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SNAP-23A PROGRAM, PHASE 1

**THERMOELECTRIC CONVERTER
DEVELOPMENT PROGRAM**

QUARTERLY REPORT NO.5

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

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**SNAP-23A PROGRAM
PHASE I**

**THERMOELECTRIC CONVERTER
DEVELOPMENT PROGRAM**

QUARTERLY REPORT NO. 5

January 1, 1968 through March 31, 1968

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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 January through 31 March 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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SECTION 1.0

SUMMARY

SNAP-23A THERMOELECTRIC CONVERTER

1.0 SUMMARY

During the quarter, fabrication of Experimental Mockup Converters (EMC's) Nos. 2 and 3 was completed; EMC No. 1 was delivered to Westinghouse where it was integrated into EMS No. 1; EMC No. 2 completed short-term testing and successfully underwent dynamic testing; and EMC No. 3 completed short-term testing.

Experimental Mockup Converter No. 3 contains two modifications which have resulted in improved power output, efficiency, and heat transfer characteristics. These modifications consisted of changing the basic thermocouple design configuration to include bonded type P-legs (rather than the simultaneously pressed P-legs used in EMC Nos. 1 and 2), and addition of indium foil at the cold cap-to-follower spherical interface to reduce the temperature differential. Analysis of data from tests conducted up to this time indicates that the converter performance is significantly better than EMC Nos. 1 and 2 (7.43 percent overall efficiency at EOL conditions for EMC No. 3 as opposed to 7.0 percent for EMC No. 2). In addition, the cold side temperature differential for EMC No. 3 is 21° F versus 45° F for EMC No. 2 and 47° F for EMC No. 1. This value is well within the required 30° F maximum average.

Efforts for the Prototype Mockup Converter (PMC) were decelerated from those originally planned at the beginning of the quarter due to a combination of factors including the unavailability of EMS No. 1 system data, and the decision to wait until EMC No. 3 test data could be included in the PMC design base. Early in the quarter 3M/Westinghouse reached agreement to the effect that the nominal interface dimensions for PMC No. 1 will be the same as those for EMC No. 1; long-lead items were procured on this basis. During the middle of the quarter,

a comprehensive review of the proposed design data base, the design approach, and the final design details was held. At the end of the quarter, 3M was awaiting AEC approval and Westinghouse concurrence of the PMC design presented at this review.

Long-term testing of 10-couple modules 1 through 8 was continued and long-term testing of modules 9 through 12 was initiated. The first statistical analysis of the data taken for modules 5 through 12 was completed, and data through the 1000-hour point is presented in paragraph 4.2.2.2 of this report.

Other significant highlights occurring during this period are summarized below:

- An improved PMC thermocouple weld technique was developed.
- Bell jar beryllium oxide (BeO) follower cold-end heat transfer evaluation tests were conducted.
- 10-couple module and bell jar test data was updated to include the "new" material characterizations.
- SNAP-23 P-2 converter was refurbished and placed back on long-term test.

SECTION 2.0
TASK I—PROGRAM MANAGEMENT

2.0 TASK I – PROGRAM MANAGEMENT

2.1 LIAISON

Coordination and liaison activities performed throughout the reporting period with Westinghouse Astronuclear Laboratory were minimized due to system component problems encountered by WANL during system test.

3M and Westinghouse liaison activities during the quarter were concerned with the following items.

- Review of EMC No. 3 Performance Data.
- Establishment of PMC No. 1 Mechanical Interface.
- Review of 3M basis for PMC Thermoelectric Design
- 3M weld tolerances and instrumentation welding investigation.

2.2 DOCUMENTATION AND REPORTS

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

- Quarterly Report No. 4, MMM 3824-0017, covering the period 1 October 1967 through 31 December 1967.
- Monthly Reports – January 1968, Report No. MMM 3824-0018; February 1968, Report No. MMM 3824-0019.

- Appendix B of Experimental Mockup Converter Test Plan and Procedures, Report No. 3M-39-IPP-105.
- SNAP-23A Converter EMC No. 1 (Investigation of Early Performance History) Report No. 3824-0621.

2.3 EFFORT PLANNED FOR THE NEXT QUARTER

Major schedule efforts for the next reporting period include:

- Fabrication release and fabrication of PMC couples.
- Revision of Inspection Criteria PMC Mechanical Interface.
- Complete Final Assembly and Processing of one (1) PMC unit.
- Development of a Westinghouse/3M Integrated PMC Program Schedule.

SECTION 3.0
TASK II – 60-WATT CONVERTER DEVELOPMENT

3.0 TASK II – CONVERTER DEVELOPMENT – 60-WATT

3.1 EXPERIMENTAL MOCKUP CONVERTER

3.1.1 DESIGN

Detail part prints and assemblies covering the use of indium foil at the cold cap-follower spherical interface were released this quarter for use on Experimental Mockup Converter No. 3. The foil was introduced to reduce the temperature drop across the cold cap-follower interface from an average 48°F noted on EMC No. 1 to the design temperature of 30 degrees. On the prototype mockup converter, followers will be fabricated from beryllium oxide material as discussed in paragraph 3.3. Long-lead time requirements precluded incorporation of beryllium oxide followers on EMC No. 3.

Detail part prints and assemblies for the procurement and installation of a pressure gage attached to the outer case were released this quarter for use on EMC No. 3. This pressure gage is being used because of vendor inability to deliver a satisfactory pressure transducer.

A final Bill of Materials reflecting any modifications on EMC No. 2 not incorporated on EMC No. 1 and a Bill of Materials for the construction of EMC No. 3 were released.

3.1.2 FABRICATION AND ASSEMBLY

3.1.2.1 Experimental Mockup Converter No. 1

EMC No. 1 was shut down on 3 January 1968 in preparation for shipment to Westinghouse.

Prior to shipment, the pressure gage was pinched off, all external thermocouples were rewelded, and the unit was assembled into the shipping container. The converter was delivered to Westinghouse for system integration on 9 January 1968.

3.1.2.2 Experimental Mockup Converter No. 2

Final assembly and processing of EMC No. 2 was completed. During final assembly, minor problems developed in the welding of the header pins. Two of the pins developed cracks and leaked, but were satisfactorily repaired as follows: the first was repaired by welding without changing the wiring; the second was rewelded, sealed, and the wire changed to an empty pin.

During final leak check of the converter, a tear through the material of the support cone became evident. This was repaired by welding using 304L filler.

Processing occurred without incident; the converter test period started on 22 January 1968.

3.1.2.3 Experimental Mockup Converter No. 3

Thermoelectric couple drawings were released and couples of the separately segmented "P" and simultaneously pressed "N" variety were fabricated during January. A yield rate of approximately 90 percent was achieved with this batch of thermoelectric couples.

A pressure gage, similar to the one used on 10-couple modules was used on EMC No. 3 in place of a pressure transducer. This was necessitated by the experience gained in obtaining an acceptable EMC No. 1. This is reported in detail in paragraph 3.2.2.1 of Quarterly Report No. 4, MMM 3824-0017.

EMC No. 3 was assembled with a 0.002 inch thick indium foil disk between the hardcoated follower and the nickel plated cold cap. Figure 3-1 shows the assembly sequence of indium foil to thermoelectric couple cold caps.

The converter was packed with 365 grams of Min-K 1301. The unit and headers were welded and leak-checked without incident.

Processing of the converter was completed on 9 February 1968 without incident except for a test station heat source failure (four out of six main heaters burned out). This equipment failure necessitated a slight modification in the processing procedure which consisted of running the final soak step at EOL rather than at BOL conditions. This process modification involves pressure stabilization of the internal converter atmosphere prior to final seal-off (temperature is not a critical factor); therefore, this heater failure did not compromise the success of the processing operation.

During the teardown to correct heater failure, it was found that the Bakelite terminal block was in close proximity of the heat source and had melted. This caused a black residue on the bottom of the converter and on other areas within the support column. The burned out heaters were replaced by new heaters that had been baked out at 600°F for 6 hours and then installed in the hot block. The converter test period started 14 February 1968.

3.1.3 TEST

3.1.3.1 EMC No. 1

Experimental Mockup Converter No. 1 short-term testing was completed during this quarter. A total of 680 test hours were logged on the unit prior to shipment to Westinghouse for SNAP-23A system integration. The observed performance during the stability conditioning period is presented in Table 3-1. Performance versus time during the same period is shown graphically in Figure 3-2.

a. Cutting Indium Foil

b. Applying Vacuum Grease

c. Placing Indium Foil on Cold Cap

Figure 3-1. Assembly Sequence of Indium Foil to Thermoelectric Couple Cold Caps

d. Forming Indium Foil

e. Placement of Thermoelectric
Couples into Assembly
Fixture

Figure 3-1. Assembly Sequence of Indium Foil to Thermoelectric
Couple Cold Caps (Continued)

Table 3-1. SNAP-23A EMC No. 1 Stability Conditioning Period Performance

Date	Test Hours	E (volts)	R (ohms)	P (watts-e)	P _T (watts-t)	T _c (°F)	T _h (°F)
12-12-67	159	53.2	9.69	72.8	1104	191	1074
12-14-67	207.5	53.3	9.75	72.6	1108	193	1073
12-16-67	262	53.4	9.86	72.0	1112	194	1073
12-19-67	330	53.4	9.86	72.0	1112	193	1072
12-22-67	400	53.7	9.93	73.0	1116	194	1072
12-25-67	474	54.0	9.86	73.5	1124	190	1073
12-28-67	547	53.9	9.86	73.3	1124	192	1073
1-1-68	614	53.9	9.83	73.5	1128	192	1070
1-3-68	680.5	54.0	9.86	73.5	1128	193	1071
<p>Key: E Instantaneous open circuit voltage R Internal resistance P Output power P_T Gross input power T_c Average cold electrode temperature T_h Average hot electrode temperature</p>

Figure 3-2. SNAP-23A EMC No. 1 Performance During Stability Conditioning Period

3.1.3.2 EMC No. 2

Experimental Mockup Converter No. 2 short-term and dynamic testing was completed during the quarter. The results of the initial performance verification (first phase of short-term converter testing) are presented in Tables 3-2 through 3-5. Initial performance at various EOL and BOL operating conditions is shown in Figures 3-3 through 3-6. Evaluation of Experimental Mockup Converter No. 2 individual leg and thermopile performance in terms of experimental-to-theoretical ratios for instantaneous open circuit (Seebeck) voltage and internal resistance is shown in Table 3-6.

This data shows that for the total thermopile (EOL conditions), the Seebeck voltage is 2 percent higher than the design base; but the internal resistance is also approximately 8.6 percent higher. It is this combined effect which produces a power-output performance level 4 percent lower. However, comparison of EMC No. 2 performance with that of EMC No. 1 indicates that P-leg resistance for EMC No. 2 is significantly lower (approximately 20 percent for EOL conditions) than that observed for EMC No. 1.

From a thermal standpoint, EMC No. 2 was nearly a perfect match of EMC No. 1 thermal performance (refer to Quarterly Report No. 4) with respect to gross power input requirements and cold interface temperature differential (cold junction electrode to outer case).

However, EMC No. 2 efficiency is markedly improved over EMC No. 1. Whereas EMC No. 1 test data showed efficiency of 6.1 percent (for EOL), EMC No. 2 performance data shows an operating efficiency of approximately 7 percent. This performance measure is 91 percent of the desired design goal (7.7 percent EOL). In addition, BOL operating conditions for EMC No. 2 illustrate that this converter achieves an operating efficiency of approximately 7.6 percent.

Experimental Mockup Converter No. 2 stability conditioning period (second phase of short-term converter testing) was completed prior to dynamic shock and vibration testing of the unit. A total of more than 500 test hours was logged on the unit. The observed performance during the stability conditioning period is

Table 3-2. EMC No. 2 Mapping Data — EOL Conditions

		Units	Nominal Design Point	Open Circuit Conditions	Off- Nominal Load Current	Off- Nominal Load Current	Short Circuit Conditions
Temp. Outer Case	T_{oc}	°F	128	131	128	129	135
Temp. Hot Frame	T_{hf}	°F	931	1103	952	872	840
Temp. Cold Junction	T_c	°F	173	177	173	173	184
Temp. Hot Junction	T_h	°F	901	1077	921	839	807
Load Voltage	V	Volts	23.0	53.2	28.2	12.0	0
Open Circuit Voltage	E	Volts	41.1	53.2	42.6	37.2	34.5
Load Current	I	Amperes	2.50	0	1.99	3.70	5.06
Total Resistance	R	Ohms	7.23	8.69	7.24	6.81	6.82
Power Output	P	Watts(e)	57.6	0	55.3	44.4	0
Gross Power Input	P_{in}	Watts(t)	860	860	860	856	860
Test Station Losses	Q_{loss}	Watts(t)	32*	-	-	-	-
Net Power Input	Q_{in}	Watts(t)	827	-	-	-	-
Efficiency, Percent	η	%	6.96	-	-	-	-

*Reference SK-39-5082

Table 3-3. EMC No. 2 Mapping Data – BOL Conditions

Parameter		Units	Nominal Design Point	Off-Nominal Load Current	Off-Nominal Load Current	Short Circuit Conditions
Temp. Outer Case	T_{oc}	°F	138	142	141	143
Temp. Hot Frame	T_{hf}	°F	1120	1088	1062	1044
Temp. Cold Junction	T_c	°F	191	197	197	202
Temp. Hot Junction	T_h	°F	1085	1052	1026	1008
Load Voltage	V	Volts	25.0	16.0	8.0	0.001
Open Circuit Voltage	E	Volts	53.6	51.4	49.5	48.3
Load Current	I	Amperes	3.20	3.99	4.72	5.47
Total Resistance	R	Ohms	8.94	8.87	8.79	8.83
Power Output	P	Watts(e)	80.0	63.8	37.8	0.005
Gross Power Input	P_{in}	Watts(t)	1100	1100	1100	1100
Test Station Losses	Q_{loss}	Watts(t)	41*	-	-	-
Net Power Input	Q_{in}	Watts(t)	1059	-	-	-
Efficiency, Percent	η	%	7.55	-	-	-

*Reference SK-39-5081

Table 3-4. EMC No. 2 Test Data for EOL Off-Design
Cold Junction Temperatures

Parameter		Units	Nominal Cold Junction Temp. -20°F	Nominal Cold Junction Temp. +20°F
Temperature Outer Case	T_{oc}	°F	108	150
Temperature Hot Frame	T_{hf}	°F	929	932
Temperature Cold Junction	T_c	°F	155	193
Temperature Hot Junction	T_h	°F	900	902
Load Voltage	V	Volts	23.0	23.0
Open Circuit Voltage	E	Volts	41.7	40.6
Load Current	I	Amperes	2.66	2.39
Total Resistance	R	Ohms	7.03	7.36
Power Output	P	Watts(e)	61.2	55.0
Gross Power Input	P_{in}	Watts(t)	888	840

Table 3-5. EMC No. 2 Test Data for BOL Off-Design
Cold Junction Temperatures

Parameter		Units	Nominal Cold Junction Temp. -20°F	Nominal Cold Junction Temp. -40°F
Temperature Outer Case	T_{oc}	°F	116	90
Temperature Hot Frame	T_{hf}	°F	1119	1121
Temperature Cold Junction	T_c	°F	172	152
Temperature Hot Junction	T_h	°F	1084	1085
Load Voltage	V	Volts	25.0	25.0
Open Circuit Voltage	E	Volts	54.4	55.2
Load Current	I	Amperes	3.33	3.48
Total Resistance	R	Ohms	8.83	8.68
Power Output	P	Watts(e)	83.2	87.0
Gross Power Input	P_{in}	Watts(t)	1132	1156

Figure 3-3. Current - Voltage Mapping of SNAP-23A Converter EMC No. 2 at EOL Conditions, $Q_{\text{Total Input}} = 860$ watts

Figure 3-4. Current - Voltage Mapping of SNAP-23A Converter EMC No. 2 at BOL Conditions, $Q_{\text{Total Input}} = 1100$ Watts

Figure 3-5. Performance Versus T_C of SNAP-23A Converter EMC No. 2 at EOL Conditions, $T_h = 900^{\circ}\text{F}$, $V = 23.0$ Volts

Figure 3-6. Performance Versus T_c of SNAP-23A Converter EMC No. 2 at BOL Conditions, $T_h = 1085^\circ\text{F}$, $V = 25.0$ Volts

Table 3-6. SNAP-23A Converter EMC No. 2 Initial Performance

Ratios $\left(\frac{\text{Experimental value}}{\text{Theoretical value}} \right)$ at EOL and BOL Design Conditions

	Seebeck Ratio			Resistance Ratio*		
	EOL	BOL	Design	EOL	BOL	Design
Thermopile	1.02	1.01	1.00	1.16	1.10	1.068
Typical N-leg	1.00	0.99	1.00	0.97	0.93	1.068
Typical P-leg	1.04	1.03	1.00	1.34	1.28	1.068

*Theoretical resistance includes no extraneous resistance allowance.

NOTE: Theoretical values are based on new materials characteristics.

presented in Table 3-7. Performance versus time during the same period is shown graphically in Figure 3-7. The results of EOL re-evaluation performed just prior to shutdown for dynamic testing are shown in Table 3-8. Performance checks run on the converter at the environmental laboratory are presented in Table 3-9 and photographs of the test setup are shown in Figure 3-8.

Analysis of the Experimental Mockup Converter No. 2 stability conditioning period data indicates that, although the internal resistance increased during the period, the instantaneous open circuit voltage also increased by an amount sufficient to cause negligible change in the output power. The input power required to maintain a given set of operating conditions increased during the period, presumably caused by outgassing of the Min-K 1301 thermal insulation and the resultant increase in internal gas pressure and thermal conductivity.

Results of Experimental Mockup Converter No. 2 dynamic testing (found in the appendix¹ at the end of this report) indicates that the converter can be subjected

¹Environ Laboratories Engineering Report No. 5056.

Table 3-7. SNAP-23A Experimental Mockup Converter No. 2 Stability Conditioning Period Performance

Date	Test Hours	E, Volts	R, 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

Key:

- E Instantaneous open circuit voltage
- R 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 3-7. SNAP-23A Experimental Mockup Converter No. 2 Performance during the Stability Conditioning Period

Table 3-8. EMC No. 2 EOL Re-evaluation at 508 Test Hours
(Pre-Dynamic Test)

E	=	42.4 volts
V	=	23.0 volts
I	=	2.50 amps
R	=	7.76 ohms
P	=	57.6 watts
T _h	=	898°F
T _c	=	172°F
T _{HF}	=	926°F
T _{oc}	=	129°F
P _{in}	=	880 watts

Table 3-9. SNAP-23A Experimental Mockup Converter No. 2
Dynamic Test Performance Checks

	T _h , °F	T _c , °F	E _X , volts	E _C , volts	E _X /E _C	R _X , ohms	R _C , ohms	R _X /R _C
Pre-Vibration	1085	198	53.9	52.92	1.02	9.3	8.13	1.14
Pre-Shock	1072	198	52.4	52.2	1.00	9.1	8.027	1.13
Post-Shock	1062	193	51.9	52.0	1.00	9.0	7.99	1.13

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 internal resistance
R_C Theoretical internal resistance

X-Axis Vibration

Z-Axis Vibration

X-Axis Shock

Z-Axis Shock

Figure 3-8. Dynamic Testing of Experimental Mockup Converter No. 2

to design shock and vibration loads (10g) while operating at BOL thermal conditions without suffering any damage or degradation. The only problem encountered during the dynamic testing was a loss of two of the six parallel electrical heaters in the heat source during the vibration test. However, the test was continued using the four remaining heaters. Current plans are to rebuild the heat source prior to placing Experimental Mockup Converter No. 2 back on long-term test.

3.1.3.3 EMC No. 3

Experimental Mockup Converter No. 3 testing began during the quarter. The initial performance verification was completed, the results of which are presented in Tables 3-10 through 3-13. Initial performance at various EOL and BOL operating conditions is shown in Figures 3-9 through 3-12. Evaluation of Experimental Mockup Converter No. 3 individual leg and thermopile performance in terms of experimental-to-theoretical ratios for instantaneous open circuit (Seebeck) voltage and internal resistance is shown in Table 3-14. The stability conditioning period had just been completed at the end of the reporting period. The observed performance during the period is presented in Table 3-15. Performance versus time during the same period is shown graphically in Figure 3-13.

Analysis of data from tests conducted on Experimental Mockup Converter No. 3 up to the present time indicates that the converter has performed significantly better than Experimental Mockup Converter No. 2 (7.43 percent overall efficiency at EOL conditions as opposed to 6.96 percent for Experimental Mockup Converter No. 2). This efficiency of 7.43 percent demonstrated by Experimental Mockup Converter No. 3 represents more than 96 percent attainment of the desired design goal of 7.7 percent minimum efficiency. This improvement is attributed primarily to the lower internal resistance of Experimental Mockup Converter No. 3.

The resistance decrease, in turn, is attributed to the bonded type of P-leg used in Experimental Mockup Converter No. 3 as opposed to the simultaneously pressed type used in Experimental Mockup Converter No. 2.

Table 3-10. EMC No. 3 Mapping Data – EOL Conditions

Parameter	Nominal Design Point	Off-Nominal Load Current	Off-Nominal Load Current	Short Circuit Conditions
T_{oc} (°F)	151	152	151	150
T_{hf} (°F)	928	1006	872	820
T_c (°F)	172	173	172	173
T_h (°F)	900	979	842	789
V (volts)	23.0	36.0	12.0	0.001
E (volts-Int)	40.7	46.5	36.9	33.5
I (amps)	2.66	1.44	3.94	5.57
R (ohms)	6.65	7.29	6.32	6.01
P_{output} (watts)	61.2	51.8	47.3	0.006
P_{in} (watts)	852	852	852	852
Q_{loss} (watts)	28.5*	-	-	-
Q_{in} (watts)	823.5	-	-	-
η (%)	7.43	-	-	-
T_{hr}	11.5	16.0	30.0	24.5
Q_{loss} , Q_{in} , and η raw data not evaluated for off-design conditions				

*Reference SK-39-5084

Table 3-11. EMC No. 3 Mapping Data – BOL Conditions

Parameter		Units	Nominal Design Point	Off-Nominal Load Current	Off-Nominal Load Current	Short Circuit Conditions
Temp. Outer Case	T_{oc}	°F	165	172	179	177
Temp. Hot Frame	T_{hf}	°F	1111	1074	1048	1021
Temp. Cold Junction	T_c	°F	191	199	206	205
Temp. Hot Junction	T_h	°F	1077	1040	1014	986
Load Voltage	V	Volts	25 0	16.0	8.0	0.003
Open Circuit Voltage	E	Volts	53.5	50.7	48.7	46.9
Load Current	I	Amperes	3.37	4.21	4.99	5.87
Total Resistance	R	Ohms	8.46	8.24	8.16	7.99
Power Output	P	Watts(e)	84.3	67.4	39.9	0.018
Gross Power Input	P_{in}	Watts(t)	1060	1060	1060	1060
Test Station Losses	Q_{loss}	Watts(t)	36*	-	-	-
Net Power Input	Q_{in}	Watts(t)	1024	-	-	-
Efficiency, Percent	η	%	8.23	-	-	-

*Reference SK-39-5083

Table 3-12. EMC No. 3 Test Data for EOL Off-Design
Cold Junction Temperatures

Parameter		Units	Nominal Cold Junction Temp. -20° F	Nominal Cold Junction Temp. +20°F
Temperature Outer Case	T_{oc}	°F	133	171
Temperature Hot Frame	T_{hf}	°F	927	931
Temperature Cold Junction	T_c	°F	154	192
Temperature Hot Junction	T_h	°F	900	903
Load Voltage	V	Volts	23.0	23.0
Open Circuit Voltage	E	Volts	41.4	40.6
Load Current	I	Amperes	2.85	2.60
Total Resistance	R	Ohms	6.45	6.77
Power Output	P	Watts(e)	65.6	59.8
Gross Power Input	P_{in}	Watts(t)	880	832

Table 3-13. EMC No. 3 Test Data for BOL Off-Design
Cold Junction Temperatures

Parameter		Units	Nominal Cold Junction Temp. -20°F	Nominal Cold Junction Temp. -40°F
Temperature Outer Case	T_{oc}	°F	144	125
Temperature Hot Frame	T_{hf}	°F	1111	1109
Temperature Cold Junction	T_c	°F	170	152
Temperature Hot Junction	T_h	°F	1076	1073
Load Voltage	V	Volts	25.0	25.0
Open Circuit Voltage	E	Volts	54.5	54.9
Load Current	I	Amperes	3.58	3.72
Total Resistance	R	Ohms	8.23	8.02
Power Output	P	Watts(e)	89.6	92.9
Gross Power Input	P_{in}	Watts(t)	1096	1120

Figure 3-9. Current-Voltage Mapping of SNAP-23A Experimental Mockup Converter No. 3 at EOL Conditions, $Q_{\text{Total}} = 852$ Watts

Figure 3-10. Current-Voltage Mapping of SNAP-23A Experimental Mockup
 Converter No. 3 at BOL Conditions, $Q_{\text{Total}} = 1060$ Watts

Figure 3-11. Performance versus T_c of SNAP-23A Experimental Mockup Converter No. 3 at EOL Conditions, $T_h = 900^\circ\text{F}$, $V = 23.0$ Volts

Figure 3-12. Performance versus T_c of SNAP-23A Experimental Mockup Converter No. 3 at BOL Conditions, $T_h = 1077^\circ\text{F}$, $V = 25.0$ Volts

Table 3-14. SNAP-23A Converter EMC No. 3 Initial Performance

$$\text{Ratios} \left(\frac{\text{Experimental value}}{\text{Theoretical value}} \right) \text{ at EOL and BOL Design Conditions}$$

	Seebeck Ratio			Resistance Ratio*		
	EOL	BOL	Design	EOL	BOL	Design
Thermopile	0.98	0.98 (1.00)**	1.00	1.09	1.07 (1.00)**	1.068
Typical N-leg	1.01	1.00 (1.00)**	1.00	1.05	1.01 (0.97)**	1.068
Typical P-leg	0.96	0.97 (1.00)**	1.00	1.13	1.13 (1.03)**	1.068
<p>*Theoretical resistance includes no extraneous resistance allowance. **Re-evaluation after 968 test hours.</p> <p>NOTE: Theoretical values are based on new materials characteristics.</p>						

Table 3-15. SNAP-23A Converter EMC No. 3 Stability Conditioning Period Performance

Date	Test Hours	E, volts	R, 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

From a thermal standpoint, Experimental Mockup Converter No. 3 was identical to Experimental Mockup Converters No. 1 and 2, with the exception of greatly improved cold end heat transfer through the use of indium foil in the interface between the follower and cold cap. The temperature drop from cold cap to outer case for Experimental Mockup Converter No. 3 was approximately 50 percent of that for Experimental Mockup Converters No. 1 and 2 as shown below.

Comparison of Typical ΔT at EOL

Unit	T_{oc} ($^{\circ}F$)	T_c ($^{\circ}F$)	ΔT ($^{\circ}F$)
EMC No. 1	126	173	47
EMC No. 2	128	173	45
EMC No. 3	151	172	21

Analysis of Experimental Mockup Converter No. 3 stability conditioning period data from a thermoelectric standpoint indicates that the internal resistance decreased and the instantaneous open circuit voltage increased, resulting in a significant increase in output power. In light of these significant changes, the individual leg and thermopile performance was re-evaluated during the stability conditioning period (968 test hours) in terms of experimental to theoretical ratios for instantaneous open circuit (Seebeck) voltage and internal resistance. The results of the re-evaluation at 968 test hours are shown in parenthesis in Table 3-14. The performance changes in the P-leg (increased Seebeck, decreased resistance) correlate well with prior evaluations of the bonded-type of P-leg versus time in the 10-couple module program (refer to module 1 data in paragraph 4.2.2). The decreased resistance of the N-leg is not typical; however it appears to be a change from higher than normal resistance down to a normal value (refer to N-leg resistance ratios at comparable test hours in 10-couple module 1 data). From a thermal standpoint, Experimental Mockup Converter No. 3 stability conditioning period performance was similar to that of Experimental Mockup Converters No. 1 and 2; that is, the input power required to maintain a given set of operating conditions increased during the period, presumably caused by out-gassing of the Min-K 1301 thermal insulation and the resultant increase in internal gas pressure and thermal conductivity.

Figure 3-13. SNAP-23A Converter EMC No. 3 Performance During Stability Conditioning Period

Since the initial BOL performance verification, the output power of Experimental Mockup Converter No. 3 has increased approximately 8 percent while the input power has increased about 6 percent. In view of this apparent increase in efficiency, current plans are to re-evaluate the performance of this converter at EOL conditions.

3.2 PROTOTYPE MOCKUP CONVERTER

3.2.1 DESIGN SUMMARY

The design efforts for the Prototype Mockup Converter during the quarter included selection of beryllium oxide as a material for PMC followers, the selection of a pressure sensing device, revision of thermocouple instrumentation design, changes to the 3M/Westinghouse Interface Drawing and release of all component parts and assembly prints except those related to leg and couple geometry.

3.2.1.1 Follower Design

The high temperature differential between the leg cold junction and the converter outer case for Experimental Mockup Converter No. 1 initiated a follower design investigation which subsequently changed the follower material from hardcoated aluminum to beryllium oxide for the PMC. Thermoelectric couple design for EMC No. 1 was based on a 30°F maximum temperature differential which was exceeded as can be noted in Table 3-16. However, test results¹ of various follower and cold cap configurations indicate that a temperature differential of not over 30°F could be achieved with beryllium oxide followers. Therefore, the design temperature differential objective for the PMC is 30°F maximum. The following discussion pertains to the final design configuration for the beryllium oxide follower used in PMC.

The beryllium oxide follower design was released in two phases this quarter. In order to get tooling and scheduling accomplished, a drawing with nominal tolerances was released early in the quarter. When the final decision of leg length

¹Presented in paragraph 3.3.1.2 of Quarterly Report No. 4, MMM 3824-0017.

Table 3-16. SNAP-23A EMC No. 1 Converter Test Data

Cold Cap — Nickel plated copper Follower — Totally hardcoated aluminum Cold Cap Ball Radius — 0.1085 ± 0.0005 Follower Socket Radius — 0.10925 ± 0.00025 Back Fill Gas — Argon Internal Gas Pressure — 10 psig Spring Pressure — 250 psi		
Device Thermocouple Location	$T_c - T_{oc}$, °F BOL Conditions	$T_c - T_{oc}$, °F EOL Conditions
Top Couple	64	53
Middle Couple	49	43
Bottom Couple	60	48
T_c — Cold junction leg temperature T_{oc} — Converter outer case temperature		

was made, a final drawing giving final dimensions (Figure 3-14) was released. In addition, follower samples were made to the nominal dimensions and forwarded to 3M for inspection. On the basis of the 3M inspection, additional tolerance relaxation was made in noncritical areas to decrease reject rate and ultimately lower piece part cost.

As discussed earlier, heat transfer improvements were required to meet the spherical cold electrode-to-follower interface temperature drop maximum of 30°F. Design discussions were presented in Quarterly Report No. 4 which demonstrate that beryllium oxide has the inherent electrical and thermal advantages

Figure 3-14. Beryllium Oxide Follower

of the required temperature drop improvement¹. Data from two vendors, American Lava and Coors Porcelain, substantiated the fact that beryllium oxide followers could be provided at acceptable costs and within delivery requirements. Details of the follower design are given in the following paragraphs.

In the design of a part such as a converter follower, which requires tightly controlled dimensions and a smooth finish for good performance, it is necessary to discuss each design point with the manufacturer so that unrealistic tolerances and finishes are not specified. Both manufacturing and inspection costs are greatly affected by these parameters.

As shown in Figure 3-14, a finish of 16 rms is noted for the socket seat and outside diameter. American Lava stated they could not hold a finer than 16 rms finish especially in the socket seat where it is difficult to measure finish. Coors will not guarantee any particular finish because of their experience in making followers for the SNAP-27 Program, the feeling being that the porous nature of the material makes it difficult to control surface finish. Therefore the 16 rms finish has been specified as an objective.

On the basis of data presented in reports received from the two vendors, socket-seat-radius-tolerance has been increased to ± 0.001 inch, with a $+0.003 - 0.001$ tolerance at a 45° included angle at the base of the socket (see Figure 3-14), and with the nominal radius being 0.001 inch less than the mating cold cap ball radius. A slightly lower temperature drop occurs when the cap contacts the follower with a ring or edge contact rather than a point contact. To prevent chipping of the socket seat lip or rim, a dimension of 0.052 ± 0.001 inch has been added to the drawing to prevent a thin or knife edge (high stress concentration point). However, a minimal amount of chipping is allowed.

The socket rim is now a flat with two rounded corners which is easier to manufacture than a lip that is completely rounded to a specified radius. A note which specifies the concentricity of the socket seat with respect to the outside diameter has also been added to the drawing. This note, which controls concentricity

¹EMC No. 1 drop was 48°F .

to within 0.002 inch TIR is considered necessary for controlling lip width and leg misalignment.

Both follower vendors agreed that the follower outside diameter could be held to within ± 0.0002 inch using conventional grinding methods. Tighter tolerances require a honing procedure which adds considerable cost to the part.

Table 3-17 shows the follower and hole dimensions for three SNAP programs.

The SNAP-27 devices, which use beryllium oxide followers, were used as a guide in determining the minimum hole clearance of 0.0007 inch. With a follower outside diameter tolerance of ± 0.0002 inch and a cold frame hole tolerance of ± 0.0002 inch, the maximum hole clearance is 0.0015 inch. A test is underway to determine the effects of hole clearance versus temperature drop with beryllium oxide. There is no information on whether this material will cause a sticking follower if tighter hole clearances are used, the present clearance being 0.0004 to 0.0010 inch with hardcoated aluminum followers.

Both vendors stated that material specifications are held when their particular material number is noted on the drawing. A comparison of the American Lava material Alsimag 754 and Coors BD-995 shows the physical properties to be very nearly the same.

3.2.1.2 Pressure Sensing Devices

Through the use of technical periodicals and directories, all known pressure transducer manufacturers were contacted in an effort to find a reliable low cost pressure

Table 3-17. Follower and Hold Dimension Comparison Data

	SNAP-23A	SNAP-21	SNAP-27
Hole Diameter	0.2192/0.2188	0.2507/0.2503	0.3405/0.3400
Follower Diameter	0.2181/0.2177	0.2496/0.2494	0.3393/0.3390
Maximum Hole Clearance	0.0015	0.0013	0.0015
Minimum Hole Clearance	0.0007	0.0007	0.0007

transducer. Additional vendors were contacted because of the present vendor's inability to deliver a satisfactory unit. In addition, a source of a low cost pressure gage was reviewed. A study of pressure requirements indicated that any instrument which could indicate a pressure loss of several pounds to determine if the unit had developed a leak would be adequate. The unit would have to be able to withstand converter shock and vibration exposure when necessary. All reliable pressure transducers were quoted at \$150.00 and up. The pressure gage was available for less than \$10.00, and was selected because it can do the job required at lower cost. The gage has no shock and vibration data; but, in the event any Prototype Mockup Converter units need to undergo dynamic testing, the gage can be easily pinched off.

This gage has passed vacuum integrity specifications and plans to give it "oxygen use" type cleanliness are being made.

This gage will be installed on PMC units for an aid to processing and for early detection of any leaks that might develop. It will be pinched off for shipment to Westinghouse. Any unit remaining at 3M will retain the pressure gage until such time as its usefulness has expired.

3.2.1.3 Thermocouple Instrumentation

3.2.1.3.1 Spot Welding

A study of thermocouple spot-weld attachments was made during this quarter. Stock thermocouple wire was spot-welded (Figure 3-17) to a piece of stainless steel (the thickness of the outer case) varying both spot-weld time and the thermocouple junction dressing. This was done because of problems encountered during integration of EMC No. 1 into the system in which diagnostic thermocouples broke loose from the outer case during handling. After spot-welds were made, they were examined and tested for strength. Two things were decided. All spot-welds on the Prototype Mockup Converter will call out a dressing note on the thermocouple junction that a flat be made in the attachment area. Direction and placement of wire will also be indicated (consistent with routing for system integration). The higher capacity spot-weld required is being developed.

3.2.1.3.2 Thermocouple Instrumentations Wire Length

Thermocouple wire lengths have been increased over those given on the Experimental Mockup Converter because of the request from Westinghouse for additional length. A system receptacle housing (sent for shock and vibration) was used as a pattern; each length was checked and lengthened where necessary.

3.2.1.3.3 Instrumentation Thermocouple Location

A proposal which would improve the arrangement for internal thermocouples but would not change the number of sensing points was forwarded to Westinghouse for concurrence this quarter.

3.2.1.4 3M/Westinghouse Interface Drawing

3.2.1.4.1 Summary

The 3M/Westinghouse Interface Drawing was thoroughly reviewed and updated this quarter. A new drawing was provided to 3M by Westinghouse.

3.2.1.4.2 Detail Parts

Prior to receipt of the PMC interface drawing, it was mutually agreed that 3M could release all PMC component parts not related to couple geometry on the basis that PMC No. 1 nominal interface dimensions were defined to be the same as those identified on Westinghouse drawing 910E413D (EMC interface drawing). This agreement was necessary so that long-lead items that would affect schedule could be procured. However, upon receipt and inspection of the Westinghouse PMC interface drawing, the PMC interface drawing contains dimensional tolerance requirements not specified before, in addition to previously agreed changes. Therefore, the majority of procured PMC in-house hardware does not meet the new interface drawing.

At the request of Westinghouse and in order to determine the dimensional quality of in-house long-lead items in relationship to the new interface drawing, an inspection was made of those items which the proposed PMC interface specifications

would affect. While all the data has been taken, the effect of individual part deviations on the assembly is still under analysis.

3.2.1.4.3 Split Lower Cover Receptacle

At the request of Westinghouse, the receptacle that provides output of lower cover instrumentation would be divided into two receptacles. Receptacle output was split according to which side of the converter lower cover they were on. In addition, a pig-tail was designed to accept this split receptacle.

3.2.1.4.4 Output Junction Terminal

The output junction terminal was revised this quarter. The new junction is more compact. The junction shown on the new interface drawing was worked out by both 3M and Westinghouse.

3.2.1.4.5 Thermocouple Instrumentation Location

The relocation of thermocouple instrumentation as discussed in 3.2.1.3.3 was inserted in the interface. This included a physical location on sheet 2 of the interface drawing as well as a complete tabulation of the wire routing on an additional page.

3.2.1.5 Couple Design

3.2.1.5.1 Introduction

Couple design for Prototype Mockup Converter No. 1 was started before Experimental Mockup Converter No. 3, and system test data were available so that approximate leg lengths could be established. Long-lead time on the beryllium oxide followers demanded that follower dimensions be fixed as soon as possible. Therefore, it was necessary to know the approximate length of the P and N legs and whether the anticipated geometry changes could be accommodated by lengthening or shortening the leg cold caps.

Figure 3-6 of the October 1967 Monthly Report presented a logic diagram of the SNAP-23A design engineering effort for the PMC. As noted on that figure, 3M/Westinghouse resolution of a converter-system thermal interface definition (interface temperatures and heat input rejected) is required before finalization of the couple design could be accomplished. However, that interface definition has not yet been completely established. Therefore, the following Design Approach and Design Summary established for the couple design is presented with recognition that integration of this design with the system will be necessary before the final design release of the thermoelectric couples and of the associated hardware may be completed.

3.2.1.5.2 Design Approach

With the decision to use separately pressed and bonded P legs in EMC No. 3 and PMC No. 1, SNAP-21 devices were also examined for leg performance. It was noted that, in several instances, the measured Seebeck voltage was below theoretical voltage using the most recent characterization data for the calculations. Since Seebeck voltage affects both the Peltier heat and the load power calculations, the individual leg computer program (in addition to the computer program for determining converter performance) was revised to accept a Seebeck voltage adjustment factor. The procedure for calculating couple geometry and converter performance is given in the appendix of the First Quarterly Report. To learn the effects of Seebeck voltage variation on performance, two converter designs were examined. One converter was designed on the basis of a 0.97 Seebeck ratio¹ for P- and N-leg and the other for a normal or 1.00 ratio for each leg, the geometry being optimized in each case. Performance results showed that an appreciable power error occurs when a low Seebeck ratio is not factored into a design. Conversely, when a low Seebeck ratio is incorporated into the design and the actual hardware has a normal Seebeck ratio, both the efficiency and power will be high for the design temperatures; a highly optimized design is not required. A highly optimized design is needed when Seebeck ratios are considerably less than 1.00. The same reasoning can be applied to resistance ratios².

¹Ratio of measured Seebeck voltage to theoretical voltage.

²Ratio of measured resistance including extraneous resistance to theoretical leg material resistance. Theoretical values are from late 1967 material characterization data.

Preliminary designs involving both Seebeck and resistance adjustment factors indicated the leg lengths would not be appreciable longer than the legs in the EMC series converters. Since leg lengths shorter than those of EMC converters can be easily compensated for by lengthening the cold caps, it was possible to establish the following length.

The design approach used in determining PMC couple geometry, after EMC No. 3 and system test data became available, involved the worst case conditions noted in Table 3-18. These values correspond to EMC No. 3 test data which, when compared to the three SNAP-21 device data in Table 3-18, show lower performance. The design conditions under which PMC is based are listed as follows:

1. $\left(\text{Heat input rate to converter at EOL} \right) = 0.782 \left(\text{Heat input rate to converter at BOL} \right)$
2. Hot frame to hot junction $\Delta T = 40^{\circ}\text{F}$
3. Cold junction to fin base $\Delta T = 30^{\circ}\text{F}$
4. Minimum power output at EOL = 60.25 watts at the converter power header
5. Fin heat rejection rate (given by System Contractor — WANL — based upon radiator test data):
 - 721 watts at 145°F (range $140\text{--}150^{\circ}\text{F}$)
 - 926 watts at 160°F (range $155\text{--}165^{\circ}\text{F}$)

Straight lines through these points provide a valid temperature-heat load relationship between the temperatures of 130 and 180°F . For this design the nominal values were used.
6. Load voltage = 24 volts
7. Maximum average hot junction temperature = 1080°F

Table 3-18. Seebeck Voltage and Resistance Ratios

Bonded P-Leg		
	<u>Resistance Exp.</u>	<u>Seebeck Exp.</u>
	Resistance Calc.	Seebeck Calc.
SNAP-21 A10D5	1.10	0.98
SNAP-21 A10D6	0.97	0.98
SNAP-21 A10D7	1.02	0.97
EMC No. 3	1.11	0.95
Nominal Factor (Avg.)	1.06	0.97
Design Factor (Worst Case)	1.11	0.95
Simultaneously Pressed N-Leg		
	<u>Resistance Exp.</u>	<u>Seebeck Exp.</u>
	Resistance Calc.	Seebeck Calc.
SNAP-23A Mod. 1	0.99	1.01
EMC No. 1	0.96	0.99
EMC No. 2	0.97	1.00
EMC No. 3	1.05	1.00
Nominal Factor (Avg.)	0.99	1.00
Design Factor (Worst Case)	1.05	1.00

8. Maximum hot junction temperature = 1100°F

Design current for conditions other than EOL will be increased to control maximum hot junction temperature until limited by 24-volt power voltage.

9. Maximum P-leg segment temperature = 600°F

10. P- and N-leg diameters = 0.1875 inch

11. P-leg Seebeck ratio = 0.95

12. N-leg Seebeck ratio = 1.00

13. P-leg resistance ratio = 1.11

14. N-leg resistance ratio = 1.05

15. Shunt heat loss curve with xenon backfill gas is

$$Q_L = 0.1714 \Delta T - 53.31 \text{ (watts)}$$

3.2.1.5.3 Design Summary

The design characteristics for PMC No. 1 are listed in Tables 3-19 through 3-21. Table 3-19 contains the dimensional and material characteristics; Tables 3-20 and 3-21 contain the performance characteristics for nominal and worst case values of Seebeck and resistance ratios are shown in Table 3-18. As noted in Table 3-20, the overall efficiency is 7.74 percent for nominal values which are the arithmetical averages of the four thermoelectric devices in Table 3-18.

The tables indicate that the total heat input parameter which enters into the overall efficiency calculation is dependent on the calculation for shunt heat loss. Therefore, the comparison is established between total heat input to a converter (as determined by a test station heat loss analysis) and total heat input (as determined theoretically). The total heat input values are shown in Table 3-22 for the three EMC series of converters. Shunt heat loss calculations for the EMC converters are based on argon backfill gas and the measured hot frame and outer case temperatures. Heat to the thermopile for each converter reflects measured Seebeck and resistance ratios. The differences between test station heat inputs to

Table 3-19. Dimensional and Material Leg Characteristics for 252-Couple PMC Converter

Characteristics	P-Leg	N-Leg
Thermoelectric Material		
Hot Segment	PbTe-SnTe (ES 1110)*	PbTe (ES 1103)
Cold Segment	(BiSb) ₂ Te ₃ (ES 1116)	PbTe (ES 1004)
Leg Dimensions, in.		
Hot Segment Length	$L_{HP} = 0.198$	$L_{HN} = 0.299$
Cold Segment Length	$L_{CP} = 0.127$	$L_{CN} = 0.161$
Total Leg Length	$L_P = 0.325$	$L_N = 0.460$
Diameter	$D_P = 0.1875$	$D_N = 0.1875$
Ratio		
Cold Segment length to total leg length	$\frac{L_{CP}}{L_P} = 0.39$	$\frac{L_{CN}}{L_N} = 0.35$
Ratio, in. ⁻¹		
Leg length/Area	$\frac{L_P}{A_P} = 11.77$	$\frac{L_N}{A_N} = 16.66$
Fabrication Method	Separately pressed and bonded	Simultaneously pressed

*3M material designation

the converters and theoretical inputs¹ are 21, 3 and 12 watts for converters EMC No. 1, EMC No. 2 and EMC No. 3 respectively. It is also noted in Table 3-22 that the test station heat losses are very nearly the same for all three converters.

¹The input is theoretical to the extent that measured Seebeck ratios, resistance ratios, cold junction temperature, hot junction temperature, hot frame temperature, and outer case temperature from the test station were necessary for the theoretical calculation.

Table 3-20. Performance Characteristics for 252-Couple PMC Converter with Nominal Adjustment Factors

Converter Parameter	Terminology	Units	BOL	EOL
Seebeck ratio, P-Leg	SR_P	-	0.97	0.97
Seebeck ratio, N-Leg	SR_N	-	1.00	1.00
Resistance ratio, P-Leg	RR_P	-	1.06	1.06
Resistance ratio, N-Leg	RR_N	-	0.99	0.99
Temperature, Cold Junction	T_c	$^{\circ}F$	190	175
Temperature, Hot Junction	T_h	$^{\circ}F$	1040	890
Shunt Heat Loss	Q_L	Watts	93	69
Total Heat Input	Q_T	Watts	996	778
Heat to Thermopile	Q_S	Watts	903	709
Rejected Heat	Q_R	Watts	915	718
Voltage, Open Circuit	E	Volts	50.1	39.7
Voltage, Load	V_L	Volts	24	24
Power Output	P	Watts	80.4	60.3
Overall Efficiency	η	Percent	8.07	7.74

The parametric performance characteristics of the PMC design at fixed hot and cold junction temperatures are presented in Figure 3-15, where power output and thermopile efficiency are plotted versus load voltage. The family of three curves represents converter performance when the Seebeck voltage and resistance ratios are worst case, nominal and best case as defined in Table 3-20. As can be noted in Figure 3-15 the maximum efficiency ranges from 7.5 percent to 8.2 percent as the ratios range from worst to best case. Figure 3-15 also shows that the load voltage at maximum efficiency is within the PMC operating band of 24 ± 1 volts over the full range of observed Seebeck voltage and resistance ratios.

Table 3-21. Performance Characteristics for 252-Couple PMC Converter With Worst Case Adjustment Factors

Converter Parameter	Terminology	Units	BOL	EOL
Seebeck ratio, P-Leg	SR_P	-	0.95	0.95
Seebeck ratio, N-Leg	SR_N	-	1.00	1.00
Resistance ratio, P-Leg	RR_P	-	1.11	1.11
Resistance ratio, N-Leg	RR_N	-	1.05	1.05
Temperature, Cold Junction	T_c	°F	192	177
Temperature, Hot Junction	T_h	°F	1080	920
Shunt Heat Loss	Q_L	Watts	100	74
Total Heat Input	Q_T	Watts	1034	733
Heat to Thermopile	Q_S	Watts	934	807
Rejected Heat	Q_R	Watts	956	747
Voltage, Open Circuit	E	Volts	52.4	41.5
Voltage, Load	V_L	Volts	24	24
Power Output	P	Watts	78.5	60.5
Overall Efficiency	η	Percent	7.59	7.49

Table 3-22. Total Converter Heat Input Comparison at EOL

Heat Quantity, Watts	EMC No. 1	EMC No. 2	EMC No. 3
A. Total heat to test station	864	860	852
B. Test station and miscellaneous losses	33	32	28
C. Total heat to converter as determined from test station analysis (Heat A - Heat B)	831	828	824
D. Total heat to converter based on theoretical calculations using 1967 leg characterization data and latest shunt heat calculations with argon backfill gas. Measured temperatures and adjustment ratios were used in the calculations.	810	831	836

Figure 3-15. SNAP-23A EMC Mapping
 $T_c = 177^\circ\text{F}$, $T_h = 920^\circ\text{F}$

The sensitivity of PMC performance to separate changes in Seebeck voltage and resistance ratios was also evaluated parametrically with the results shown in Tables 3-23 and 3-24. With worst case resistance, an improvement in Seebeck voltage is shown in Table 3-23 to increase the load voltage and current at maximum efficiency. This results in higher power output and efficiency at the fixed cold and hot junction temperatures. The effects of change in the resistance ratio are illustrated in Table 3-24 where the major effect is shown to be an increase in current, efficiency and power at maximum efficiency. In addition to illustrating the PMC sensitivity to resistance and Seebeck voltage ratios, Tables 3-23 and 3-24 show that load voltage at peak efficiency can be expected to fall within the PMC operating band of 24 ± 1 volts for any anticipated set of resistance and Seebeck voltage ratios.

3.2.1.6 Shunt Heat Losses

Shunt heat loss values for the three Experimental Mockup Converters have been adjusted to incorporate measured test temperatures and updated thermal conductivity figures for various converter insulations. The Prototype Mockup Converter shunt heat losses are based on both revised thermal conductivity values and operating temperatures. A recent investigation by 3M, using a combination experimental-analytical procedure, established new thermal conductivity curves for powdered Min-K 1301, molded Min-K 1301, and Microquartz. A detailed method for calculating converter shunt heat loss was presented previously in paragraph 3.2.2.3 of Quarterly Report No. 3, MMM 3824-0013.

The shunt heat losses for the Experimental Mockup Converter series converters and recent Prototype Mockup Converter design are shown in Table 3-25. To compare the effects of different gases on shunt heat loss, Experimental Mockup Converter No. 3 and Prototype Mockup Converter losses are shown for both argon and xenon gas. Experimental Mockup Converter No. 3 has indium foil between the cold cap and follower, thereby enabling the converter to operate within the design temperature differential of 30°F maximum, between the leg cold junction and converter outer case. Experimental Mockup Converter Nos. 1 and 2, however, experienced temperature differentials of 48°F at EOL and 57°F at BOL with argon gas. Consequently, shunt heat losses for these converters are slightly greater as a result of the lower outer case temperature necessary for establishing the design

Table 3-23. PMC Sensitivity to Seebeck Voltage Ratio*

Condition	Worst Case Seebeck	Nominal Seebeck	Best Case Seebeck
T_h	920	920	920
T_c	177	177	177
Seebeck Voltage	41.5	41.9	42.1
Load Voltage (Max η)	24.0	24.3	24.4
Current	2.51	2.54	2.55
Power Output	60.46	61.6	62.1
Q_{Input}	807	810	812
Q_{Loss}	74	74	74
Efficiency (η)	7.49	7.60	7.65

*Worst case resistance ratio assumed.

Table 3-24. PMC Sensitivity to Resistance Ratio*

Condition	Worst Case Resistance	Nominal Resistance	Best Case Resistance
T_h	920	920	920
T_c	177	177	177
Seebeck Voltage	41.5	41.5	41.5
Load Voltage (Max η)	24.0	24.1	24.2
Current	2.51	2.65	2.77
Power Output	60.46	63.7	66.7
Q_{Input}	807	817	825
Q_{Loss}	74	74	74
Efficiency (η)	7.49	7.80	8.08

*Worst case Seebeck ratio assumed.

Table 3-25. Shunt Heat Losses for EMC and PMC Converters

Device	BOL Loss with Argon	BOL Loss with Xenon	EOL Loss with Argon	EOL Loss with Xenon
EMC Nos. 1 and 2	110	---	79.2	---
EMC No. 3	106.8	100	77.2	71.1
PMC	105.7	100	80.2	74.2

cold junction temperatures of 174°F EOL and 191°F BOL. The Prototype Mockup Converter, having been optimized for revised thermal and electrical characteristics, has different operating temperatures; therefore, shunt heat losses are unlike those of the Experimental Mockup Converter losses.

As can be observed from reference to Table 3-25, xenon gas reduces the shunt losses by approximately 6 watts (or 7 percent). The increased cold end temperature differential in Experimental Mockup Converter No. 1 and No. 2 resulted in shunt losses of 2 to 3 watts greater than the losses in Experimental Mockup Converter No. 3.

3.2.1.7 Extraneous Resistance Analysis for Bonded Legs

SNAP-23A bell jar and 10-couple module data has shown values for extraneous resistance that are less than zero (based upon the relationship of experimental data to theoretical data). As a result, test data from several SNAP-21 devices using bonded legs were analyzed. In some instances, open circuit voltages have been higher or lower than the theoretical values. Therefore, two sets of extraneous resistances are presented in the following tabulations. One set is based on the difference between total measured resistance and calculated leg material resistance. The other set includes the effect of Seebeck voltage variation. For example, when Seebeck voltage is low, extraneous resistance is increased so that a theoretical computation will yield a load voltage equal to measured voltage.

Leg material resistance, R_m , is calculated from a computer program which has the new recharacterization coefficients for bonded legs. Extraneous electrical resistance, R_e , is equal to the difference between total measured experimental resistance, R_x , and material resistance, R_m or:

$$R_e = R_x - R_m$$

For the first tabulated set, extraneous resistance is presented as a percentage of total resistance which gives

$$\%R_e = \frac{R_e}{R_x} \times 100$$

Resistance ratio is another method of comparing device resistances and is given by the relation

$$RR = \frac{R_x}{R_m}$$

Seebeck or open circuit voltage, E , is compared by means of a ratio which is calculated by the expression

$$SR = \frac{E_x}{E}$$

where E_x is actual or measured Seebeck voltage.

Data for the SNAP-21 devices have been corrected to EOL conditions by applying the same resistance ratio change that was noticed in SNAP-23A devices for bonded legs from BOL to EOL. No appreciable change was noticed for SR.

The following tabulations contain an extraneous resistance percentage which allows for Seebeck voltage deviation from theoretical or calculated values. Knowing the experimental voltage, V_x , and experimental current, I_x , for a device under test, a device resistance can be calculated using a theoretical or calculated Seebeck voltage. The relationship is

$$R = \frac{E - V_x}{I_x}$$

This resistance may be higher or lower than measured R_x depending on how E varies in relation to E_x . When theoretical Seebeck voltage, E , is greater than measured Seebeck voltage E_x , R will be greater than R_x . The percentage of extraneous resistance is formed from the

$$\% R'_e = \frac{R - R_m}{R} \times 100$$

Where R'_e is the extraneous resistance which includes an allowance for Seebeck voltage deviation from theoretical.

Comparing Table 3-28 to Table 3-26 or Table 3-29 to Table 3-27, it is noticed that in most cases the extraneous resistance must be increased several percent to offset a low Seebeck voltage.

3.2.2 FABRICATION AND ASSEMBLY

3.2.2.1 Components

Long-lead time components were released for final machining on 15 January 1968. The parts were on a "hold" basis from a previous preliminary drawing release. All components were to be placed in bonded stock by 15 April 1968. In addition, a decision was made to go to a low cost pressure gage in place of a pressure transducer (refer to paragraph 3.3.1.3 for details).

The majority of the parts for the PMC's are in Quality Control awaiting inspection with the exception of the thermoelectric couples. The couple drawings have not been released for fabrication.

3.2.2.2 Hot Frame/Lower Cover Weld Development

A hot frame/lower cover weld development program was undertaken to provide a schedule that would assure a weld with minimum weld "roll over" onto the hot frame surface and to produce a weld that would assure a structurally sound converter. A determination was also made that the hot frame/lower cover interface tolerance of ± 0.025 could be held as shown in Table 3-20 for Sample No. 1.

Table 3-26. Device Resistance Comparisons Based on Resistance Measurements at BOL

Device	Hours Operated	% R_e	$\frac{R_x}{R_m}$	$\frac{E_x}{E}$
SNAP-21 10D1	487	-0.70	0.993	0.975
SNAP-21 10D2	370	-0.97	0.9904	0.9935
SNAP-21 10D5	730	+5.20	1.0548	1.0044
SNAP-21 10D6	545	-5.04	0.952	0.970
SNAP-23A 10-Couple Module No. 1	1543	-8.46	0.922	0.990
SNAP-23A Bell Jar	75	-19.0	0.840	0.94

Table 3-27. Device Resistance Comparisons Based on Resistance Measurements at EOL

Device	Hours Operated	% R_e	$\frac{R_x}{R_m}$	$\frac{E_x}{E}$
SNAP-21 10D1	487	+1.48	1.015	0.975
SNAP-21 10D2	370	+1.22	1.0124	0.9935
SNAP-21 10D5	730	+7.13	1.0768	1.0044
SNAP-21 10D6	545	-2.67	0.974	0.970
SNAP-23A 10-Couple Module No. 1	1543	-5.93	0.944	0.990
SNAP-23A Bell Jar	75	-16.02	0.862	0.94

Table 3-28. Device Resistance Comparisons Based on Both Resistance and Seebeck Voltage Measurements at BOL

Device	Hours Operated	% R_e	$\frac{R_x}{R_m}$	$\frac{E_x}{E}$
SNAP-21 10D1	487	+4.18	0.993	0.975
SNAP-21 10D2	370	+0.27	0.9904	0.9935
SNAP-21 10D5	730	+4.33	1.0548	1.0044
SNAP-21 10D6	545	+0.76	0.952	0.970
SNAP-23A 10-Couple Module No. 1	1543	-4.45	0.922	0.990
SNAP-23A Bell Jar	75	-6	0.840	0.94

Table 3-29. Device Resistance Comparisons Based on Both Resistance and Seebeck Voltage Measurements at EOL

Device	Hours Operated	% R'_e	$\frac{R_x}{R_m}$	$\frac{E_x}{E}$
SNAP-21 10D1	487	+6.36	1.015	0.975
SNAP-21 10D2	370	+2.46	1.0124	0.9935
SNAP-21 10D5	730	+6.26	1.0768	1.0044
SNAP-21 10D6	545	+3.13	0.974	0.970
SNAP-23A 10-Couple Module No. 1	1543	-1.92	0.944	0.990
SNAP-23A Bell Jar	75	-3.02	0.862	0.94

Weld samples of the hot frame/lower cover were made using a copper chill block (Figure 3-16). Inspection of the weld samples revealed that there was minor weld "roll over" and that the parts did "grow" because of the internal stresses caused by the welding (inspection data is shown in Tables 3-30 and 3-31). The samples will be stress relieved within the converter operating temperature range (1200°F to 1500°F) to determine if this will relieve the internal stresses within the stainless steel. Results of this will be covered in the next reporting period.

The copper chill block, used to prevent weld "roll over" and excessive parts shrinkage during welding, 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 lower diameter of the hot frame at the lower end.

Samples No. 1 and No. 3 were welded using a 37 and 30 ampere current setting, respectively. These are considerably higher than the 15-ampere welding current used for Experimental Mockup Converters, but were necessitated by use of the chill block.

3.2.2.3 Thermocouple Weld Development

Thermocouple weld samples were made using the same type of thermocouples and 0.02 inch thick stainless steel plate as that used in the converter assembly. The method and equipment used incorporate a preset pressure and amperage (Figure 3-17). The samples withstood a hand pull of approximately 10 pounds. This method of thermocouple attachment will be incorporated into the PMC weld schedule.

3.3 SUPPORT EQUIPMENT

3.3.1 PROCESS AND TEST STATION

Rapid deterioration of the heater leads occurred in Experimental Mockup Converter No. 2 causing four of the six heaters to fail. A chemical analysis by both 3M Central Research Laboratories and the heater manufacturer showed that the

Figure 3-16. Weld Sample Assembly with Chill Block

Figure 3-17. PMC Spot-Weld Sample

nickel heater leads had been attacked by boron oxide which is sometimes present in grades of boron nitride other than the highly purified grade. Boron nitride is used to support and electrically insulate the two nickel bus bars to which the heater leads are welded.

An investigation was conducted this quarter into possible changes that could be made to correct the situation. It was determined that grade A Lava and Alsimag 222 (already used on other 3M programs) form a glass at 900°F which allows corrosive action on the nickel. An inspection of the damaged nickel bus bars disclosed high corrosion at a point of maximum current flow which indicates I^2R overheating. It was decided to split the two bars into four, thus cutting the current flow of each bus bar in half. As a part of this action, the test station wiring and voltage taps were redesigned.

Additional studies of insulators (i.e., sauerisen cement, alundum) at processing temperatures are planned to prevent reoccurrence of nickel breakdown. New bus bars will be used with the currently designed boron nitride, but compounds will be used between the nickel and boron nitride. This will minimize the presence of air which will reduce oxidation, and lessen any possible interaction between nickel and boron nitride.

3.3.2 SHOCK AND VIBRATION FIXTURE ANALYSIS

In preparation for the EMC No. 2 shock and vibration test, further stress analysis was performed on the shock and vibration fixture which is used to attach the converter to the vibration machine. The analysis showed two highly stressed areas: the juncture at the tube and flange, and the mounting bolts for attaching the mounting fixture to the converter assembly. A triangular shaped gusset was added between each of the base mounting holes as shown in Figure 3-18. The previous bolt pattern consisted of six equally spaced bolts. To decrease the load on these bolts, six additional bolts were added to form a twelve bolt equally spaced pattern.

The mounting fixture analysis determined the acceleration loads created by three types of deflection occurring in the fixture: (1) vertical shear deflection, (2) bending deflection, and (3) rotation deflection. These deflections are referenced to the center of gravity of the converter and are added together to produce a total

Figure 3-18. Shock and Vibration Fixture

deflection on which the maximum acceleration load is based. A schematic assembly of the converter and mounting fixture is shown in Figure 3-19.

In the analysis, the adapter and heat input stud are considered as a rigid extension of the beam, which is noted as the mounting fixture (the point of analysis is section A-A). The deflection of the converter center of gravity generated by beam vertical shear is calculated in the following paragraphs.

1. Vertical Shear Deflection

Vertical shear deflection at the end of the beam is shown in Figure 3-20. Although the rigid extension does not magnify the deflection at the location of the converter center of gravity, it is included in Figure 3-19 to show that center of gravity deflection and beam vertical shear deflection are the same.

Figure 3-19. Converter and Mounting Fixture Schematic

Figure 3-20. Vertical Shear Deflection

Vertical shear, δ_s , is found from the equation:

$$\delta_s = \frac{\alpha Fx}{AG}$$

where α is a shape factor and equals 1.33 for cylindrical section

F equals maximum acceleration load at the center of gravity in pounds

X is beam length and equals 1.75 inch

A is beam cross-sectional area at section A-A and equals $\frac{\pi}{4} (d_o^2 - d_i^2)$, d_o and d_i being the beam outside and inside diameters which equal 4.00 and 3.75 inches, respectively

G is shear modulus of elasticity and equals 11,500,000 psi

Substituting,

$$\delta_s = \frac{1.33 (F) (1.75)}{\frac{\pi}{4} (4.00^2 - 3.75^2) 11,500,000}$$

$$\delta_s = \frac{1.3 F}{10^7}$$

2. Bending and Rotation Deflection

Bending and rotation deflection at the center of gravity location is shown in Figure 3-21.

It can be observed in Figure 3-21 that the total deflection at the center of gravity is equal to the bending deflection, δ_b (which occurs at the end of beam) plus the rotation deflection, δ_r (generated by the angle θ at the end of the beam). The bending deflection at the end of the beam is given by the relation:

$$\delta_b = \frac{F}{EI} \left(\frac{\ell x^2}{2} - \frac{x^3}{6} \right)$$

Figure 3-21. Bending and Deflection Rotation at the Center of Gravity

where: I is the beam moment of inertia and equals

$$\frac{\pi}{64} (d_o^4 - d_i^4)$$

E is modulus of elasticity in tension and compression, and equals
29,000,000 psi

l equals length of beam plus rigid extension

Substituting,

$$\delta_b = \frac{F}{29,000,000 \frac{\pi}{64} (4^4 - 3.75^4)} \left(\frac{6.75 \times 1.75^2}{2} - \frac{1.75^3}{6} \right)$$

$$\delta_b = \frac{1.14 F}{10^7}$$

The rotation deflection, δ_r , is equal to the slope of the beam, θ , multiplied the length of the rigid extension. Expressed mathematically,

$$\delta_r = \theta (\ell - x)$$

where θ is in radians and is equal to $\frac{F\ell^2}{2EI} \left[1 - \frac{(\ell - x)^2}{\ell^2} \right]$

Substituting,

$$\delta_r = \frac{5 F 6.75^2}{2 \times 29,000,000 \frac{\pi}{4} (4^4 - 3.75^4)} \left(1 - \frac{5^2}{6.75^2} \right)$$

$$\delta_r = \frac{6.20 F}{10^7}$$

Total deflection at the converter center of gravity can now be found by adding the three foregoing deflections.

$$\text{Total deflection} = \delta_T = \delta_s + \delta_b + \delta_r$$

$$\delta_T = \frac{1.3 F}{10^7} + \frac{1.14 F}{10^7} + \frac{6.20 F}{10^7}$$

$$\delta_T = \frac{8.64 F}{10^7}$$

The spring rate at the center of gravity is necessary for the determination of the maximum acceleration force.

$$\text{Spring rate} = k = \frac{\text{Load}}{\text{Deflection}} = \frac{F}{\delta_T}$$

Therefore, from the total deflection calculation,

$$k = \frac{F}{\delta_T} = \frac{10^7}{8.64} \text{ lb per inch}$$

The converter and mounting fixture assembly is subjected to an excitation amplitude of 0.036 inch at a vibration frequency of 52 cycles per second. This is a system imposed vibration requirement. Amplitude, as defined by the Mil-Std-810A shock and vibration specification is 0.018 inch at 52 cycles per second. The maximum amplitude, r , achieved at the converter center of gravity as allowed by the assembly flexibility is found from the expression:

$$r = \frac{a}{1 - \frac{(2\pi f)^2 W}{kg}}$$

where a is excitation amplitude and is equal to 0.036 inch

f is excitation frequency and is equal to 52 cps

W is static load or weight of assembly and is equal to 112 pounds

g is gravitational acceleration and is equal to 32.2 ft/sec^2

k is assembly spring rate at center of gravity and is equal to $10^7/8.64$ pound per inch

Substituting,

$$r = 0.0531 \text{ inch}$$

Maximum acceleration force is found from the relation

$$F = \frac{W}{g} (2\pi f)^2 r$$

Substituting,

$$F = 1,643 \text{ pounds}$$

In a design subject to vibration, the natural frequency of the system should be well above the excitation frequency to avoid a resonant condition. The natural frequency is found from the expression

$$F_N = \frac{1}{2\pi} \sqrt{\frac{kg}{W}}$$

Substituting,

$$F_N = 91.8 \text{ cps}$$

This is well above the excitation frequency of 52 cps.

With a known value for maximum acceleration force, beam stress at section A-A, Figure 3-19, can now be calculated. The bending stress, S, is found from the relation

$$S = \frac{(F\ell) d_o/2}{\frac{\pi}{64} (d_o^4 - d_i^4)}$$

Substituting,

$$S = \frac{1,643 \times 6.75 \times 4/2}{\frac{\pi}{64} (4^4 - 3.75^4)}$$

$$S = 7,760 \text{ psi}$$

Considering the lower yield of 304 stainless steel at 1000°F and the possibility of a crack being generated next to the weld at section A-A, the stress of 7,760 psi is too high. Therefore, triangular shaped gussets, as noted in Figure 3-18, were added to the mounting fixture.

One of the six bolts which attached the mounting fixture to the test station adapter is shown in Figure 3-19. Maximum bolt stress occurs in the bolt furthest from the fulcrum point as shown in Figures 3-22(a).

Taking moments about the fulcrum point and letting the tensile force in bolt No. 1 be denoted by F_1 , in bolt No. 2 by F_2 , etc., $F_1 \times 3.09 + 2(F_2 \times 2.47) + 2(F_3 \times 1.22) + F_4 \times 0.59 = 1643 \times 4.5$. Since bolt force is proportional to bolt elongation and since elongation is proportional to distance from fulcrum point.

Figure 3-22. Mounting Fixture Bolt Arrangement and Stress

$$F_4 = F_1 \cdot \frac{0.59}{3.09}$$

$$F_3 = F_1 \cdot \frac{1.22}{3.09}$$

$$F_2 = F_1 \cdot \frac{2.47}{3.09}$$

Substituting,

$$3.09F_1 + 2(F_1 \cdot \frac{2.47}{3.09}) 2.47 + 2(F_1 \cdot \frac{1.22}{3.09}) 1.22 + (F_1 \cdot \frac{0.59}{3.09}) 0.59 =$$

$$1643 \times 4.5$$

$$8.11 F_1 = 7400$$

$$F_1 = 914 \text{ pounds}$$

With a bolt cross-sectional area of 0.0318 square inch at thread root, the bolt stress is

$$S = \frac{914}{0.0318}$$

$$S = 29,000 \text{ psi}$$

The yield strength of the high strength bolt material at 1200°F is 56,000 psi. Since the safety factor is less than 2.0, six additional bolts were added to the original 6-bolt pattern.

3.3.3 SHIPPING CONTAINER

The shipping container (Figure 3-23) was used to ship Experimental Mockup Converter No. 1 to Westinghouse by plane on 9 January 1968. Based on use, several modifications will be incorporated including external precautionary shipping handling notes.

Figure 3-23. Shipping Container

3.4 QUALITY ASSURANCE

3.4.1 QUALITY CONTROL

Experimental Mockup Converter No. 1 was shipped to Westinghouse on 9 January 1968 by company airplane and was met at the Alleghany County Airport by the Westinghouse SNAP-23A Program Manager. The converter was trucked to the Westinghouse facility, where it was unpacked and inspected. Westinghouse inspection results were correlated with 3M inspection data. No major differences were noted.

A cystoscope was obtained by the Inspection Department during the period and was first used for inspecting the EMC No. 3 thermopile. This instrument allows a close examination of the internal structure of the pile after the assembly is complete. In this way, the precise location and fit of the parts can be assured. Some 20 hot or cold ends were repositioned on EMC No. 3 as a result of this examination.

Consideration of the converter interface dimensions resulted in the necessity for investigative measurements on all of the piece parts which could affect the PMC module interface. In addition, EMC No. 2 interface dimensions were measured to determine which dimensions were most likely to change during assembly and processing operations. All of these measurements were taken to the nearest 0.0001 inch.

In consideration of the WANL requirements for maximum thermal contact, primary stress was placed on measurements of the thermal contact surfaces. Precise mapping of the contours of these surfaces was carried out wherever applicable instruments were available. A number of formats were used in transmitting the data to Engineering so that the data could be easily and precisely interpreted. Some of the formats are shown in Figures 3-24 through 3-26.

Figure 3-24 shows the formats used for transmitting the hot frame taper data. The work sheet is used to indicate deviations from a true taper. Points on the large end of the taper were taken as zero points, and deviations from a sine bar standard were then measured at set points along the length of the taper. These measurements were recorded in succession toward the center of the circle on the

Figure 3-24. Hot Frame Taper Data

Figure 3-25. Diagram of Locations of Check Points for Outer Case Sin "E"

work sheet. A series of readings were taken in this manner at each 30° interval around the hot frame.

The Boice Gage charts were taken at four intervals along the length of the taper. These plots show the deviation from roundness which exists at each of the planes where the measurements were taken.

The final presentation format for the outer case data is shown in Figures 3-25 and 3-26. The first figure only serves to describe the locations referred to in the data presentation sheet. The format of Figure 3-26 has essentially unrolled the outer case diameter and shows, at each measurement point, the deviation from the true surface. From this sheet a contour plot could be made of either a diameter or a line along the surface parallel to the center axis.

The measurements made on EMC No. 2 were not as precise or comprehensive as those made on the piece parts. This was due to the problem of fixturing the complete converter with the connector bracket mounted. Figure 3-27 shows the converter mounted on the present fixture for outer case measurements. A special mounting fixture is being fabricated to allow precise positioning for improved measurements on future units.

Measurements were also made on weld samples prepared for duplication of the bottom hot frame weld as shown in Tables 3-30 and 3-31. The samples were measured both before and after the welding operation to determine if deformation occurred. An exploded view of the assembly (with the chill block used during welding) is shown in Figure 3-16.

3.4.2 RELIABILITY

During the early part of this period, the Reliability Group monitored the assembly of EMC's No. 2 and No. 3. The monitoring effort was then transferred to the test activities for the remainder of the period. In addition, reliability effort was spent in preparation of the PMC design review meeting. This was a comprehensive review of the design data base, the design approach, and the final design details.

[illegible]

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Table 3-30. Weld Sample No. 1 Weld:
Out of Roundness Data

<u>Diameter</u>	
Desired:	3.750 ± 0.002
Actual Before Weld:	3.751/3.749
After Weld:	3.7462/3.7446

Table 3-31. Hot Frame/Lower Cover Weld Sample Shrinkage
Measurement Data

	Hot Frame Before Weld 5/16 from Bottom	Hot Frame After Weld 5/16 from Bottom	Hot Frame Before Weld 1/16 from Bottom	Hot Frame After Weld 1/16 from Bottom
0°	0.0000	0.0000	0.0000	0.0000
30°	-0.0006	+0.0007	-0.0005	+0.0008
60°	-0.00085	+0.001	-0.0005	+0.0012
90°	-0.00135	+0.0003	-0.00095	+0.0008
120°	-0.0021	+0.0007	-0.0018	+0.002
150°	-0.0018	-0.0003	-0.0018	+0.002
180°	-0.0006	0.0000	-0.0005	+0.0018
210°	-0.0000	-0.0018	0.0000	-0.0003
240°	-0.0005	-0.002	-0.0008	-0.0018
270°	-0.0016	+0.0008	-0.0021	+0.0018
300°	-0.0015	+0.0027	-0.0018	+0.003
330°	-0.0003	+0.0018	-0.0005	+0.001

SECTION 4.0

TASK III – THERMOELECTRIC COUPLE DEVELOPMENT

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 baseline 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.

Efforts expended under the post-test analyses were concluded and reported during the previous quarter. All efforts expended this quarter were test efforts and are reported in paragraph 4.2.

4.2 TEST

4.2.1 BELL JAR TESTS

Bell jar tests 5-15, 16, 5-17, and 9-18 were completed during the quarter. Number 5-15 was a relatively long and complex test designed to reproduce the high P-leg resistance observed in EMC No. 1. It consisted of duplicating the converter assembly (on a two-couple scale) from both an environmental and time standpoint. Performance results are as follows:

Bell Jar Test 5-15 Data

Test Time Hrs.	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
69	895	170	0.99	1.04	0.99	0.95
148	1089	192	1.00	1.11	0.99	0.92
403	1093	189	1.03	1.26	0.98	0.92

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 extraneous resistance allowance.

As indicated in the performance summary, this test ran for over 400 hours. The short-term results correlate quite well with prior evaluations of similar leg configurations (refer to Bell Jar Test 5-11 in Quarterly Report No. 4) which does not substantiate the theory that assembly time or environment was the cause of the high initial P-leg resistance on EMC No. 1. However, the P-leg resistances observed at 148 and 403 hours correlate well with those observed on the odd-circuit of 10-couple Module No. 1 (refer to paragraph 4.4.2) and on EMC No. 2 (refer to paragraph 3.1.3) although the exact test time tends to vary between the devices as a result of differences encountered in processing time.

Test 16 was an evaluation of SNAP-21 couples for test fixture comparison purposes. The results indicate good correlation with similar tests run of the SNAP-21 Program using a completely different test fixture. Bell jar test No. 5-17

was an evaluation of Experimental Mockup Converter No. 3 couples. Performance results are summarized in Table 4-1. P-leg resistance results are high when compared to previous bell-jar evaluations of individually segmented and bonded soft nose legs but low in comparison to Experimental Mockup Converter No. 3 test results. N-leg resistance results are high when compared to previous bell jar evaluations of similar legs but correlated well with Experimental Mockup Converter No. 3 test results (see Table 3-14). It is believed these are manufacturing variabilities in thermoelectric leg batches.

Test 9-18 utilized 10-couple module bonded, soft nose P-leg couples with iron hot buttons, 250 psi contact pressure, and approximately 5 degrees intentional leg misalignment. Results of this test are presented in Table 4-2. The effect of varying degrees of intentional leg misalignment on experimental-to-theoretical resistance ratios is shown graphically in Figure 4-1. Some of the data is based on previous bell jar tests (refer to Quarterly Report No. 4).

The dual bell jar test station was completed during the quarter. The completed station is shown in Figure 4-2.

4.2.2 10-COUPLE MODULES

Long-term test of modules 1 through 8 continued, and long-term test of modules 9 through 12 began during the quarter.

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 4-5 through 4-16. As indicated by the graphs, performance trends are basically unchanged since Quarterly Report No. 4.

Figure 4-1. Effect of Leg Misalignment in Resistance
(Iron Hot Contact Material, 1100°F Hot Junction)

Figure 4-2. SNAP-23A Dual Bell Jar Test Station

Table 4-1. Bell Jar Test 5-17 Data

Operating Conditions	$T_h, ^\circ\text{F}$	$T_c, ^\circ\text{F}$	P-Leg		N-Leg	
			E_x/E_c	R_x/R_c	E_x/E_c	R_x/R_c^*
EOL	899	175	0.92	0.98	0.99	1.05
BOL	1082	193	0.95	1.01	0.99	1.04

*Theoretical resistance includes no extraneous resistance allowance.

In addition to the thermoelectric bell jar test effort, cold-end heat transfer tests evaluating beryllium oxide (BeO) followers in a 6-couple bell jar module were also conducted. Effects of both radial mismatch at the ball-socket interface and diametral difference at the follower-cold frame interface were investigated. The difference in radii of the cold cap and follower socket was allowed to vary by as much as 0.005 inch with the cap both larger and smaller than the follower radii. Figure 4-2 presents the results of these tests. The solid line is the predicted temperature drop or average of the data. The broken line indicates the range through which most data may deviate. Experimental Mockup Converter No. 3 test results with hardcoated aluminum followers and indium interfacial foil show a comparable temperature drop of 20°F.

One test was run to determine effectiveness of opening tolerances on the cold frame hole diameter. A cold frame was constructed with different size holes, and a standard BeO follower was used. The ball-socket mismatch was consistently 0.002-inch and ring contact was used so the temperature drop would be consistent. The range of difference between diameters tested was from 0.0015 to 0.0101 inch (refer to Figure 4-3 for results of this test). Data for 0.0007 delta D (obtained from the aforementioned tests) is also plotted.

Table 4-2. Bell Jar Test 9-18 Data

Operating Conditions	P-Leg (bonded, soft nose)		N-Leg (bonded)	
	E_x/E_c	R_x/R_c^*	E_x/E_c	R_x/R_c^*
BOL, 250 psi, 5° misalignment, iron hot contact	0.92	1.00	0.99	0.94

Key: E_x experimental Seebeck voltage

E_c theoretical Seebeck voltage

R_x experimental resistance

R_c^* theoretical resistance (includes no extraneous resistance allowance)

Figure 4-3. Cold End Temperature Drop versus Radial Mismatch

Figure 4-4. Cold End Temperature Drop versus Follower-to-Hole Clearance

Figure 4-5. Seebeck Voltage Ratio versus Elapsed Time (Module 1)
 Ratio = $V_{\text{Experimental}} / V_{\text{Theoretical}}$

Figure 4-6. Resistance Ratio versus Elapsed Time (Module 1)
 Ratio = $R_{\text{Experimental}} / R_{\text{Theoretical}}$

Figure 4-7. Power Ratio versus Elapsed Time (Module 1)
Ratio = $P_{\text{Experimental}} / P_{\text{Theoretical}}$

Figure 4-8. Seebeck Voltage Ratio versus Elapsed Time (Module 2)
 Ratio = $V_{\text{Experimental}} / V_{\text{Theoretical}}$

Figure 4-9. Resistance Ratio versus Elapsed Time (Module 2)
 Ratio = $R_{\text{Experimental}} / R_{\text{Theoretical}}$

Figure 4-10. Power Ratio versus Elapsed Time (Module 2)
 Ratio = $P_{\text{Experimental}} / P_{\text{Theoretical}}$

Figure 4-11. Seebeck Voltage Ratio versus Elapsed Time (Module 3)
 Ratio = $V_{\text{Experimental}} / V_{\text{Theoretical}}$

Figure 4-12. Resistance Ratio versus Elapsed Time (Module 3)
 Ratio = $R_{\text{Experimental}}/R_{\text{Theoretical}}$

Figure 4-13. Power Ratio versus Elapsed Time (Module 3)
 Ratio = $P_{\text{Experimental}} / P_{\text{Theoretical}}$

Figure 4-14. Seebeck Voltage Ratio versus Elapsed Time (Module 4)
 Ratio = $V_{\text{Experimental}} / V_{\text{Theoretical}}$

Figure 4-15. Resistance Ratio versus Elapsed Time (Module 4)
 Ratio = $R_{\text{Experimental}} / R_{\text{Theoretical}}$

Figure 4-16. Power Ratio versus Elapsed Time (Module 4)
 Ratio = $P_{\text{Experimental}} / P_{\text{Theoretical}}$

4.2.2.2 Modules 5 Through 12

Statistical analyses of the data taken on 10-couple modules 5 through 12 at their respective 225-, 550-, and 1000-hour points were completed during this quarter. These analyses are based on data developed using the new thermoelectric material characterization coefficients (S , K and ρ). As reported previously in Quarterly Report No. 4 (MMM 3824-0017) and delineated herein, statistical analyses of modules 5 through 12 are necessary, since they contain a mixture of leg configurations within each module, rather than similar types, as is the case with modules 1 through 4 (refer to SNAP-23A, 10-Couple Module Variable Matrix, Table 4-1, Quarterly Report No. 1 (MMM 3824-0006)).

Representative samples of the statistical analyses output are shown in Figures 4-17 through 4-19 and show respectively, P-leg input data and measured effect of design variables on Seebeck voltage, resistance and power ratios. Similarly, complete analyses were also made of the N-legs. The P-leg data is shown because indicated effects are more evident than those contained in the N-leg analyses.

The intent of the 10-couple module test effort was such that six variables* were to be examined for their effects on converter performance, both long- and short-term. The variables to be tested were:

- a. Leg manufacturing technique
- b. Hot junction button material
- c. Hot junction temperatures
- d. Hot contact pressure
- e. Thermal insulation
- *f. Leg hot end (contact type, conventional or soft nose)

Each of these variables could consist of more than one level. That is, there were two leg manufacturing techniques to be examined, two possible hot contact materials,

*P-legs only, F variable does not apply to N-legs. Therefore, N-leg test consists of five variables, A B C D and E.

FACTS ANALYSIS OF VARIANCE					
T-TEST ANALYSIS					
RESPONSE 1 - SEEBECK RATIO					
DESIGN NUMBER	BATCH DESC.	OBSERVED RESPONSE	EFFECT DESCRIPTION	MEAN EFFECT	ERROR VARIANCE
1	111111	0.9090	A	0.10391	0.17274261
2	211111	1.0000	AF	0.0516	0.00367537
3	121111	0.9000	AE	-0.01172	0.00219727
4	221111	1.0100	ABDF	0.01172	0.00219726
5	112111	0.9150	C	0.01047	0.00175354
6	212111	1.0300	E	0.00828	0.00109725
7	122111	0.9400	BDF	-0.00766	0.00093789
8	222111	1.0200	B	0.00766	0.00093788
9	111211	0.9000	AEF	-0.00672	0.00072224
10	211211	1.0000	ABCF	0.00609	0.00059414
11	121211	0.9300	ADF	0.00609	0.00059412
12	221211	1.0000	CDE	0.00578	0.00053477
13	112211	0.9000	BCF	-0.00578	0.00053476
14	212211	1.0000	ADEF	0.00516	0.00042539
15	122211	0.9300	ABD	0.00484	0.00037539
16	222211	1.0100	EF	0.00453	0.00032853
17	111121	0.9200	ABCDEF	0.00453	0.00032851
18	211121	1.0100	ACDF	-0.00422	0.00028476
19	121121	0.9100	ABF	0.00391	0.00024415
20	221121	1.0100	ABDE	0.00391	0.00024414
21	112121	0.9350	AB	-0.00359	0.00020665
22	212121	1.0100	CDF	0.00328	0.00017227
23	122121	0.9300	ADE	0.00328	0.00017226
24	222121	1.0100	DF	0.00297	0.00014101
25	112221	0.9200	BE	-0.00297	0.00014100
26	212221	1.0000	F	0.00266	0.00011287
27	121221	0.9200	DE	0.00234	0.00008790
28	221221	0.9900	ABE	0.00203	0.00006602
29	112221	0.9050	BCDE	0.00203	0.00006602
30	212221	1.0200	ACDE	0.00203	0.00006602
31	122221	0.9500	BD	-0.00203	0.00006601
32	222221	1.0100	BDE	0.00203	0.00006601
33	111112	0.8700	BEF	0.00203	0.00006601
34	211112	1.0200	ACF	0.00172	0.00004727
35	121112	0.9300	AD	0.00172	0.00004727
36	221112	1.0050	BCF	-0.00172	0.00004727
37	112112	0.8900	CEF	0.00172	0.00004726
38	212112	1.0300	ABCF	0.00172	0.00004726
39	122112	0.9100	ABCDE	-0.00172	0.00004726
40	222112	1.0300	BCE	0.00172	0.00004726
41	111212	0.8800	BC	0.00141	0.00003164
42	211212	1.0200	BF	0.00141	0.00003164
43	121212	0.8800	ABCE	-0.00141	0.00003164
44	221212	1.0500	D	0.00141	0.00003164
45	112212	0.9000	BDEF	-0.00141	0.00003164
46	212212	1.0300	CF	-0.00141	0.00003163
47	122212	0.8700	AC	0.00109	0.00001914
48	222212	1.0450	CE	0.00109	0.00001914
49	111122	0.9000	ABEF	0.00078	0.00000977
50	211122	1.0100	ABCEF	-0.00078	0.00000977
51	121122	0.9400	ACE	-0.00078	0.00000977
52	221122	1.0250	ABDEF	-0.00078	0.00000976
53	112122	0.9100	ACD	0.00078	0.00000976
54	212122	1.0200	BCD	0.00047	0.00000976
55	122122	0.9300	ABCD	-0.00047	0.00000352
56	222122	1.0300	CD	0.00047	0.00000352
57	111222	0.9200	CDEF	-0.00047	0.00000352
58	211222	1.0300	BCDEF	-0.00047	0.00000352
59	121222	0.9100	ABC	0.00047	0.00000352
60	221222	1.0200	DEF	0.00047	0.00000351
61	112222	0.9500	ACDEF	-0.00047	0.00000351
62	212222	1.0300	BCF	0.00016	0.00000039
63	122222	0.9200	ACEF	-0.00016	0.00000039
64	222222	1.0400	AVERAGE	0.96500	0.0

Figure 4-17. Sample Computer Program Printout Showing Seebeck Ratio Data for 10-Couple Modules 5 through 12

RESISTANCE RATIO					
DESIGN NUMBER	BATCH DESC.	OBSERVED RESPONSE	EFFECT DESCRIPTION	MEAN EFFECT	ERROR VARIANCE
1	111111	0.8800	A	0.02467	0.01559023
2	211111	1.3900	E	0.17656	0.49879050
3	121111	0.8900	F	0.13900	0.29139880
4	221111	1.4500	D	-0.11562	0.21390617
5	112111	0.9250	ABCEDEF	0.07656	0.09378880
6	212111	1.4100	B	-0.07583	0.09150630
7	122111	1.0400	EF	-0.07156	0.06193856
8	222111	1.4000	ABCEF	0.07094	0.08051383
9	111211	0.8900	BF	-0.06875	0.07562548
10	211211	1.3900	ADF	0.06125	0.08002505
11	121211	0.8500	ADE	0.05219	0.04357655
12	221211	1.3900	AE	-0.05219	0.04357655
13	112211	0.8950	BCDE	-0.05031	0.04050166
14	212211	1.3100	ABCDE	0.04969	0.03950132
15	122211	0.9800	ACF	0.04812	0.03705805
16	222211	1.3700	AC	0.04375	0.03042437
17	111121	0.8900	BEF	0.03281	0.01722662
18	211121	1.4500	ACEF	-0.02906	0.01351402
19	121121	0.8300	ABCDF	-0.02875	0.01322439
20	221121	1.2700	ABDE	0.02844	0.01293903
21	112121	0.8950	ABCE	-0.02719	0.01182445
22	212121	1.2800	DF	-0.02462	0.01050622
23	122121	0.8800	CDE	0.02469	0.00975161
24	222121	1.3700	CD	0.02230	0.00810000
25	111221	0.8650	BCE	0.02094	0.00701404
26	211221	1.1100	ABD	0.02063	0.00680625
27	121221	0.9800	BC	0.02000	0.00639997
28	221221	1.0800	ACE	-0.01781	0.00507659
29	112221	0.8950	BE	0.01781	0.00507654
30	212221	1.1900	CE	-0.01719	0.00472656
31	122221	0.8800	ABE	0.01626	0.00438901
32	222221	1.1500	CF	0.01562	0.00390624
33	111112	1.2500	ACDF	-0.01562	0.00390623
34	211112	1.7600	ABCF	0.01562	0.00390620
35	121112	1.4600	BD	0.01500	0.00360004
36	221112	1.3050	ABCD	-0.01500	0.00360000
37	112112	1.4500	ABE	0.01500	0.00359995
38	212112	1.7000	CDEF	0.01469	0.00345157
39	122112	0.9300	ABEF	-0.01406	0.00316405
40	222112	1.6700	AB	-0.01187	0.00225625
41	111212	1.2400	BCDF	0.01187	0.00225623
42	211212	1.5900	ACDEF	-0.01094	0.00191407
43	121212	0.8900	ABDEF	-0.01031	0.00170135
44	221212	1.4400	C	0.01000	0.00160001
45	112212	1.0900	AF	0.01000	0.00160000
46	212212	1.7000	CD	0.01000	0.00159999
47	122212	0.8800	DEF	0.00969	0.00150157
48	222212	1.6050	BCEF	0.00844	0.00139907
49	111122	1.2400	BDEF	0.00844	0.00139904
50	211122	1.4000	ACDE	0.00844	0.00139904
51	121122	0.8800	ADEF	-0.00781	0.00097656
52	221122	1.3500	ACD	-0.00667	0.00075624
53	112122	0.8600	BCD	0.00687	0.00075624
54	212122	1.4800	ABDF	0.00687	0.00075624
55	122122	0.9800	ABE	0.00531	0.00045157
56	222122	1.2700	BDE	0.00531	0.00045156
57	111222	0.8900	AD	-0.00500	0.00040000
58	211222	1.2600	ABC	-0.00500	0.00039998
59	121222	0.8400	CEF	0.00469	0.00035156
60	221222	1.1650	BD	0.00230	0.00010000
61	112222	0.8700	BCDE	0.00156	0.00003986
62	212222	1.2900	BCF	0.00062	0.00000625
63	122222	0.8900	DE	0.00031	0.00000156
64	222222	1.2250	AVERAGE	1.17346	0.0

Figure 4-18. Sample Computer Program Printout Showing Resistance Ratio Data for 10-Couple Modules 5 through 12

RESPONSE 3 - POWER RATIO					
DESIGN NUMBER	BATCH DESC.	OBSERVED RESPONSE	EFFECT DESCRIPTION	MEAN EFFECT	ERROR VARIANCE
1	111111	0.0650	A	-0.13493	0.00801569
2	211111	0.7194	E	0.12446	0.24784184
3	121111	0.0101	F	-0.08229	0.10834601
4	221111	0.7035	D	0.07132	0.08137495
5	112111	0.9052	B	0.05491	0.05181889
6	212111	0.6589	DE	0.04174	0.05646673
7	122111	0.8496	AF	0.04448	0.03457266
8	222111	0.7431	EF	0.04628	0.03426649
9	111211	0.9166	ABCEF	0.04112	0.02974325
10	211211	0.7194	BCDE	0.04235	0.02869202
11	121211	1.0175	ABCDE	0.04052	0.02626418
12	221211	0.7299	ACDEF	-0.03250	0.01849680
13	112211	0.9719	ACF	-0.03222	0.01661126
14	212211	0.7634	ADF	0.03203	0.01641279
15	122211	0.9380	ADE	0.02887	0.01233758
16	222211	0.7446	ACF	-0.02771	0.01223696
17	111121	0.9515	AC	0.02273	0.00826505
18	211121	0.7035	DE	0.02008	0.00649418
19	121121	0.9977	BC	-0.01988	0.00632618
20	221121	0.8032	ACEF	0.01930	0.00595790
21	112121	1.0226	BEF	-0.01814	0.00526329
22	212121	0.7970	ABEF	0.01646	0.00432458
23	122121	0.9828	ABDE	0.01603	0.00411041
24	222121	0.7446	ABDF	0.01340	0.00279607
25	111221	1.0027	CF	0.01438	0.00330770
26	211221	0.9009	ABCE	0.01423	0.00324187
27	121221	0.9404	BCFE	-0.01390	0.00308993
28	221221	0.9575	BCF	-0.01343	0.00288767
29	112221	0.9289	CE	0.01304	0.00272093
30	212221	0.8763	C	0.01260	0.00253888
31	122221	1.0494	BCE	-0.01212	0.00224859
32	222221	0.8870	BCF	-0.01183	0.00223844
33	111112	0.6099	BDE	-0.01175	0.00220786
34	211112	0.5911	ABF	-0.01163	0.00216874
35	121112	0.5924	BE	0.01078	0.00186086
36	221112	0.7801	CDF	-0.01057	0.00174825
37	112112	0.5463	CDEF	0.01033	0.00170980
38	212112	0.6241	DE	0.01015	0.00164733
39	122112	0.8904	ADEF	-0.01008	0.00162711
40	222112	0.6395	BCDF	-0.01008	0.00162509
41	111212	0.6245	ABE	0.00993	0.00157707
42	211212	0.6712	ABCDF	0.00992	0.00152807
43	121212	0.9111	ACDF	0.00873	0.00121890
44	221212	0.7658	BDEF	0.00712	0.00081010
45	112212	0.7714	CDE	-0.00690	0.00076102
46	212212	0.6251	ABCF	0.00658	0.00069366
47	122212	0.8601	CD	0.00609	0.00059353
48	222212	0.6874	AE	-0.00593	0.00056227
49	111122	0.6532	BD	-0.00570	0.00052040
50	211122	0.7286	ABD	0.00540	0.00046710
51	121122	1.0041	ABDEF	0.00332	0.00043213
52	221122	0.7803	ABC	0.00324	0.00043942
53	112122	0.5629	AB	0.00458	0.00039651
54	212122	0.7090	ABCD	0.00426	0.00038773
55	122122	0.8828	ACD	0.00395	0.00034924
56	222122	0.8356	ACDE	-0.00296	0.00014013
57	111222	0.9510	BCDEF	-0.00162	0.00004208
58	211222	0.7970	AD	-0.00153	0.00003767
59	121222	0.9658	ACE	0.00124	0.00002463
60	221222	0.8934	DEF	0.00123	0.00002438
61	112222	1.0374	BCD	-0.00080	0.00001016
62	212222	0.6224	DEF	0.00048	0.00000366
63	122222	0.9058	ACDEF	0.00001	0.00000000
64	222222	0.8801	ACDEF	0.00000	0.00000000

Figure 4-19. Sample Computer Program Printout Showing Power Ratio Data for 10-Couple Modules 5 through 12

several conceivable hot junction temperatures, etc. The following two levels of each variable were chosen for incorporation in the 10-couple test effort:

- a. Leg manufacturing technique
 - (+) simultaneously pressed legs
 - (-) separately pressed and bonded legs
- b. Hot junction button material
 - (+) iron buttons
 - (-) molybdenum buttons
- c. Hot junction temperatures
 - (+) 1100° F
 - (-) 1000° F
- d. Hot contact pressure
 - (+) 250 psi
 - (-) 150 psi
- e. Thermal insulation
 - (+) Min-K 1301
 - (-) microquartz
- f. Leg hot end
 - (+) conventional
 - (-) soft nose

The (+) or (-) signs accompanying the levels above are symbols used in the subsequent analyses. In most cases, the (+) level represents the level a variable believed to be most preferred, and in fact used in other SNAP-23 evaluations. The (-) levels were levels which presented possible sources of device improvement and therefore needed evaluation.

Several different test arrangements were considered to evaluate in the best way possible all the variables at their different levels with a resultant compromise. Four 10-couple modules were placed on test (modules 1 through 4). These included certain levels of the variables identified. The combinations chosen were the most illustrative and representative of design intent. Modules 5 through 12 were used in a different test arrangement and included all possible combinations of the test variables (two levels each of k variables = 2^k possible combinations or, in the case of the P-leg, 2^6 or 64 combinations). The many combinations were distributed throughout these eight modules. Analysis techniques were available which made it possible to determine the effect of any one variable, despite the fact that it was tested in the presence of other variables. For this test, the "Yates Analysis of Variance" was subsequently employed and has led to the present discussion of test results.

The first three columns of Figures 4-17 through 4-19 are a recapitulation of the 225-hour input data or the response (performance) measurements and the variables contained in the 10-couple test effort that were associated with the P-legs.

The test variables are the same as those identified in earlier paragraphs as are their corresponding (+) and (-) levels. These (-) and (+) levels are subsequently coded 1 and 2, respectively (an analysis program requisite) and are found in this coded form in the second column from the left. In line 1 this column entry is 111111 and represents the following combination of variables ABCDEF: separately pressed and bonded leg, molybdenum hot junction buttons, 1000° F hot junction temperature, 150 psi contact pressure, microquartz thermal insulation, and a soft nose contact. The entry in column three, "Observed Response" is either the average measurement of the selected response (Seebeck voltage ratio, resistance ratio, or power ratio) associated with the combination of variables just described, or else, in each subsequent entry, it is the combination adjacent to it in the "Batch Description" column.

NOTE: No attempts should be made to relate these first three columns to the three remaining columns. The last three columns should be considered separately.

The last three columns contain the Yates analysis results; their relative meanings are as follows: the entries in the "Effect Description" column are the variables, independent or in combination, affecting the given response. They are ranked in descending order of their contribution, which is reflected in the adjacent "Mean Effect" column. For example, examining Figure 4-17 indicates that the mean effect associated with variable A (leg manufacturing technique) is seen to be 0.10391. This means that as A is varied from separately pressed and bonded to simultaneously pressed, Seebeck voltage ratio undergoes a 10.39% change, and in this case, increases 10.39%. At 225 hours, the Seebeck voltage for simultaneously pressed and bonded P-legs is 10.39% higher than that of the separately pressed P-legs.

NOTE: In considering the variables independently, as A alone, B alone, etc., the mean effect associated with it is a measure of the change brought about by first considering the (-) level of the variable and then the (+) level of that same variable. In cases where combinations of variables are considered (AF, AE, ABDF, etc.) the mean effect is not as functional and will be discussed later.

The utility of the "Error Variance" column is realized only when the value recorded in this column is compared to the error estimate (a calculation representative of statistical significance confidence level). The calculated error estimate for the P-leg Seebeck ratio is 0.0031 for the 225-hour analysis. Therefore, Error Variance value greater than 0.0031 implies that the associated effect on Seebeck ratio may be a real one and not entirely due to the inherent data variability. Any Error Variance value less than 0.0031 implies that the associated effect is either not a true one, or lacks significance because it cannot be separated from the natural variation of the data. In attributing significance or the lack of it to any variable or combination of variables, it is necessary to look at both the Error Variance and the mean effect values.

Ranked second in the significance of its effect on Seebeck ratio at 225-hours, there is a second order interaction, AF. There are four possible arrangements of these two variables, A and F (again, 2 levels of k variables = $2^k = 2^2 = 4$ combinations).

The mean effect associated with AF in this case is not as functional as a mean effect value associated with any one independent variable. Whereas, in the case of A's effect, it was possible to define the change induced in Seebeck as A is changed, in the combination of two or more variables, the mean effect now becomes only an indicator of significance. To understand fully the mechanism occurring in a second or third order interaction (combinations of 2 variables or 3 variables, respectively), it is necessary to perform a breakdown of the possible combinations and examine each for its effect on the measured response. In this case, there are four possible AF combinations: (A+ and F+), (A- and F+), (A+ and F-), and (A- and F-).

There are 16 response measurements associated with each of the four combinations. Arranging them as shown below and calculating their mean values, we can make the following observations by examining the differences between their means.

	A-		A+	
F-	0.9050	0.9200	1.000	1.010
	0.9000	0.9100	1.010	1.010
	0.9150	0.9350	1.030	1.010
	0.9400	0.9300	1.020	1.010
	0.9000	0.9200	1.000	1.000
	0.9300	0.9200	1.000	0.990
	0.9000	0.9050	1.000	1.020
	0.9300	0.9500	1.010	1.010
	AVE = 0.9194		AVE = 1.015	
F+	0.8700	0.9000	1.020	1.010
	0.9300	0.9400	1.005	1.025
	0.8900	0.9100	1.030	1.020
	0.9100	0.9300	1.030	1.030
	0.8800	0.9200	1.020	1.010
	0.8800	0.9100	1.050	1.020
	0.9000	0.9500	1.030	1.030
	0.8700	0.9200	1.045	1.040
	AVE = 0.9069		AVE = 1.026	

Maintaining the separately pressed and bonded P-leg, as the hot end is changed from soft nose to conventional, the Seebeck ratio is decreased by 0.0125 or 1.25%, (A-, F-) to (A-, F+).

Maintaining the simultaneously pressed P-leg, as the hot end is changed from soft nose to conventional, the Seebeck ratio is increased by 1.1%, (A+, F-) to (A+, F+).

Retaining a soft nose in both cases, the simultaneously pressed leg manufacturing technique results in a 9.56% improvement in Seebeck ratio over the separately pressed and bonded leg, (A-, F-) to (A+, F-).

Retaining a conventional leg contact in both cases, the simultaneously pressed leg manufacturing technique results in an 11.91% improvement in Seebeck ratio over the separately pressed and bonded leg, (A-, F+) to (A+, F+).

With respect to Seebeck ratio, the best combination of leg manufacture and hot end type would, therefore, be simultaneously pressed P-legs with a conventional contact. If a separately pressed and bonded P-leg were to be used, the soft nose type would produce better Seebeck voltages.

An examination of this type will be made of all second and third order interactions that become significant. While the AF interaction is ranked second at 225 hours, its actual contribution or effect on Seebeck performance is relatively minor, as indicated by the data printout. In breaking down the AF interaction, an increase occurs in its importance when a mean effect of 11.91% is found to exist for one combination. In some cases, therefore, it is necessary to go beyond the statistical analysis and examine the second and third order interactions, looking for significant combinations which might be masked from view otherwise. Analysis of covariance programs is available for this application.

Note the relatively low contribution of the C effect on the Seebeck voltage ratio. Actually, its attributed effect lies well within the defined error limits of 0.0031 (C's error estimate = 0.0017). The temperature model for the 10-couple module P-leg Seebeck performance is well defined, based on its negligible effect at 225 hours.

The P-leg resistance ratio and power ratio printouts can be examined in much the same way as has been done thus far for the Seebeck ratio. It would not be practical at this point to explain each point. Rather, more meaning can be achieved when the data is examined over a period of time, as is done in the following paragraphs.

Tables 4-3 through 4-8 present summaries of the N- and P-leg statistical analyses for the 225-, 550-, and 1000-hour data points. Data in each case is presented in a standard order, rather than a ranked one. Presentation of the data in this form facilitates the detection of changes in effects with time. For example, note in Table 4-6 that for the P-leg Seebeck ratio, the E effect at 225 hours is relatively small (and statistically insignificant). By 1000 hours, the E or thermal emulation mean effect has become 0.03547 or 3.5%; the effect has now achieved statistical significance.

The first entry in these tables is the "Average". This number represents the average value for Seebeck ratio, resistance ratio, or power ratio for N- and P-legs in modules 5 through 12. It is a composite made up of an average N- or P-leg with all variables at their midpoints. Since this value is, therefore, a true average and does not represent an existing condition, it serves as a baseline to which the mean effects can be related.

Each mean effect is related to the average in the following manner. The P-leg Seebeck ratio at 225 hours (as A is changed from its low level (simultaneously pressed) to its high level (separately pressed)) changes 10.39%. This change is about the average condition or the average Seebeck ratio of 0.96508. The total effect, therefore, of varying A is a resultant change in the Seebeck ratio ranging from a low of 0.9131 to a high of 1.0173 (see Figure 4-24). The mean effects should range around an average value if a model is to be reconstructed. At 1000 hours, the mean effects considered significant are in order of magnitude:

N-leg Seebeck Ratio	None
N-leg Resistance Ratio	None
N-leg Power Ratio	None
P-leg Seebeck Ratio	A, E
P-leg Resistance	A, E
P-leg Power Ratio	A, E

Table 4-3. SNAP-23A 10-Couple Modules 5 through 12 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 at Test Hours						
	225	550	1000	1500			
Average	1.01068	1.00755	1.01494				
A	0.00594	0.00303	0.00511				
B	0.00032	0.00240	-0.00302				
C	0.00738	0.01281	0.00469				
D	-0.00032	-0.00656	0.00239				
E	-0.01364	-0.01969	-0.00406				
AB	0.00073	0.00198	0.00301				
AC	-0.00218	-0.00054	-0.00136				
AD	-0.00781	-0.00406	-0.00198				
AE	0.00219	-0.00011	0.00114				
BC	-0.00656	-0.00741	-0.00073				
BD	0.00407	0.00281	-0.00011				
BE	0.00157	0.00551	0.00177				
CD	0.00323	0.00615	0.00468				
CE	0.00906	0.01510	0.00281				
DE	-0.00197	-0.00302	0.00011				
ABC	-0.00199	-0.00094	-0.00093				
ABD	0.00406	0.00031	0.00302				
ABE	-0.00177	-0.00156	-0.00218				
ACD	0.00239	0.00322	0.00073				
ACE	0.00239	0.00010	0.00093				
ADE	-0.00906	-0.00802	-0.00344				
BCD	0.00052	-0.00615	0.00136				
BCE	-0.00198	-0.00302	-0.00219				
BDE	0.00282	0.00510	-0.00282				
CDE	-0.00759	-0.00239	-0.00636				
ABCD	-0.00114	-0.00073	-0.00344				
ABCE	-0.00282	0.00198	-0.00157				
ABDE	0.00491	0.00010	0.00448				
ACDE	0.00032	0.00219	-0.00198				
BCDE	-0.00156	-0.00844	-0.00011				
ABCDE	0.00053	-0.00051	-0.00323				

Table 4-4. SNAP-23A 10-Couple Modules 5 through 12 N-Leg
Statistical Analysis Summary-Resistance 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 at Test Hours							
	225	550	1000	1500	2000	2500	3000	3500
Average	1.00037	0.99474	1.00224					
A	0.00989	0.02261	0.02282					
B	0.01676	0.01324	0.00219					
C	0.00989	-0.01072	-0.01926					
D	0.01136	-0.02281	-0.02114					
E	-0.02260	-0.03903	-0.03949					
AB	-0.00489	-0.00865	-0.00114					
AC	0.01531	0.01074	0.00448					
AD	0.00551	0.00240	0.00677					
AE	0.00990	-0.00678	-0.00198					
BC	-0.03031	-0.02239	-0.00864					
BD	-0.00386	0.00677	-0.00261					
BE	-0.01073	0.01010	-0.00136					
CD	-0.00906	0.01614	-0.00073					
CE	-0.00178	0.01614	0.00177					
DE	-0.02615	-0.01760	-0.00927					
ABC	-0.02074	-0.00760	-0.01498					
ABD	0.01449	0.01031	0.01198					
ABE	-0.00572	-0.00594	-0.00387					
ACD	-0.01199	-0.00448	-0.01157					
ACE	0.00365	0.00595	0.00303					
ADE	-0.02115	-0.00824	-0.00553					
BCD	0.01864	-0.00385	0.00656					
BCE	0.00552	-0.00843	-0.00384					
BDE	0.01697	0.00489	-0.00366					
CDE	0.01010	0.00595	-0.00636					
ABCD	0.00156	-0.00449	-0.00261					
ABCE	0.00510	0.00801	0.00239					
ABDE	0.00948	-0.00072	0.00511					
ACDE	0.02967	0.01699	0.01698					
BCDE	-0.01720	-0.01614	-0.00364					
ABCDE	-0.00177	0.00158	-0.00698					

Table 4-5. SNAP-23A 10-Couple Modules 5 through 12 N-Leg
Statistical Analysis Summary-Power 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 at Test Hours							
	225	550	1000	1500	2000	2500	3000	3500
Average	1.02341	1.02209	1.02934					
A	0.00363	-0.01822	-0.01312					
B	-0.01826	-0.00931	-0.00862					
C	0.00201	0.03581	0.02942					
D	-0.01422	0.01028	0.02672					
E	-0.00713	-0.00066	0.03213					
AB	0.00519	0.01374	0.00731					
AC	-0.02174	-0.01171	-0.00746					
AD	-0.02244	-0.01043	-0.01108					
AE	-0.00723	0.00596	0.00331					
BC	0.01919	0.00817	0.00694					
BD	0.01352	-0.00171	0.00279					
BE	0.01488	0.00005	0.00491					
CD	0.01766	-0.00426	0.01053					
CE	0.02247	0.01380	0.00439					
DE	0.02524	0.01304	0.01097					
ABC	0.01844	0.00915	0.01309					
ABD	-0.00521	-0.00911	-0.00598					
ABE	0.00348	0.00330	-0.00024					
ACD	0.01718	0.01021	0.01151					
ACE	0.00247	-0.00577	-0.00191					
ADE	0.00452	-0.00881	-0.00176					
BCD	-0.01918	-0.00790	-0.00362					
BCE	-0.01024	-0.00354	0.00054					
BDE	-0.01362	0.00442	-0.00213					
CDE	-0.02791	-0.01120	-0.00524					
ABCD	-0.00501	0.00262	-0.00352					
ABCE	-0.01189	-0.00434	-0.00498					
ABDE	-0.00179	0.00107	0.00292					
ACDE	-0.03093	-0.01243	-0.02099					
BCDE	0.01626	0.00024	0.00338					
ABCDE	0.00463	-0.00324	0.00071					

Table 4-6. SNAP-23A 10-Couple Modules 5 through 12 P-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
F	Contact Type	Hard Nose	Soft Nose

Effect	Mean Effect at Test Hours							
	225	550	1000	1500	2000	2500	3000	3500
Average	0.96508	0.96875	0.97758					
A	0.10391	0.11844	0.13234					
B	0.00766	0.00344	0.00797					
C	0.01407	0.02094	0.01328					
D	-0.00141	-0.00531	0.00203					
E	0.00828	0.01375	0.03547					
F	0.00266	0.00969	0.00109					
AB	-0.00359	0.00000	-0.00047					
AC	0.00109	-0.00625	0.00391					
AD	0.00172	-0.00062	-0.00016					
AE	-0.01172	-0.00719	-0.00359					
AF	0.01516	0.01375	0.00766					
BC	-0.00141	0.00125	0.00047					
BD	-0.00203	-0.00312	-0.00203					
BE	-0.00297	-0.00219	-0.00422					
BF	0.00141	0.00125	0.00078					
CD	-0.00047	0.00000	-0.00109					
CE	0.00109	0.00656	0.00109					
CF	-0.00141	-0.01000	-0.00766					
DE	0.00234	-0.00094	0.00484					
DF	0.00297	0.00937	0.00609					
EF	0.00453	0.01781	0.01016					
ABC	0.00047	-0.00156	0.00141					
ABD	0.00484	0.00469	0.00391					
ABE	0.00203	0.00625	-0.00141					
ABF	0.00391	-0.00031	0.00047					
ACD	0.00078	0.00156	-0.00016					
ACE	-0.00078	0.00250	0.00016					
ACF	0.00172	0.00219	0.00078					
ADE	-0.00328	-0.00312	-0.00359					
ADF	0.00609	0.00469	0.00203					
AEF	-0.00672	-0.00625	-0.00953					

Table 4-6. SNAP-23A 10-Couple Modules 5 through 12 P-Leg Statistical Analysis Summary – Seebeck Ratio (Continued)

Effect	Mean Effect at Test Hours							
	225	550	1000	1500	2000	2500	3000	3500
BCD	0.00078	-0.00094	-0.00078					
BCE	0.00172	0.00000	0.00078					
BCF	-0.00578	-0.00531	-0.00234					
BDE	-0.00203	0.00188	0.00328					
BDF	-0.00766	-0.00781	-0.00484					
BEF	0.00203	-0.00125	-0.00266					
CDE	0.00578	0.00750	0.00422					
CDF	0.00328	-0.00594	0.00109					
CEF	0.00172	-0.00750	0.00141					
DEF	0.00047	0.00812	0.00266					
ABCD	-0.00047	-0.00250	-0.00297					
ABCE	-0.00141	-0.00594	-0.00453					
ABCF	0.00609	0.00750	0.00547					
ABDE	-0.00391	-0.00344	-0.00453					
ABDF	0.01172	0.00938	0.01047					
ABEF	0.00078	0.00031	0.00328					
ACDE	0.00203	0.00219	0.00141					
ACDF	-0.00422	-0.00250	0.00141					
ACEF	-0.00016	-0.00344	0.00109					
ADEF	-0.00516	-0.00469	-0.00266					
BCDE	0.00203	0.00219	0.00203					
BCDF	-0.00172	-0.00250	0.00078					
BCEF	-0.00016	-0.00344	-0.00078					
BDEF	-0.00141	0.00281	0.00422					
CDEF	-0.00047	-0.00406	0.00266					
ABCDE	-0.00172	-0.00250	-0.00141					
ABCDF	-0.00172	0.00406	0.00172					
ABCEF	-0.00078	0.00250	0.00078					
ABDEF	-0.00078	-0.00687	-0.00422					
ACDEF	-0.00047	-0.00375	-0.00078					
BCDEF	-0.00047	0.00125	-0.00016					
ABCDEF	0.00453	0.00594	0.00453					

Table 4-7. SNAP-23A 10-Couple Modules 5 through 12 P-Leg
Statistical Analysis Summary-Resistance Ratio

Effect	Mean Effect at Test Hours							
	225	550	1000	1500	2000	2500	3000	3500
BCE	0.02094	-0.00516	-0.01578					
BCF	0.00062	-0.00578	0.02672					
BDE	0.00531	0.01578	0.00578					
BDF	0.00250	-0.01234	-0.00984					
BEF	0.03281	0.03047	0.03422					
CDE	0.02469	0.03453	0.01703					
CDF	0.02250	0.01578	0.03328					
CEF	-0.00469	-0.01953	0.02422					
DEF	0.00969	0.02516	0.00703					
ABCD	-0.01500	-0.01578	-0.01234					
ABCE	-0.02719	-0.00922	-0.02266					
ABCF	0.01562	0.01266	0.01859					
ABDE	-0.02844	-0.02578	-0.04547					
ABDF	0.00687	-0.00641	0.01891					
ABEF	-0.01406	-0.01797	-0.00203					
ACDE	0.00844	-0.00016	-0.01359					
ACDF	-0.01562	0.00734	0.02391					
ACEF	-0.02906	-0.03984	-0.03516					
ADEF	-0.00781	-0.00016	0.01578					
BCDE	-0.05031	-0.05016	-0.04422					
BCDF	0.01187	0.03109	0.02078					
BCEF	0.00844	0.00516	-0.01703					
BDEF	0.00844	0.00984	0.00891					
CDEF	-0.01469	-0.03203	-0.02422					
ABCDE	0.04969	0.02953	0.04266					
ABCDF	-0.02875	-0.02797	-0.04109					
ABCEF	-0.07094	-0.04203	-0.04891					
ABDEF	-0.01031	-0.02234	-0.02859					
ACDEF	-0.01094	-0.02109	-0.04234					
BCDEF	0.00156	-0.00484	0.00953					
ABCDEF	0.07656	0.07922	0.07641					

Table 4-7. SNAP-23A 10-Couple Modules 5 through 12 P-Leg Statistical Analysis Summary – Resistance Ratio (Continued)

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	
F	Contact Type	Hard Nose		Soft Nose	

Effect	Mean Effect at Test Hours							
	225	550	1000	1500	2000	2500	3000	3500
Average	1. 17344	1. 21351	1. 24586					
A	0. 42687	0. 54172	0. 64172					
B	-0. 07563	-0. 07578	-0. 07391					
C	0. 01000	-0. 01266	-0. 05453					
D	-0. 11562	-0. 13797	-0. 11484					
E	-0. 17656	-0. 21141	-0. 22703					
F	0. 13500	0. 14984	0. 12359					
AB	-0. 01187	-0. 00797	-0. 02016					
AC	0. 04375	0. 03203	0. 00734					
AD	-0. 00500	-0. 01828	-0. 04359					
AE	-0. 05219	-0. 06609	-0. 12828					
AF	-0. 01000	-0. 00609	-0. 00516					
BC	0. 02000	0. 02828	0. 04297					
BD	0. 01500	0. 01047	0. 01703					
BE	0. 01781	0. 02891	0. 03109					
BF	-0. 06875	-0. 05484	-0. 06328					
CD	0. 01000	0. 01922	0. 00203					
CE	-0. 01719	-0. 00797	0. 00047					
CF	-0. 01562	-0. 05234	-0. 05828					
DE	0. 00031	-0. 00703	0. 00016					
DF	-0. 02562	-0. 00141	-0. 00047					
EF	-0. 07156	-0. 07672	-0. 09516					
ABC	0. 00500	-0. 01641	-0. 00266					
ABD	0. 02063	0. 03578	0. 04453					
ABE	-0. 00531	-0. 00141	0. 00109					
ABF	0. 01500	0. 00859	0. 00672					
ACD	-0. 00687	0. 00391	0. 01266					
ACE	-0. 01781	-0. 04641	-0. 04141					
ACF	0. 04812	0. 02922	0. 03359					
ADE	-0. 05219	-0. 05797	-0. 02984					
ADF	0. 06125	0. 05766	0. 04203					
AEF	0. 01656	0. 01672	0. 00734					
BCD	0. 00687	0. 02141	0. 01203					

Table 4-8. SNAP-23A 10-Couple Modules 5 through 12 P-Leg
Statistical Analysis Summary-Power 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
F	Contact Type	Hard Nose	Soft Nose

Effect	Mean Effect at Test Hours							
	225	550	1000	1500	2000	2500	3000	3500
Average	0.82558	0.81544	0.81807					
A	-0.13693	-0.18007	-0.20851					
B	0.05691	0.04685	0.04835					
C	0.01260	0.04631	0.05538					
D	0.07132	0.08285	0.07587					
E	0.12446	0.14730	0.17542					
F	-0.08229	-0.07760	-0.06997					
AB	-0.00498	-0.00569	-0.00253					
AC	-0.02273	-0.03038	-0.01668					
AD	-0.00153	-0.00815	0.00311					
AE	-0.00593	-0.00165	0.02681					
AF	0.04648	0.04586	0.03823					
BC	-0.01988	-0.02209	-0.02553					
BD	-0.00510	-0.00500	-0.00620					
BE	-0.01078	-0.01645	-0.01466					
BF	0.04774	0.03547	0.03881					
CD	-0.00609	-0.01288	0.00359					
CE	0.01304	0.01195	0.00596					
CF	0.01438	0.02022	0.02457					
DE	0.01015	0.00787	0.01393					
DF	0.02008	0.01559	0.01446					
EF	0.04628	0.06721	0.06923					
ABC	0.00524	0.01901	0.01750					
ABD	-0.00540	-0.01283	-0.01081					
ABE	0.00993	0.01598	0.00607					
ABF	-0.01163	-0.01038	-0.01449					
ACD	0.00395	0.00445	-0.00404					
ACE	0.00124	0.02346	0.02199					
ACF	-0.02771	-0.01365	-0.02362					
ADE	0.02887	0.03267	0.02170					
ADF	-0.03203	-0.02962	-0.02960					
AEF	-0.03222	-0.03523	-0.04334					

Table 4-8. SNAP-23A 10-Couple Modules 5 through 12 P-Leg Statistical Analysis Summary – Power Ratio (Continued)

Effect	Mean Effect at Test Hours									
	225	550	1000	1500	2000	2500	3000	3500		
BCD	-0.00080	-0.01037	-0.00351							
BCE	-0.01212	0.00688	0.00284							
BCF	-0.01183	-0.00337	-0.01068							
BDE	-0.01175	-0.01265	-0.00628							
BDF	-0.01343	-0.00835	-0.00083							
BEF	-0.01814	-0.01810	-0.01836							
CDE	-0.00690	-0.01350	-0.00657							
CDF	-0.01057	-0.01445	-0.01398							
CEF	0.00123	0.00448	-0.01133							
DEF	0.00048	0.00348	0.00720							
ABCD	0.00424	0.00285	-0.00460							
ABCE	0.01423	-0.00619	0.00528							
ABCF	0.00658	0.00577	0.00432							
ABDE	0.01603	0.01169	0.01487							
ABDF	0.01540	0.02203	0.00962							
ABEF	0.01646	0.01782	0.01381							
ACDE	-0.00296	0.00829	0.01003							
ACDF	0.00873	-0.00277	0.00068							
ACEF	0.01930	0.01216	0.02596							
ADEF	-0.01008	-0.01518	-0.01847							
BCDE	0.04235	0.03725	0.03771							
BCDF	-0.01008	-0.02632	-0.01964							
BCEF	-0.01390	-0.02034	-0.01007							
BDEF	-0.00712	-0.00185	-0.00005							
CDEF	0.01033	0.01499	0.01004							
ABCDE	-0.04052	-0.02705	-0.03377							
ABCDF	0.00992	0.02142	0.02276							
ABCEF	0.04312	0.03327	0.03079							
ABDEF	0.00532	0.00335	0.00457							
ACDEF	0.00001	-0.00198	0.01419							
BCDEF	-0.00162	0.00813	0.00024							
ABCDEF	-0.03250	-0.03386	-0.02855							

At present, the N-leg mean effects are on the borderline. While some effects do appear statistically significant, their measurement lies within data capturing error limits and test noise. The P-leg noise level is somewhat higher than that of the N-legs, due in part to the additional test variable, incomplete duplication (N-leg test is actually completely duplicated, P-leg test is only one-fourth duplicated), and the inherent instability of P-leg performance in the early part of its life.

Figures 4-20 through 4-23 graphically present the N- and P-leg average Seebeck ratios, resistance ratios, and power ratios over time. In the case of the P-legs, the significant effects are shown on a second scale. While it is the purpose of the 10-couple tests to evaluate all six variables, A B C D E F, only those which have a readily apparent performance effect are plotted. Conceivably, other variables will achieve importance with time and will then be added to subsequent graphic presentations; while those whose effect becomes insignificant will be removed from the graphs.

An attempt is made in Figures 4-24, 4-25, and 4-26 to portray the direct relationship of the mean effects associated with variables A and E on the average P-leg ratios. In the case of variable A (leg manufacturing technique), the simultaneously pressed P-leg (A+) results in an improved Seebeck ratio. Unfortunately, it results in higher resistance as shown by the higher resistance ratio with A+, and leads to a decreased power ratio. Since the primary performance gauge is the power ratio, the A- level (separately pressed and bonded P-leg) affords an improved performance, despite its accompanying lower Seebeck performance.

The lowest resistance ratio could be achieved by using the A-, E+ combination, since both have a beneficial mean effect. The theoretical reduction in resistance ratio is determined by the average $+ 1/2 [(A- \text{ mean effect}) + (E+ \text{ mean effect})]$. The theoretical result and the experimental result of such a combination are shown on the resistance ratio curve, Figure 4-25. The net difference between theoretical and experimental results changes with time. The discrepancy between the theoretical and experimental results represents an AE interaction which increases with time.

Figure 4-20. N-Leg Statistical Analysis Summary Data
10-Couple Modules 5 through 12
Average Effects for All Factors for
Seebeck Ratio, Resistance Ratio, Power Ratio

Figure 4-21. 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 4-22. 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 4-23. 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 4-24. P-Leg Statistical Analysis Summary Data
10-Couple Modules 5 through 12
Effects of Variables A and E on P-Leg Seebeck Ratio

Figure 4-25. P-Leg Statistical Analysis Summary Data
 10-Couple Modules 5 through 12
 Effects of Variables A and E on P-Leg Resistance Ratio

Figure 4-26. P-Leg Statistical Analysis Summary Data
10-Couple Modules 5 through 12
Effects of Variables A and E on P-Leg Power Ratio

Both the difference in the theoretical and the experimental results, and the change in the difference are small. The comparison was made to point out that the A and E variables are not truly indefinite and should be considered in union with one another (if the true net effect is to be gauged).

Any conclusions drawn at this time might not be applicable at the 2000-hour point. Any survey in depth is a cumulative effort. Subsequent presentations will increase in both depth and meaning as more data is gathered. Trends or mechanisms not evident now can be expected to emerge and their coverage will be added.

Math modeling (both linear and higher order curve fits, and extrapolations of averages and significant mean effects versus time) will be performed. Much can and will be done with an analysis of this type.

This discussion serves as an introduction to the analysis and its associated techniques. As the data base increases, more comprehensive coverage will become available.

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 4-9 and shown graphically in Figure 4-27.

Nomenclature for Table 4-9 and Figure 4-27 is as follows. In this table and graph, the following nomenclature is used:

- 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 27,000 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

During the quarter, refurbishment of the converter and test station were completed and the converter placed back on long-term test.

Among refurbishing modifications made to the test station was the addition of twenty-one thermocouples (location shown in Figure 4-28) which provides sufficient temperature information to allow computation of test station losses. Eight are chromel-alumel thermocouples and are located around the heater block where temperatures are high. At the upper end, one chromel-alumel

Table 4-9. SNAP-23 Six-Couple Module A3 Performance Data
(Start of Test: 3/5/65; current reading: 4/1/68)

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
166	1103	196	1.26	2.76	0.24	1.64
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
2,130	1100	189	1.29	2.66	0.26	1.59
2,490	1100	192	1.28	2.65	0.26	1.58
3,000	1100	190	1.28	2.50	0.26	1.61
4,120	1100	191	1.28	2.60	0.26	1.60
5,010	1100	191	1.27	2.58	0.26	1.58
5,520	1100	186	1.27	2.57	0.26	1.57
6,020	1100	191	1.26	2.54	0.26	1.54
7,150	1100	197	1.25	2.51	0.26	1.52
8,180	1090	197	1.22	2.44	0.26	1.47
8,900	1090	190	1.22	2.46	0.26	1.46
10,130	1085	189	1.22	2.45	0.25	1.46
11,230	1100	190	1.23	2.48	0.26	1.50
12,600	1100	192	1.23	2.50	0.25	1.52
14,910	1076	190	1.18	2.37	0.25	1.42
17,710	1095	193	1.20	2.35	0.24	1.47
20,160	1100	195	1.18	2.36	0.24	1.43
22,630	1100	193	1.17	2.33	0.24	1.42
23,688	1095	190	1.17	2.36	0.24	1.43
25,128	1100	192	1.17	2.34	0.24	1.41
27,648	1099	191	1.16	2.33	0.24	1.38

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

Figure 4-27. SNAP-23 Performance Data - Module A-3

Figure 4-28. P-2 Converter Test Vehicle Assembly

thermocouple is located next to the converter hold down bolt. The remaining thermocouples (located in low temperature areas) are iron-constantan, and are located in areas of low temperature.

Performance data for the converter after it was placed back on long-term test is presented in Table 4-10. Normalized performance curves are shown in Figure 4-29; data is normalized to $T_h = 1070^\circ\text{F}$, $T_c = 200^\circ\text{F}$.

4.3 QUALITY ASSURANCE

Reliability continued to monitor the test data accumulated from the 10-couple modules. This effort assures that the data is analyzed for reliability considerations.

Table 4-10. 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
7/2/65	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
1/5/66	4,006	1033	202	48.7	2.60	9.37	63.3	51.2	9.75	67.3
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	51.2	9.52	68.8
6/23/66	7,984	1020	195	48.4	2.52	9.60	61.0	----	----	----
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
3/28/68	10,687	1068	190	51.2	2.74	9.60	68.2	50.9	9.73	66.7

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 4-29. SNAP-23 Prototype P-2 Converter Performance (Normalized Data)

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SECTION 5.0
TASK IV – 25 - AND 100 - WATT
CONCEPTUAL DESIGN

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

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

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