
B	Hot Contact Material		Iron	Molybdenum
C	Hot Junction Temperature		1100°F	1000°F
D	Hot Contact Pressure		250 PSI	150 PSI
E	Thermal Insulation		Min-K 1301	Microquartz

Effect	Mean Effect and Test Hours							
	225	550	1000	1500	2000	2500	3000	3500
Average	1.00006	0.99396	0.99990	0.99985	0.99041	1.00604	1.01677	
A	0.00926	0.02105	0.01813	0.01447	0.01062	0.01292	0.01416	
B	0.01739	0.01480	0.00688	0.00509	0.01812	0.01417	0.01416	
C	0.00926	-0.01229	-0.02394	-0.02614	-0.01146	-0.02084	-0.00584	
D	0.01199	-0.02125	-0.01646	-0.01864	-0.01978	-0.03353	-0.03041	
E	-0.02197	-0.03750	-0.03481	-0.01969	-0.02042	-0.04042	-0.05750	
AB	-0.00426	-0.00709	-0.00354	-0.00093	0.00208	0.00083	0.00229	
AC	0.01469	0.00917	0.00021	0.00823	-0.00249	-0.00751	-0.00771	
AD	0.00614	0.00396	0.01146	0.01656	0.00833	0.01063	0.00979	
AE	0.01052	-0.00521	-0.00271	0.00303	0.00687	-0.00208	0.00230	
BC	-0.02969	-0.02082	-0.00396	0.00636	-0.00124	0.00374	0.00854	
BD	-0.00449	0.00521	-0.00729	-0.00782	-0.00542	-0.01187	-0.00396	
BE	-0.01135	0.00854	-0.00604	-0.00259	-0.00563	-0.00083	-0.00895	
CD	-0.00844	0.01770	-0.00396	-0.00906	-0.01709	-0.00563	-0.01189	
CE	-0.00115	0.01770	0.00646	-0.00886	-0.01021	0.01748	0.00352	
DE	-0.02678	-0.01916	-0.01396	-0.01968	-0.01438	-0.00063	-0.00687	
ABC	-0.02011	-0.00604	-0.01019	-0.00677	-0.01146	0.00291	-0.00584	
ABD	0.01386	0.00817	0.00729	0.00823	0.00522	0.01147	0.01209	
ABE	-0.00635	-0.00750	-0.00856	-0.00407	-0.00917	-0.00667	0.00000	
ACD	-0.01136	-0.00291	-0.00688	-0.01011	-0.01146	-0.00312	-0.01084	
ACE	0.00427	0.00751	0.00772	-0.00073	0.00126	0.00167	0.00167	
ADE	-0.02177	-0.00980	-0.01022	-0.01073	-0.02207	-0.02647	-0.02000	
BCD	0.01801	-0.00541	0.00187	-0.00448	0.00354	-0.00062	0.00416	
BCE	0.00490	-0.00999	-0.00853	-0.01386	-0.00749	0.00292	-0.00082	
BDE	0.01760	0.00645	-0.00103	0.00364	0.01418	0.01353	0.00750	
CDE	0.00947	0.00439	-0.01104	-0.00842	-0.00249	-0.01271	-0.01625	
ABCD	0.00094	-0.00605	-0.00729	-0.01468	0.00166	-0.00563	0.00436	
ABCL	0.00448	0.00645	0.00229	-0.00323	0.00979	-0.00377	0.00977	
ABDE	0.01010	-0.00084	0.00979	0.01344	0.01062	0.00687	0.01187	
ACDE	0.02905	0.01543	0.01229	0.01178	0.00564	0.00146	0.00563	
BCDE	-0.01657	-0.01458	-0.00104	0.01116	0.01064	0.01146	0.00438	
ABCDE	-0.00115	0.00314	-0.00229	0.00221	-0.00374	0.00479	0.00375	

Table 4-5. SNAP-23A N-Leg Statistical Analysis Summary – Power Ratio

Effect	Effect Description		Mean Effect and Test Hours		(+) Level	(-) Level
A	Leg Segmenting Technique				Simultaneous Press	Bonded
B	Hot Contact Material				Iron	Molybdenum
C	Hot Junction Temperature				1100° F	1000° F
D	Hot Contact Pressure				250 PSI	150 PSI
E	Thermal Insulation				Min-K 1301	Microquartz

Effect	Mean Effect and Test Hours							
	225	550	1000	1500	2000	2500	3000	3500
Average	1.02371	1.02252	1.03090	1.03678	1.03432	1.02267	1.01503	
A	0.00421	-0.01736	-0.01001	-0.00689	-0.01531	-0.01149	-0.01519	
B	-0.01884	-0.01018	-0.01173	-0.00691	-0.01306	-0.01196	-0.01327	
C	0.00259	0.03668	0.03253	0.03227	0.02201	0.02549	0.01200	
D	-0.01480	0.00941	0.02361	0.03098	0.01843	0.05399	0.03985	
E	-0.00771	-0.00021	0.02902	0.00591	0.03717	0.03566	0.04931	
AB	0.00461	0.01287	0.00419	0.01044	0.00394	0.00774	0.00085	
AC	-0.02116	-0.01084	-0.00434	-0.01536	-0.00392	-0.00413	-0.00578	
AD	-0.02302	-0.01129	-0.01419	-0.02329	-0.00982	-0.01218	-0.01630	
AE	-0.00781	0.00509	0.00019	0.00053	-0.00111	0.00233	-0.00011	
BC	0.01861	0.00731	0.00383	-0.00782	0.00071	0.00148	-0.00366	
BD	0.01410	-0.00084	0.00591	0.00692	0.00341	0.00898	0.00209	
BE	0.01546	0.00092	0.00802	0.00894	0.00347	0.00147	0.00842	
CD	0.01708	-0.00513	0.00742	0.01729	0.02912	0.01436	0.02176	
CE	0.02189	0.01293	0.00128	0.02414	0.02353	0.00479	0.01375	
DE	0.02582	0.01391	0.01408	0.00498	0.00973	-0.00341	0.00253	
ABC	0.01786	0.00828	0.00998	0.00316	0.01583	0.00898	0.01144	
ABD	-0.00462	-0.00824	-0.00287	-0.01156	-0.00274	-0.00697	-0.00959	
ABE	0.00406	0.00417	-0.00287	-0.00273	0.00224	-0.00063	-0.00248	
ACD	0.01660	0.00934	0.00839	0.01379	0.01144	0.00733	0.00849	
ACE	0.00189	-0.00664	-0.00502	-0.00139	-0.00122	-0.00618	-0.00275	
ADE	0.00510	-0.00794	-0.00136	0.00383	0.00106	0.00212	0.00575	
BCD	-0.01860	-0.00703	-0.00051	0.00371	0.00014	-0.00248	-0.00332	
BCE	-0.00968	-0.00441	0.00366	0.00281	0.00413	-0.00302	-0.00001	
BDE	-0.01420	0.00356	-0.00524	-0.00803	-0.00339	-0.00512	-0.00194	
CDE	-0.02732	-0.01033	-0.00213	0.00222	-0.01593	-0.01227	-0.00581	
ABCD	-0.00443	0.00349	-0.00041	0.01101	-0.00053	0.00582	-0.00372	
ABCE	-0.01131	-0.00347	-0.00187	0.00436	-0.00527	-0.00007	-0.00469	
ABDE	-0.00238	0.00021	0.00019	-0.00308	-0.00547	0.00403	0.00151	
ACDE	-0.03035	-0.01156	-0.01788	-0.01366	-0.01063	-0.00554	-0.00746	
BCDE	0.01567	0.00063	0.00027	-0.00967	-0.00751	-0.00661	-0.00535	
ABCDE	0.00405	-0.00411	0.00241	-0.00624	0.00189	0.00034	-0.00397	

Table 4-6. SNAP-23A P-Leg Statistical Analysis Summary – Seebeck Ratio

Effect	Effect Description		Level	
A	Leg Segmenting Technique		Simultaneous Press	Bonded
B	Hot Contact Material		Iron	Molybdenum
C	Hot Junction Temperature		1100° F	1000° F
D	Hot Contact Pressure		250 PSI	150 PSI
E	Thermal Insulation		Min-K 1301	Microquartz
F	Contact Type		Hard Nose	Soft Nose

Effect	Mean Effect and Test Hours							
	225	550	1000	1500	2000	2500	3000	3500
Average	0.96523	0.96859	0.97758	0.98531	0.98234	0.98609	0.98351	
A	0.10359	0.11875	0.13234	0.13594	0.14187	0.14625	0.14703	
B	0.00797	0.00313	0.00797	0.00594	0.00875	0.00625	0.00831	
C	0.01078	0.02062	0.01328	0.01969	0.01531	0.01281	0.01297	
D	-0.00109	-0.00562	0.00203	0.00063	-0.00313	0.00469	-0.00109	
E	0.00797	0.01406	0.03547	0.02812	0.05094	0.04219	0.04078	
F	0.00234	0.01000	0.00109	0.00469	0.00125	0.00375	0.00516	
AB	-0.00391	0.00031	0.00047	-0.00188	0.00031	0.00031	0.00141	
AC	0.00078	-0.00594	0.00391	-0.00438	-0.01062	-0.01063	-0.01203	
AD	0.00141	-0.00031	-0.00016	-0.00094	0.00219	0.00187	0.00047	
AE	-0.01141	-0.00750	-0.00359	-0.00531	-0.00375	0.00563	-0.00547	
AF	0.01547	0.01344	0.00766	0.00688	0.00281	0.00469	0.00641	
BC	-0.00109	0.00094	0.00047	0.00062	0.00250	0.00063	0.00234	
BD	-0.00172	-0.00344	0.00203	0.00094	-0.00469	-0.00687	0.00734	
BE	-0.00328	-0.00188	-0.00422	-0.00281	-0.00313	0.00062	-0.00359	
BF	0.00109	0.00156	0.00078	0.00187	0.00344	0.00344	0.00078	
CD	-0.00016	-0.00031	-0.00109	0.00719	0.00250	-0.00344	-0.00141	
CE	0.00078	0.00687	0.00109	0.00594	0.00219	0.00469	-0.00016	
CF	-0.00172	-0.00969	-0.00766	-0.00812	-0.00750	-0.00563	-0.00516	
DE	0.00203	-0.00063	0.00484	-0.00625	-0.00250	-0.00156	0.00422	
DI	0.00266	0.00969	0.00609	0.00531	0.00906	0.00562	0.00641	
EI	0.00484	0.01750	0.01016	0.00844	0.01063	0.00937	0.01016	
ABC	0.00016	-0.00125	0.00141	-0.00031	0.00469	0.00156	0.00484	
ABD	0.00453	0.00500	0.00391	0.00312	0.00375	0.00594	0.00453	
ABE	0.00234	0.00594	-0.00141	-0.00437	-0.00719	-0.00156	-0.00484	
ABF	0.00422	-0.00062	0.00047	-0.00094	-0.00188	-0.00250	-0.00297	
ACD	0.00047	0.00187	-0.00016	-0.00062	-0.00031	0.00125	0.00172	
ACE	-0.00047	0.00219	0.00016	0.00187	0.00062	0.00062	-0.00016	
ACF	0.00203	0.00187	0.00078	0.00094	-0.00031	0.00031	-0.00391	
ADE	-0.00297	-0.00344	-0.00359	-0.00531	-0.00531	0.00500	-0.00484	
ADF	0.00641	0.00438	0.00203	0.00187	0.00250	0.00094	0.00203	
AEF	-0.00703	-0.00594	0.00953	-0.01062	-0.00594	-0.00781	0.00984	

Table 4-6. SNAP-23A P-Leg Statistical Analysis Summary – Seebeck Ratio (Continued)

Effect	Mean Effect and Test Hours							
	225	500	1000	1500	2000	2500	3000	3500
BCD	0, 00109	-0, 00125	-0, 00078	-0, 00313	-0, 00094	-0, 00125	-0, 00016	
BCE	0, 00141	0, 00031	0, 00078	0, 00062	0, 00000	0, 00188	0, 00422	
BCF	-0, 00609	-0, 00500	-0, 00234	-0, 00031	-0, 00094	-0, 00219	0, 00047	
BDE	-0, 00234	0, 00219	0, 00328	0, 00469	0, 00656	0, 00500	0, 00828	
BDF	-0, 00797	-0, 00750	-0, 00484	-0, 00687	-0, 00313	-0, 00656	-0, 00734	
BEF	0, 00234	-0, 00156	-0, 00266	-0, 00187	-0, 00156	-0, 00281	-0, 00047	
CDE	0, 00547	0, 00781	0, 00422	0, 00094	-0, 00000	0, 00094	-0, 00141	
CDI	0, 00297	-0, 00562	0, 00109	-0, 00187	-0, 00219	-0, 00250	-0, 00516	
CEF	0, 00203	-0, 00781	0, 00141	0, 00062	0, 00375	0, 00188	0, 00422	
DEF	0, 00078	0, 00781	0, 00266	0, 00344	0, 00156	0, 00125	0, 00203	
ABCD	-0, 00078	-0, 00219	-0, 00297	0, 00031	-0, 00187	-0, 00094	-0, 00078	
ABCE	-0, 00109	-0, 00625	-0, 00453	-0, 00406	-0, 00469	-0, 00281	0, 00328	
ABCF	0, 00641	0, 00719	0, 00547	0, 00313	0, 00563	0, 00187	0, 00172	
ABDE	-0, 00359	-0, 00375	-0, 00453	-0, 00625	-0, 00438	-0, 00406	-0, 00359	
ABDF	0, 01203	0, 00906	0, 01047	0, 01156	0, 00969	0, 01062	0, 00953	
ABEF	0, 00047	0, 00062	0, 00328	0, 00469	0, 00375	0, 00188	0, 00203	
ACDE	0, 00234	0, 00188	0, 00141	-0, 00125	0, 00281	0, 00250	0, 00172	
ACDF	-0, 00391	-0, 00281	0, 00141	-0, 00094	-0, 00313	-0, 00219	0, 00203	
ACEF	-0, 00047	-0, 00313	0, 00109	-0, 00031	0, 00156	-0, 00031	0, 00297	
ADLF	-0, 00547	-0, 00438	-0, 00266	-0, 00250	-0, 00188	-0, 00281	0, 00141	
BCDE	0, 00172	0, 00250	0, 00203	-0, 00125	-0, 00156	-0, 00125	-0, 00016	
BCDF	-0, 00203	-0, 00219	0, 00078	0, 00031	0, 00000	-0, 00094	0, 00109	
BCEF	-0, 00016	-0, 00375	-0, 00078	-0, 00094	-0, 00281	-0, 00156	-0, 00266	
BDEF	-0, 00109	0, 00250	0, 00422	0, 00375	0, 00125	0, 00344	0, 00203	
CDEF	-0, 00016	-0, 00437	0, 00266	0, 00250	0, 00594	0, 00625	0, 00484	
ABCDE	-0, 00141	-0, 00281	-0, 00141	-0, 00094	-0, 00062	-0, 00031	-0, 00078	
ABCDF	-0, 00141	0, 00375	0, 00172	0, 00187	-0, 00031	0, 00125	0, 00047	
ABCEF	-0, 00109	0, 00281	0, 00078	-0, 00312	-0, 00937	-0, 00687	-0, 00891	
ABDEF	-0, 00109	-0, 00656	-0, 00422	-0, 00281	-0, 00656	-0, 00250	-0, 00484	
ACDEF	-0, 00078	-0, 00344	-0, 00078	0, 00219	-0, 00062	-0, 00031	0, 00047	
BCDEF	-0, 00016	0, 00094	-0, 00016	-0, 00156	-0, 00125	-0, 00531	-0, 00141	
ABCDEF	0, 00422	0, 00625	0, 00453	0, 00375	0, 00156	0, 00125	0, 00047	

Table 4-7. SNAP-23A P-Leg Statistical Analysis Summary – Resistance Ratio

Effect	Effect Description		Level	
	Effect Description		(+) Level	(-) Level
A	Leg Segmenting Technique		Simultaneous Press	Bonded
B	Hot Contact Material		Iron	Molybdenum
C	Hot Junction Temperature		1100° F	1000° F
D	Hot Contact Pressure		250 PSI	150 PSI
E	Thermal Insulation		Min-K 1301	Microquartz
F	Contact Type		Hard Nose	Soft Nose

Effect	Mean Effect and Test Hours							
	225	550	1000	1500	2000	2500	3000	3500
Average	1.17515	1.21633	1.24789	1.26094	1.27156	1.28750	1.29047	
A	0.42344	0.53609	0.63766	0.66625	0.69062	0.70375	0.70094	
B	-0.07219	-0.07016	-0.06984	-0.08312	-0.07437	-0.06938	-0.07156	
C	0.01344	-0.00703	-0.05047	-0.06250	-0.07375	-0.08750	-0.07469	
D	-0.11219	-0.13234	-0.11078	-0.11813	-0.08594	-0.09750	-0.08031	
E	-0.18000	-0.21703	-0.23109	-0.26094	-0.25375	-0.29219	-0.31313	
F	0.13156	0.14422	0.11953	0.13063	0.09625	0.09813	0.08406	
AB	-0.01531	-0.01359	-0.02422	-0.03625	-0.03687	-0.03688	-0.03906	
AC	0.04031	0.02641	0.00328	-0.01063	-0.02375	-0.03813	-0.04156	
AD	-0.00844	-0.02391	-0.04766	-0.05438	-0.05094	-0.05563	-0.06156	
AE	-0.04875	-0.06047	-0.12422	-0.15594	-0.17188	-0.19031	-0.19937	
AF	-0.00656	-0.00047	-0.00109	0.01625	-0.02250	-0.00937	-0.00969	
BC	0.02344	0.03391	0.04703	0.06000	0.05750	0.05750	0.05219	
BD	0.01844	0.01609	0.02109	0.03375	0.01031	0.00625	0.00094	
BE	0.01437	0.02328	0.02703	0.04844	0.03688	0.03781	0.02687	
BF	-0.07219	-0.06047	-0.06734	-0.08312	-0.04125	-0.04375	-0.04594	
CD	0.01344	0.02484	0.00609	0.01125	-0.00531	-0.00687	-0.00656	
CE	-0.02063	-0.01359	-0.00359	0.00906	-0.00250	0.01906	0.01375	
CF	-0.01906	-0.05797	-0.06234	-0.08625	-0.07312	-0.08375	-0.08344	
DE	-0.00312	-0.01266	-0.00391	-0.00031	-0.02219	-0.00594	-0.02875	
DF	-0.02906	-0.00703	-0.00453	-0.00875	0.02594	0.01500	0.02406	
EF	-0.06812	-0.07109	-0.09109	-0.10531	-0.08500	-0.09594	-0.07500	
ABC	0.00156	-0.02203	-0.00672	0.00438	0.00750	-0.00062	0.00156	
ABD	0.01719	0.03016	0.04047	0.05375	0.04781	0.05812	0.05219	
ABE	-0.00188	-0.00422	0.00516	0.02719	0.01000	0.01719	0.02312	
ABF	0.01844	0.01422	0.01078	-0.01500	0.01000	0.00500	0.00281	
ACD	-0.01031	-0.00172	0.00859	0.01625	0.01094	0.01437	0.01281	
ACE	-0.01438	-0.04078	-0.03734	-0.03344	-0.05187	-0.05219	-0.04937	
ACF	0.05156	0.03484	0.03766	0.02437	0.04812	0.04063	0.03969	
ADE	-0.04875	-0.05234	-0.02578	-0.00719	-0.01156	-0.01094	-0.00250	
ADF	0.06469	0.06328	0.04609	-0.01750	0.02719	0.01687	0.01156	
AEF	0.01312	0.01109	0.00328	-0.00781	0.01188	-0.00406	-0.00250	

Table 4-7. SNAP-23A P-Leg Statistical Analysis Summary – Resistance Ratio (Continued)

Effect	Mean Effect and Test Hours						
	225	550	1000	1500	2000	2500	3000
BCD	0.01031	0.02703	0.01609	-0.00062	0.01344	0.01750	0.01906
BCE	0.01750	-0.01078	-0.01984	-0.04656	-0.04437	-0.04531	-0.04438
BCF	-0.00281	-0.01141	0.02266	0.04750	0.03313	0.03500	0.02219
BDE	0.00187	0.01016	0.00172	-0.01281	0.01094	0.00219	0.00875
BDF	-0.00094	-0.01797	-0.01391	-0.00188	-0.02031	-0.03250	-0.03219
BEF	0.03625	0.03609	0.03828	0.04906	0.03438	0.03531	0.03750
CDE	0.02125	0.02891	0.01297	-0.02031	0.02406	0.00844	0.01000
CDF	0.01906	0.01016	0.02922	0.04188	0.01781	0.02500	0.01594
CEF	-0.00125	-0.01391	0.02828	0.04469	0.05000	0.06719	0.06000
DEF	0.01313	0.03078	0.01109	0.01469	-0.01344	-0.00031	-0.00813
ABCD	-0.01844	-0.02141	-0.01641	-0.02187	-0.02531	-0.02500	-0.02031
ABCE	-0.02375	-0.00359	-0.01859	-0.03031	-0.02000	-0.01281	-0.01625
ABCF	0.01906	0.01828	0.02266	0.03063	0.01937	0.01687	0.00906
ABDE	-0.02500	-0.02016	-0.04141	-0.06469	-0.04719	-0.04906	-0.05000
ABDF	0.01031	-0.00078	0.02297	0.04312	0.03344	0.03937	0.03281
ABEF	-0.01750	-0.02359	-0.00609	0.01281	-0.00000	0.00469	0.00250
ACDE	0.01187	-0.00547	-0.00953	-0.02594	-0.01281	-0.01844	-0.02062
ACDF	-0.01219	0.01297	0.02797	-0.04938	0.03031	0.04500	0.03281
ACEF	-0.03250	-0.04547	-0.03922	-0.04281	-0.04937	-0.04531	-0.04562
ADEF	-0.01125	-0.00578	0.01172	0.02906	0.02719	0.03094	0.03688
BCDE	-0.05375	-0.05578	-0.04828	-0.02906	-0.04656	-0.03906	-0.03812
BCDF	0.00844	0.02547	0.01672	-0.00750	0.00656	-0.00312	0.00531
BCEF	0.01188	0.01078	-0.01297	-0.02594	-0.03063	-0.03719	-0.02938
BDEF	0.01187	0.01547	0.01297	0.00344	0.01844	0.02531	0.02438
CDEF	-0.01125	-0.02641	-0.02016	-0.03656	-0.00969	-0.02281	-0.01375
ABCDE	0.05312	0.03516	0.04672	0.06281	0.04281	0.03656	0.03500
ABCDF	-0.02531	-0.02234	-0.03703	-0.04875	-0.03594	-0.03937	-0.04406
ABCEF	-0.07437	-0.04766	-0.05297	-0.06219	-0.04875	-0.04844	-0.03625
ABDEF	-0.01375	-0.02797	-0.03266	-0.05719	-0.04719	-0.04219	-0.04562
ACDEF	-0.01438	-0.02672	-0.04641	-0.04594	-0.04906	-0.05219	-0.04688
BCDEF	0.00500	0.00078	0.01359	0.02344	0.00844	0.00844	0.00937
ABCDEF	0.07312	0.07359	0.07234	0.07656	0.05281	0.05156	0.04750

Table 4-8. SNAP-23A P-Leg Statistical Analysis Summary – Power Ratio

Effect	Effect Description			(+) Level		(-) Level		
A B C D E F	Leg Segmenting Technique Hot Contact Material Hot Junction Temperature Hot Contact Pressure Thermal Insulation Contact Type			Simultaneous Press Iron 1100° F 250 PSI Min-K 1301 Hard Nose		Bonded Molybdenum 1000° F 150 PSI Microquartz Soft Nose		

Effect	Mean Effect and Test Hours							
	225	550	1000	1500	2000	2500	3000	3500
Average	0.82432	0.81254	0.81605	0.82458	0.81400	0.81180	0.80455	
A	-0.13442	-0.17407	-0.20447	-0.21094	-0.20996	-0.20263	-0.19363	
B	0.05440	0.04085	0.04431	0.04543	0.04373	0.03673	0.04278	
C	0.01008	0.04031	0.05134	0.06280	0.06335	0.06325	0.05452	
D	0.06880	0.07686	0.07183	0.07230	0.05075	0.06876	0.04855	
E	0.12697	0.15329	0.17946	0.17769	0.20343	0.20863	0.22022	
F	-0.07978	-0.07161	-0.06593	-0.05964	-0.05329	-0.04428	-0.03474	
AB	-0.00247	0.00031	0.00151	-0.00200	0.00857	0.00753	0.00972	
AC	-0.02022	-0.02438	-0.01263	-0.00872	-0.00565	0.00118	0.00438	
AD	0.00098	-0.00215	0.00715	0.00143	0.01175	0.00837	0.01505	
AE	-0.00844	-0.00765	0.02277	0.03208	0.04322	0.04550	0.04550	
AF	0.04397	0.03986	0.03418	0.02812	0.03749	0.03180	0.02980	
BC	-0.02240	-0.02809	-0.02957	-0.02855	-0.02298	-0.02662	-0.01936	
BD	-0.00822	-0.01099	-0.01024	-0.01181	-0.00925	-0.00685	-0.00618	
BE	-0.00827	-0.01046	-0.01062	-0.01369	-0.00909	-0.00280	0.00189	
BF	0.05025	0.04147	0.04285	0.03972	0.02723	0.02817	0.02440	
CD	-0.00860	-0.01888	-0.00045	-0.00618	0.00908	0.00458	0.00344	
CE	0.01555	0.01794	0.01000	0.01775	0.01509	0.00729	0.00147	
CF	0.01689	0.02622	0.02862	0.03721	0.03726	0.04146	0.04482	
DE	0.01266	0.01386	0.01797	0.00408	0.01454	0.00944	0.02083	
DF	0.02260	0.02159	0.01850	0.01046	0.00615	0.00307	0.00017	
EF	0.04377	0.06121	0.06518	0.06883	0.06470	0.06386	0.05347	
ABC	0.00775	0.02501	0.02154	0.01577	0.01575	0.01786	0.01852	
ABD	-0.00289	-0.00684	-0.00677	-0.00857	-0.00807	-0.01028	-0.00952	
ABE	0.00742	0.00999	0.00203	-0.00895	-0.00760	-0.00343	-0.01348	
ABF	-0.01415	-0.01637	-0.01853	-0.00727	-0.01499	-0.01576	-0.01310	
ACD	0.00646	0.01045	-0.00000	0.00137	-0.00067	0.00237	0.00435	
ACE	-0.00127	0.01746	0.01795	0.02258	0.02870	0.03425	0.03450	
ACF	-0.03022	-0.01965	-0.02766	-0.02742	-0.03815	-0.03583	-0.04008	
ADE	0.02636	0.02667	0.01766	0.01195	0.01000	0.01540	0.00472	
ADF	-0.03454	-0.03562	-0.03364	-0.01937	-0.01906	-0.01652	-0.01064	
AEF	-0.02971	-0.02923	-0.03930	-0.04232	-0.03752	-0.03158	-0.02898	

Table 4-8. SNAP-23A P-Leg Statistical Analysis Summary – Power Ratio (Continued)

Effect	Mean Effect and Test Hours							
	225	550	1000	1500	2000	2500	3000	3500
BCD	-0.00331	-0.01637	-0.00755	-0.00655	-0.00687	-0.01172	-0.00762	
BCE	-0.00960	0.01288	0.00688	0.01538	0.01758	0.02067	0.02356	
BCF	-0.00932	0.00263	-0.00663	-0.01292	-0.00731	-0.00863	0.00009	
BDE	-0.00923	-0.00665	-0.00224	0.00137	-0.00090	-0.00127	0.00337	
BDF	-0.01092	-0.00235	0.00321	-0.00236	-0.00642	0.01148	0.00725	
BEF	-0.02065	-0.02410	-0.02240	-0.02052	-0.01613	-0.01513	-0.01353	
CDE	-0.00438	-0.00750	-0.00253	0.00885	-0.01396	-0.00538	-0.00797	
CDF	-0.00806	-0.00845	-0.00993	-0.01060	-0.00877	-0.00688	-0.01172	
CEF	-0.00128	-0.00151	-0.01537	-0.02362	-0.02656	-0.03558	-0.02822	
DEF	0.00203	-0.00252	0.00316	0.00933	0.01553	0.01024	0.01329	
ABCD	0.00685	0.00885	-0.00056	0.00205	0.00622	0.00813	0.00490	
ABCE	0.01172	-0.01219	0.00124	0.00086	-0.00123	-0.00406	-0.00073	
ABCF	0.00407	-0.00023	0.00028	-0.00025	0.00101	0.00027	0.00000	
ABDE	0.01352	0.00569	0.01083	0.01452	0.01168	0.01002	0.01284	
ABDF	0.01289	0.01603	0.00558	0.00484	0.00048	-0.00314	0.00030	
ABEF	0.01897	0.02382	0.01785	0.01451	0.01075	0.00565	0.00695	
ACDE	-0.00547	0.00229	0.00599	0.00224	0.01383	0.01398	0.01428	
ACDF	0.00622	-0.00877	-0.00336	-0.01699	-0.01028	-0.01720	-0.00805	
ACEF	0.02181	0.01816	0.03000	0.03744	0.03983	0.03918	0.04065	
ADEF	-0.00757	-0.00919	-0.01443	-0.02066	-0.02343	-0.02402	-0.02098	
BCDE	0.04486	0.04325	0.04175	0.03661	0.03316	0.02686	0.02661	
BCDF	-0.00757	-0.02033	-0.01560	-0.00651	-0.00638	-0.00341	-0.00708	
BCEF	-0.01641	-0.02634	-0.01411	-0.01003	-0.00645	-0.00236	-0.00140	
BDEF	-0.00963	-0.00784	-0.00409	-0.00844	-0.01185	-0.01358	-0.01340	
CDEF	0.00782	0.00899	0.00600	0.01129	0.00520	0.00955	0.00563	
ABCDE	-0.04303	-0.03304	-0.03781	-0.03873	-0.03180	-0.02369	-0.02290	
ABCDF	0.00741	0.01542	0.01872	0.01818	0.01015	0.01184	0.01710	
ABCEF	0.04563	0.03927	0.03483	0.03081	0.01592	0.01662	0.00805	
ABDEF	0.00783	0.00935	0.00861	0.02202	0.01322	0.01649	0.01582	
ACDEF	0.00252	0.00401	0.01823	0.01439	0.01738	0.01653	0.01710	
BCDEF	-0.00413	0.00213	-0.00380	-0.00584	-0.00579	-0.00987	-0.00532	
ABCDEF	-0.02998	-0.02786	-0.02451	-0.02319	-0.01486	-0.01224	-0.01212	

The results indicated by the analyses are summarized in Table 4-9. Figures 4-13 through 4-16 graphically present the N- and P-leg average Seebeck ratios, resistance ratios, and power ratios over time. Any significant effects (as indicated in Table 4-9) are shown on a second scale. By analyzing these graphs from a stability standpoint, the following conclusions can be drawn:

Table 4-9. Summary of Statistical Analysis Findings
(After 3000 hours of operation)

Variable		Differences Between Variable Levels (+) and (-)	
Code	Description	N-Leg	P-Leg
A	Leg Segmenting Technique	I	Note 1
B	Hot Contact Material	I	I
C	Hot Junction Temperature	I	I
D	Hot Contact Material	I	I
E	Thermal Insulation	I	Note 2
F	Contact Type	I	I

KEY: I indicates insignificant effect

NOTE 1: On the average, a simultaneously pressed P-leg exhibits a 14.7% higher Seebeck ratio, a 70% higher resistance ratio, and a 19.3% lower power ratio than a corresponding bonded type P-leg.

NOTE 2: On the average, P-legs operating in a Min-K 1301 environment exhibit a 4% higher Seebeck ratio, a 31.3% lower resistance ratio, and a 22% higher power ratio than those operating in a microquartz environment.

- a. N-legs appear to show only minor fluctuations during the first 3000 hours.
- b. Bonded P-legs appear to show only minor changes during the first 3000 hours.
- c. Simultaneously pressed P-legs show a slight increase in Seebeck ratio and a considerable increase in resistance ratio with time, with a resultant decrease in power ratio.
- d. A Min-K 1301 environment for P-legs tends to increase the Seebeck ratio slightly, stabilize the resistance ratio, and hence increase the power ratio slightly as a function of time.

- e. A microquartz environment for P-legs tends to stabilize the Seebeck ratio, increase the resistance ratio, and hence decrease the power ratio as a function of time.

4.2.3 SNAP-23 CONTINUATION TESTING

4.2.3.1 Module A-3

Long-term test of SNAP-23 six-couple Module A-3 continued during the quarter. Performance data for the module is summarized in Table 4-10 and shown graphically in Figure 4-17.

Nomenclature for Table 4-10 is as follows:

- T_h - Average hot electrode temperature ($^{\circ}\text{F}$)
- T_c - Average cold electrode temperature ($^{\circ}\text{F}$)
- E_x - Experimental open circuit voltage (volts)
- I_x - Experimental load current (amps)
- R_x - Experimental internal resistance (ohms)
- P_x - Experimental power-to-load (watts)

The long-term testing of Module A-3 has continued without interruption for over 29,000 hours. The module exhibited about a 10 percent increase in internal resistance (almost entirely P-leg based) within the first 1000 hours of operation; but it has shown relative long-term stability since that time, with a gradual decrease in both resistance and open circuit voltage, and consequent decrease in power delivered to the load.

4.2.3.2 Converter P-2

Long-term test of SNAP-23 Converter P-2 continued during the quarter. Performance data for the converter is summarized in Table 4-11. Normalized performance curves are shown in Figure 4-18, data is normalized to $T_h = 1070^{\circ}\text{F}$, $T_c = 200^{\circ}\text{F}$. As the graph indicates, performance has been relatively stable following an initial stability conditioning period.

Table 4-10. SNAP-23 Six-Couple Module A3 Performance Data
(Start of Test: 3/5/65; current reading: 6/28/68)

Hours	T _h * (°F)	T _c (°F)	E _x (volt)	I _x (amp)	R _x (ohm)	P _x (watt)
70	1102	190	1.26	2.84	0.23	1.75
454	1104	197	1.27	2.58	0.25	1.62
1,010	1100	194	1.28	2.55	0.26	1.57
1,630	1100	197	1.28	2.64	0.26	1.57
5,010	1100	191	1.27	2.58	0.26	1.58
11,230	1100	190	1.23	2.48	0.26	1.50
17,710	1095	193	1.20	2.35	0.24	1.47
23,688	1095	190	1.17	2.36	0.24	1.43
29,711	1100	191	1.15	2.38	0.23	1.42

* All T_h parameters after the 166-hour point were established on the basis of Seebeck voltage.

4.3 QUALITY ASSURANCE

Test data accumulated from the 10-couple modules has been monitored by Reliability. This effort assures analysis of the data for reliability considerations.

Table 4-11. SNAP-23 Converter P-2 Performance Data

Date	Hours	T _h (°F)	T _c (°F)	E _x (volt)	I _x (amp)	R _x (ohm)	P _x (watt)	E _n (volt)	R _n (ohm)	P _n (watt)
7/23/65	48	1071	194	49.9	2.89	8.61	72.3	49.7	8.67	71.2
8/2/65	288	1070	201	50.0	2.70	9.25	67.6	50.2	9.25	68.1
8/16/65	624	1080	202	50.8	2.67	9.51	67.8	50.2	9.41	67.0
Installed into System No. 1										
9/3/65	1,030	1075	200	51.0	2.62	9.73	66.8	50.7	9.68	66.4
10/5/65	1,805	1040	201	49.0	2.58	9.59	63.2	51.2	9.87	66.4
11/30/65	3,065	1030	203	48.5	2.56	9.47	62.1	51.2	9.80	66.9
2/2/66	4,679	1030	200	48.3	2.60	9.30	62.8	51.2	9.68	67.7
5/14/66	7,095	1023	204	47.6	2.60	9.15	61.9	51.0	9.60	67.5
8/12/66	9,183	1008	203	46.8	2.57	9.11	60.1	51.2	9.63	68.1
9/2/66	9,757	Shutdown because of heater failure.								
2/19/68	9,757	Put back on test.								
2/29/68	10,009	1060 (est)	186	50.6	2.66	9.59	66.8	50.8	9.85	65.4
6/28/68	12,600	1066	199	50.6	2.73	9.34	68.3	50.8	9.39	68.5

Key:

T_h — Average hot electrode temperature

T_c — Average cold electrode temperature

E_x — Experimental instantaneous open circuit (Seebeck) voltage

I_x — Experimental load current

R_x — Experimental internal resistance

P_x — Experimental output power

E_n — Normalized Seebeck voltage

R_n — Normalized internal resistance

P_n — Normalized output power

Figure 4-1. Seebeck Voltage Ratio versus Elapsed Time (Module 1)

Ratio = $V_{\text{Experimental}} / V_{\text{Theoretical}}$

Figure 4-2. Resistance Ratio versus Elapsed Time (Module 1)
 Ratio = $R_{\text{Experimental}} / R_{\text{Theoretical}}$

Figure 4-3. Power Ratio versus Elapsed Time (Module 1)
Ratio = $P_{\text{Experimental}} / P_{\text{Theoretical}}$

Figure 4-4. Seebeck Voltage Ratio versus Elapsed Time (Module 2)
 Ratio = $V_{\text{Experimental}} / V_{\text{Theoretical}}$

○ — P LEG, ODD, SIMULTANEOUSLY PRESSED, CONVENTIONAL
 △ - - P LEG, EVEN, BONDED, CONVENTIONAL
 □ — N LEG, ODD, SIMULTANEOUSLY PRESSED, CONVENTIONAL
 x - - N LEG, EVEN, BONDED, CONVENTIONAL

SNAP-23A TEN COUPLE MODULE NO. 2
 THERMAL INSULATION: MK 99
 CONTACT PRESSURE: 250 PSI
 HOT ELECTRODE: 1100° F
 COLD ELECTRODE: 190° F

Figure 4-5. Resistance Ratio versus Elapsed Time (Module 2)
 Ratio = $R_{\text{Experimental}} / R_{\text{Theoretical}}$

Figure 4-6. Power Ratio versus Elapsed Time (Module 2)
 Ratio = $P_{\text{Experimental}} / P_{\text{Theoretical}}$

Figure 4-7. Seebeck Voltage Ratio versus Elapsed Time (Module 3)
 Ratio = $V_{\text{Experimental}} / V_{\text{Theoretical}}$

Figure 4-8. Resistance Ratio versus Elapsed Time (Module 3)
Ratio = $R_{\text{Experimental}} / R_{\text{Theoretical}}$

Figure 4-9. Power Ratio versus Elapsed Time (Module 3)
 Ratio = $P_{\text{Experimental}} / P_{\text{Theoretical}}$

Figure 4-10. Seebeck Voltage Ratio versus Elapsed Time (Module 4)
 Ratio = $V_{\text{Experimental}} / V_{\text{Theoretical}}$

○ — P LEG, ODD, SIMULTANEOUSLY PRESSED, SOFT NOSE
 △ — P LEG, EVEN, BONDED, SOFT NOSE
 □ — N LEG, ODD, SIMULTANEOUSLY PRESSED, CONVENTIONAL
 x — N LEG, EVEN, BONDED, CONVENTIONAL

SNAP-23A TEN COUPLE MODULE NO. 4
 THERMAL INSULATION: MK 99
 CONTACT PRESSURE: 150 PSI
 HOT ELECTRODE: 1100° F
 COLD ELECTRODE: 190° F

Figure 4-11. Resistance Ratio versus Elapsed Time (Module 4)
 Ratio = $R_{\text{Experimental}} / R_{\text{Theoretical}}$

Figure 4-12. Power Ratio versus Elapsed Time (Module 4)
 Ratio = $P_{\text{Experimental}} / P_{\text{Theoretical}}$

Figure 4-13. N-Leg Statistical Analysis Summary Data, 10-Couple Modules 5 through 12 Average Seebeck, Resistance and Power Ratios

Figure 4-14. P-Leg Statistical Analysis Summary Data, 10-Couple Modules 5 through 12
Average Effect and Main Effects of Factors "A" and "E" for Seebeck Ratio

Figure 4-15. P-Leg Statistical Analysis Summary Data, 10-Couple Modules 5 through 12
Average Effect and Main Effects of Factors "A" and "E" for Resistance Ratio

Figure 4-16. P-Leg Statistical Analysis Summary Data, 10-Couple Modules 5 through 12
Average Effect and Main Effects of Factors "A" and "E" for Power Ratio

Figure 4-17. SNAP-23 6-Couple Module A3 Performance ($T_h = 1100^\circ\text{F}$, $T_c = 200^\circ\text{F}$)

Figure 4-18. SNAP-23 Prototype P-2 Converter BOL Performance (Normalized Data)

5.0 TASK IV – 25- AND 100-WATT CONCEPTUAL DESIGNS

No effort was expended on this task during this reporting period.