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**SNAP-23A PROGRAM, PHASE 1
THERMOELECTRIC CONVERTER
DEVELOPMENT PROGRAM
QUARTERLY REPORT NO. 11**

P3578

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

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Available from:

Clearinghouse for Federal Scientific and Technical Information
National Bureau, U.S. Department of Commerce
Springfield, Virginia 22151

Price: Printed Copy \$3.00, Microfiche \$0.65

Report No. MMM-3824-0040

Issue Date: October 31, 1969

AEC RESEARCH AND DEVELOPMENT REPORT

This report has been prepared under Contract AT(30-1)-3824
3824 with the U. S. Atomic Energy Commission

SNAP-23A PROGRAM, PHASE I

THERMOELECTRIC CONVERTER

DEVELOPMENT PROGRAM

QUARTERLY REPORT NO. 11

July 1, 1969 through September 30, 1969

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SNAP-23A
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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 July 1969 through 30 September 1969.

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

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

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

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SNAP-23A 60-WATT THERMOELECTRIC CONVERTER
(PMC-2 CONFIGURATION)

1.0 SUMMARY

Major effort during this quarter was on the SNAP-23A Converter PMC-2 and the Fire Safety Program. PMC-2 effort was in the following areas:

- Completion of weld and potting development.
- Completion of component design including those requiring data from the weld development.
- Completion of sub-assembly drawings.
- Fabrication and assembly of the converter.
- Technical interfacing with Westinghouse.

Fire Safety Program effort consisted of:

- Completion of Fire Safety Module design.
- Completion and submittal of Fire Safety Evaluation Test Procedure to the AEC.
- Design meeting with Westinghouse on the Fire Safety Test Stand.

Long term operation and testing continued on the following devices:

- 10-couple modules 1, 3 and 5-12.
- Converter 23P2.

- Six-couple module 23A-3.
- Converters EMC-2, EMC-3 and PMC-1B.

Table 1-1 summarizes the operating time of the long term devices, while Table 1-2 shows the EOL data for EMC-2, EMC-3 and PMC-1B.

Table 1-1
Operating Time of SNAP-23A Devices

Device	Operating Time	
	Hours	Years
EMC-2	11,840	1.35
EMC-3	14,211	1.62
PMC-1A	8,954	1.02
PMC-1B	8,061	0.92
10-Couple Modules 1 & 3	16,976	1.94
10-Couple Modules 5-12	14,000	1.60
23P2	23,640	2.70
23A3	40,101	4.58

Table 1-2
History of Converter Performance
for
End-of-Life Conditions

Parameter	Symbol	Unit	EMC-1	EMC-2	EMC-3	PMC-1A	PMC-1B
Net Power Input	P_{in}	Watts (t)	834	873	882	849	874
Power Output	P_o	Watts (e)	50.9	60.2	61.3	69.4	65.9
Efficiency	η	Percent	6.08	6.90	6.95	8.16	7.54
Open Circuit Voltage	E_o	Volts	40.9	41.1	40.9	41.8	41.3
Load Voltage	V_1	Volts	23.0	24.0	24.0	24.0	24.0
Load Current	I_1	Amps	2.21	2.51	2.56	2.89	2.75
Internal Resistance	R_g	Ohms	8.10	6.80	6.63	6.16	6.29
Temperatures							
Hot Junction	T_h	°F	900	900	900	919	921
Cold Junction	T_c	°F	173	172	172	177	176
Heat Loss	P_I	Watts (t)	27	28	28	28	28
Gross Power	P_t	Watts (t)	864	901	910	880	902
Internal Gas Pressure	P_g	PSIG	9.4		8.7	10.0	10.4
Test Time	Hrs	Hours	43	11,810	14,211	507	8,061

Values are for latest measurements taken by 3M on each converter.

2.0 PROGRAM MANAGEMENT

2.1 LIAISON

Liaison activities conducted with Westinghouse during this quarter were related to 1) a procedure for mating a "cold" PMC-2 converter to a "hot" spud on the Fueled Prototype Mockup System (FPMS), 2) revised shock and vibration requirements, 3) review and approval of PMC-2 Interface Inspection Plan, 4) review and concurrence of the Fire Safety Module Test Procedure, 5) a revised PMC-2 converter hot frame FPMS spud interface dimension and 6) specific definition of insulation material in a) hot frame cavity, and b) area adjacent to internal surface of the support cone.

Discussions were conducted with Westinghouse on the maximum stud temperature allowed during system assembly of the FPMS, and the procedure for mating the converter to the systems. This is the first time this procedure is required since previous systems were electrically heated. This procedure specifies a maximum differential temperature between the converter and "hot" spud plus a maximum rate of temperature rise. 3M and Westinghouse have agreed to a procedure for mating the converter to the FPMS.

System dynamic testing has indicated that the laterally imposed shock loads reach 15G's. This is higher than the design specifications for PMC-2. As a result, Westinghouse would have to redesign their support structure to reduce the magnification factor from 3 to 2, or have 3M analyze the converter structure to determine its capability to withstand a 15G lateral shock load. The decision was to analyze the converter structure which was subsequently completed. Analysis

indicated that structually the converter is capable of withstanding a 15G lateral shock load, but that for the converter and thermoelectric to be qualified for 15G's a unit should be dynamically tested.

The inspection plan for measuring the thermal mechanical interfaces was submitted to Westinghouse Quality for review and concurrence. The plan was reviewed with concurrence obtained on 7 August 1969.

The Fire Safety Module Test procedure less the Hittman Associate Incorporated (HAI) fire incident response curves were reviewed by Westinghouse. Preliminary concurrence was received at the 30 July interface meeting. Subsequent design activity at 3M after receipt of the HAI response curves dictated design changes to the fire safety test stand which would alter the test procedure. A subsequent AEC/3M/Westinghouse meeting on 9 September stressed the urgency of completing the fire safety effort. As a result of this meeting, 3M stated that fire incident tests will be conducted to provide initial test data by 7 November 1969.

Liaison activity was conducted with Westinghouse on the hot frame interface dimensions. The dimension of the taper and one of the diameters would produce an out-of-tolerance condition. Since the identity of this condition occurred prior to fabrication of the FPMS stud, Westinghouse, after analyzing the 3M data for the hot frame, agreed to change the dimensions on their stud. Since these changes occur only on the piece parts for PMC-2 it was decided that these changes in dimensions would not be made on the Interface Control Drawing. Instead Westinghouse will prepare a variation request which will be included in the software for PMC-2.

The insulation material for the last two undefined areas were discussed and resolved by 3M and Westinghouse. It was decided to use microquartz pads internal to the converter and adjacent to the support cone because of defined irregularities. Secondly, it was agreed to use powdered Min-K 2002 in the hot frame cavity to within one inch of the top of the hot frame web while on test at 3M. When the converter is shipped to Westinghouse and incorporated into a system, block and powdered Min-K 2002 will be utilized in this same area.

2.2 DOCUMENTATION AND REPORTS

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

- Quarterly Report No. 10 (MMM-3824-0037)
- May Monthly Report (MMM-3824-0036)
- July Monthly Report (MMM-3824-0038)
- August Monthly Report (MMM-3824-0039)
- Fire Safety Evaluation Test Plan and Procedures (MMM-3824-1203)
- 10-Couple Module Data for month of June 1969 (MMM-3824-1215).

2.3 WORK FORECAST FOR NEXT QUARTER

Major effort scheduled for next quarter is as follows:

- Complete welding of PMC-2 converter
- Initiate and complete processing of converter PMC-2
- Complete fabrication and assembly of Fire Safety Evaluation Test Devices
- Initiate and complete testing of Fire Safety Evaluation Test Devices
- Start Development Plan for SNAP-23A Phase II
- Continue long-term testing of the following devices:
 - Experimental Mockup Converter No. 2 (EMC-2)
 - Experimental Mockup Converter No. 3 (EMC-3)
 - Prototype Mockup Converter No. 1B (PMC-1B)

- 10-Couple Modules
 - Converter 23P2
 - Module 23 A-3
- Evaluation of long-term test data.

3.0 CONVERTER DEVELOPMENT – 60-WATT

3.1 LONG-TERM TEST CONVERTERS

3.1.1 Experimental Mockup Converters (EMC)

3.1.1.1 Experimental Mockup Converter No. 2 (EMC-2)

EMC-2 long-term test continued during the quarter. Converter performance was re-evaluated at EOL design conditions; the results are presented in Table 3-1. EMC-2 BOL performance history for over one year of operation is presented in Table 3-2 and shown graphically in Figure 3-1. Initial and current EMC-2 experimental-to-theoretical performance ratios are presented in Table 3-3. Analysis of recent EMC-2 data indicates that:

- The Seebeck voltage and resistance of the simultaneously pressed P-legs continues to decrease. This agrees with performance trends observed for comparable legs in ten-couple module 1 (see Figures 4-1 and 4-2).
- The Seebeck voltage of the simultaneously-pressed N-legs appears to have stabilized while resistance remains basically unchanged.
- Thermal performance of the converter remains relatively stable. However, the thermal input required to maintain a given set of conditions appears to be decreasing slightly with time.

- As a result of the above changes, converter EOL efficiency decreased slightly during the past quarter.

3.1.1.2 Experimental Mockup Converter No. 3 (EMC-3)

EMC-3 long-term test continued during the quarter. Converter performance was re-evaluated at EOL design conditions; the results are presented in Table 3-4. EMC-3 BOL performance history is presented in Table 3-5 and shown graphically in Figure 3-2. Initial and current EMC-3 experimental-to-theoretical performance ratios are presented in Table 3-6. Analysis of recent EMC-3 data indicates that:

- The resistance of the bonded-type P-legs continues to decrease slightly with time while the Seebeck voltage remains relatively stable. This long-term trend agrees with the initial trends observed on comparable P-legs in PMC-1a and 1b.
- The resistance of the simultaneously-pressed N-legs continues to increase. This agrees only with those random comparable legs where the Seebeck voltage has not shown a significant decrease.
- Thermal performance during the past quarter was quite stable.
- EOL efficiency tended to remain unchanged as a result of the thermoelectric changes tending to compensate one another from a power standpoint.

3.1.2 Prototype Mockup Converters (PMC)

3.1.2.1 Prototype Mockup Converter No. 1A (PMC-1A)

PMC-1a long-term test continued during the quarter. This converter is on test at Westinghouse Astronuclear Laboratory (WANL) as a component in the experimental mockup system life-test. PMC-1A performance history is presented in Table 3-7

in the form of experimental-to-theoretical performance ratios. Analysis of the PMC-1A data indicates that the converter continues to perform in a stable manner with no significant long-term changes.

3.1.2.2 Prototype Mockup Converter No. 1B (PMC-1B)

PMC-1B long-term test continued during the quarter. Converter performance was re-evaluated at EOL design conditions; the results are presented in Table 3-8. PMC-1B BOL performance history is presented in Table 3-9 and shown graphically in Figure 3-3. Initial and current PMC-1B experimental-to-theoretical performance ratios are presented in Table 3-10. Analysis of recent PMC-1B data indicates that:

- The Seebeck voltage of the bonded-type P-legs is decreasing while the resistance increased slightly. This does not agree with performance trends observed for comparable legs in other devices. However, the voltage trend agrees with that observed on comparable legs in Module 12.
- The resistance of the simultaneously-pressed N-legs increased slightly during the past quarter. This trend is typical of N-legs whose Seebeck voltage remains stable (refer to EMC-3 discussion). The higher rate of resistance increase observed on EMC-3 N-legs is likely due to a greater sublimate resulting from a higher nominal hot junction temperature on EMC-3 (1085°F versus 1011°F).
- Thermal performance of the converter remains relatively stable.
- Converter EOL efficiency has decreased slightly as a result of the thermoelectric changes.

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

Parameter	Symbol	Units	Measured Values at Specified Hours						
			3.5	508 (Pre- dynamic Test)	628 (Post- dynamic Test)	3683	7142	9488**	11,810**
Net Power Input	P_{in}	Watts (t)	832	852	860	896	891	881	873
Power Output	P_o	Watts (e)	57.6	57.6	57.1	63.2	63.6	61.2	60.2
Efficiency	η	Percent	6.92	6.16	6.64	7.05	7.14	6.95	6.90
Open Circuit Voltage	E	Volts	41.1	42.4	42.9	43.2	42.8	41.9	41.1
Load Voltage	V_l	Volts	23.0	23.0	24.0	24.0	24.0	24.0	24.0
Load Current	I_l	Amps	2.50	2.50	2.38	2.63	2.65	2.55	2.51
Internal Resistance	R_g	Ohms	7.23	7.76	7.94	7.28	7.08	7.00	6.80
Temperatures									
Hot Frame	T_{hf}	°F	931	926	934	933	935	932	930
Hot Junction	T_h	°F	901	898	904	903	905	902	900
Cold Junction	T_c	°F	173	172	176	171	175	174	172
Outer Case	T_{oc}	°F	128	129	125	119	119	116	114
Gross Power Input*	P_t	Watts (t)	860	880	888	924	919	909	901

*Watts-transducer was recalibrated at 3511 hours and 6440 hours.

**Reading recorded on 29 September 1969

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

Parameter	Symbol	Units	Measured Values at Specified Hours											
			75.5	170.0	483	820	1612	3009	4469	6010	7349	8167	10,370	11,840***
Power Output	P_o	Watts (e)	79.5	79.0	79.7	78.3	78.8	84.0	85.2	86.2	86.2	84.0	83.6	82.9
Normalized Power Output	P_N	Watts (e)	79.6	79.1	79.9	78.9	80.7	83.8	84.1	84.6	84.6	84.2	82.9	81.7
Open Circuit Voltage	E	Volts	53.7	54.2	54.5	54.1	54.2	55.2	55.6	55.3	55.3	54.3	54.0	53.4
Normalized O. C. Voltage	E_N	Volts	53.8	54.3	54.8	54.8	54.7	55.0	55.5	55.2	55.0	55.0	53.8	53.0
Internal Resistance	R_g	Ohms	9.03	9.24	9.26	9.30	9.27	8.99	8.99	8.79	8.77	8.73	8.67	8.59
Norm. Int. Resistance	R_N	Ohms	9.04	9.25	9.31	9.42	9.33	9.12	8.98	8.83	8.81	8.77	8.67	8.59
Load Voltage	V_l	Volts	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
Load Current	I_l	Amps	3.18	3.16	3.19	3.13	3.15	3.36	3.41	3.45	3.45	3.36	3.34	3.31
Temperature														
Hot Junction	T_h	°F	1084	1084	1081	1076	1076	1078	1089	1036	1086	1082	1087	1088
Cold Junction	T_c	°F	191	191	190	189	195	186	188	185	185	190	189	187
Gross Power Input**	P_t	Watts (t)	1104	1112	1120	1132	1128	1156	1179	1175	1153	1145	1150	1144

* Data normalized to $T_h = 1085^\circ\text{F}$ and $T_c = 191^\circ\text{F}$

** Watts-transducer was recalibrated at 3511 and 6440 hours

*** Reading recorded on 30 September 1969

Figure 3-1
 SNAP-23A EMC-2 Performance History
 (Beginning-of-Life Conditions)

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

Thermoelectric Designation	Time Evaluated in Hours	Seebeck Ratio		Resistance Ratio ⁽¹⁾		Power Ratio ⁽²⁾	
		EOL	BOL	EOL	BOL	EOL	BOL
Thermopile ⁽³⁾	Initial EOL - 3.5	1.02		1.16		0.90	
	Initial BOL - 47.5		1.01		1.10		0.93
	5288		1.03		1.10		0.98
	7349		1.03		1.09		0.98
	9559		1.01		1.08		0.95
	11840		1.00		1.06		0.94
Typical N-Leg ⁽³⁾	Initial EOL - 3.5	1.00		0.97		1.03	
	Initial BOL - 47.5		0.99		0.93		1.05
	5288		1.00		0.94		1.06
	7349		1.00		0.96		1.04
	9559		0.98		0.96		1.00
	11840		0.98		0.97		0.99
Typical P-Leg ⁽³⁾	Initial EOL - 3.5	1.04		1.34		0.80	
	Initial BOL - 47.5		1.03		1.28		0.83
	5288		1.06		1.24		0.91
	7349		1.05		1.21		0.92
	9559		1.03		1.19		0.90
	11840		1.01		1.16		0.88

(1) Theoretical resistance includes no extraneous resistance allowance.

(2) Matched load power ratio = $\frac{(\text{Seebeck Ratio})^2}{\text{Resistance Ratio}}$

(3) Design value = 1.0 for Seebeck, 1.068 for Resistance.

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

Parameter	Symbol	Units	Measured Values at Specified Hours							
			11.5	1203	2783	3750	6078	9539	11,906	14,211**
Net Power Input	P_{in}	Watts (t)	824	860	864	848	866	851	882	882
Power Output	P_o	Watts (e)	61.2	65.3	66.5	66.2	67.2	64.1	61.2	61.3
Efficiency	η	Percent	7.43	7.59	7.79	7.81	7.76	7.53	6.94	6.95
Open Circuit Voltage	F	Volts	40.7	41.5	41.3	41.5	41.6	41.5	41.2	40.9
Load Voltage	V_l	Volts	23.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
Load Current	I_l	Amps	2.66	2.72	2.77	2.77	2.80	2.67	2.55	2.56
Internal Resistance	R_g	Ohms	6.65	6.43	6.25	6.34	6.30	6.56	6.72	6.63
Temperatures										
Hot Frame	T_{hf}	°F	928	931	925	930	928	930	931	930
Hot Junction	T_h	°F	900	903	899	900	898	901	901	900
Cold Junction	T_c	°F	172	172	174	175	171	176	174	172
Outer Case	T_{oc}	°F	151	150	151	151	146	151	149	149
Gross Power Input*	P_t	Watts (t)	852	888.0	892	876	894	879	910	910
Internal Gas Pressure	P_g	PSIG	8.4	9.4	9.6	9.4	9.1	8.8	8.9	8.7

* Watts-transducer was recalibrated at 3507, 5907, 8837, 11,690, and 13,943 hours.

** Reading recorded on 29 September 1969

Table 3-5
SNAP-23A Converter EMC-3 Performance History
(Beginning-of-Life Conditions)

Parameter	Symbol	Units										
			123	681	1107	1800	4014	6223	8407	10,563	12,765	14,237***
Power Output	P_o	Watts (e)	88.0	89.3	91.0	91.5	92.3	92.9	90.8	90.2	87.8	87.5
Normalized Power Output	P_N^*	Watts (e)	88.2	91.2	92.6	92.9	93.3	91.7	91.0	88.9	88.1	87.4
Open Circuit Voltage	E	Volts	54.1	53.7	54.1	53.9	54.3	54.8	54.5	54.4	53.7	53.9
Normalized O. C. Voltage	E_N^*	Volts	54.4	54.6	54.6	54.7	54.9	54.5	54.7	54.2	54.0	53.8
Internal Resistance	R_g	Ohms	8.27	8.04	7.99	7.90	7.94	8.02	8.11	8.15	8.17	8.26
Norm. Int. Resistance	R_N^*	Ohms	8.34	8.14	8.01	8.02	8.03	8.03	8.14	8.20	8.22	8.25
Load Voltage	V_l	Volts	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
Load Current	I_l	Amps	3.52	3.57	3.64	3.66	3.69	3.71	3.63	3.61	3.51	3.49
Temperature												
Hot Junction	T_h	°F	1080	1074	1080	1074	1077	1087	1083	1085	1081	1086
Cold Junction	T_c	°F	189	193	195	191	191	187	191	185	190	191
Gross Power Input**	P_t	Watts(t)	1096	1108	1120	1124	1112	1140	1122	1123	1161	1161
Internal Gas Pressure	P_g	PSIG	10.4	11.2	11.1	11.0	11.0	10.9	10.3	10.2	10.2	10.3

* Data normalized to $T_h = 1085^\circ\text{F}$ and $T_c = 191^\circ\text{F}$

** Watts-transducer was recalibrated at 3507, 5907, 8837, 11,690 and 13,943 hours

*** Reading recorded on 30 September 1969

Figure 3-2
 SNAP-23A Converter EMC-3 Performance History
 (BOL Condit.)

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

Thermoelectric Designation	Time Evaluated in Hours	Seebeck Ratio		Resistance Ratio ⁽¹⁾		Power Ratio ⁽²⁾	
		EOL	BOL	EOL	BOL	EOL	BOL
Thermopile ⁽³⁾	Initial EOL – 11.5	0.98		1.07		0.90	
	Initial BOL – 41		0.98		1.05		0.91
	5500		0.99		0.99		0.99
	10563		0.98		1.00		0.96
	12765		0.98		1.01		0.95
	14237		0.98		1.02		0.94
Typical N-Leg ⁽³⁾	Initial EOL – 11.5	1.01		1.05		0.97	
	Initial BOL – 41		1.00		1.01		0.99
	5500		1.00		0.96		1.04
	10563		0.99		1.00		0.98
	12765		0.99		1.03		0.95
	14237		0.99		1.05 to 1.06		0.92
Typical P-Leg ⁽³⁾	Initial EOL – 11.5	0.96		1.13		0.82	
	Initial BOL – 41		0.96		1.09		0.84
	5500		0.97		1.02		0.92
	10563		0.97		1.00		0.94
	12765		0.96		0.97		0.95
	14237		0.96		0.96		0.95

(1) Theoretical resistance includes no extraneous resistance allowance.

(2) Matched load power ratio = $\frac{(\text{Seebeck Ratio})^2}{\text{Resistance Ratio}}$

(3) Design value = 1.0 for Seebeck, 1.068 for Resistance.

Table 3-7
 SNAP-23A Converter PMC-1A Performance Data
 (Ratio of Experimental-to-Theoretical Values)

Thermoelectric Designation	Time Evaluated in Hours	Seebeck Ratio	Resistance Ratio ^(*)
Thermopile ⁽²⁾	47.5	0.98 ⁽³⁾	0.98 ⁽³⁾
	508	0.99 ⁽³⁾	0.96 ⁽³⁾
	704	(0.98)	(0.98)
	1782.5	(0.98)	(0.96)
	3798	(0.98)	(0.94)
	7758	(0.99)	(0.95)

(1) The theoretical resistance values include only T/E material resistance.

(2) Design Value: Seebeck Ratio = 0.98 - 0.99 .
 Resistance Ratio = 0.97 - 1.08

(3) EOL ratios obtained during performance verification tests.

() Based on Westinghouse system experimental data with the converter hot junction temperature at approximately 1000° F.

Table 3-8
SNAP-23A Converter PMC-1B Performance Data
(End-of-Life Conditions)

Parameter	Symbol	Units	Measured Value at Specified Hours				
			28	1104	3457	5644**	8061**
Net Power Input*	P_{in}	Watts	824	870	893	884	87.4
Power Output	P_o	Watts	63.8	67.2	70.1	68.4	65.9
Efficiency	η	Percent	7.74	7.72	7.85	7.74	7.54
Open Circuit Voltage	E	Volts	41.2	41.4	41.9	41.6	41.3
Load Voltage	V_1	Volts	24.0	24.0	24.0	24.0	24.0
Load Current	I_1	Amps	2.66	2.80	2.92	2.85	2.75
Internal Resistance	R_g	Ohms	6.47	6.21	6.14	6.18	6.29
Temperatures							
Hot Frame	T_{hf}	°F	965	961	962	960	961
Hot Junction	T_h	°F	920	921	922	920	921
Cold Junction	T_c	°F	176	177	175	174	176
Outer Case	T_{oc}	°F	145	149	148	142	146
Gross Power Input***	P_t	Watts	852	898	921	912	902
Internal Gas Pressure	P_g	PSIG	9.6	11.3	10.9	10.4	10.4

* Estimated values based on PMC-1A test station losses.

** Reading recorded on 29 September 1969

*** Watts-transducer was recalibrated at 5543 hours.

Table 3-9
SNAP-23A Converter PMC-1B Performance History
(Beginning-of-Life Conditions)

Parameter	Symbol	Units	Measured Values at Specified Hours													
			126	267	558	1059	1540	2285	2906	3722	4426	5169	5810	6626**	7270**	8091**
Power Output	P_o	Watts (e)	86.2	89.0	90.2	90.0	90.5	91.2	91.2	83.2	80.0	79.5	79.6	79.6	79.2	78.3
Normalized Power Output	P_N^*	Watts (e)	86.1	88.7	90.3	89.2	91.1	90.7	91.1	90.0	87.3	87.7	86.6	86.7	86.7	85.7
Open Circuit Voltage	E	Volts	52.4	52.6	52.6	52.3	52.7	52.6	52.5	48.2	47.9	47.5	47.4	47.5	47.4	47.3
Normalized O. C. Voltage	E_N^*	Volts	52.4	52.4	52.7	52.2	52.8	52.3	52.7	52.6	52.4	52.4	52.0	52.0	52.0	51.8
Internal Resistance	R_g	Ohms	7.94	7.76	7.66	7.58	7.64	7.55	7.54	6.96	7.15	7.07	7.04	7.06	7.08	7.12
Norm. Int. Resistance	R_N^*	Ohms	7.93	7.79	7.67	7.63	7.53	7.51	7.53	7.66	7.86	7.81	7.78	7.75	7.75	7.79
Load Voltage	V_l	Volts	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
Load Current	I_l	Amps	3.45	3.56	3.61	3.60	3.62	3.65	3.65	3.33	3.20	3.18	3.18	3.18	3.17	3.13
Temperatures***																
Hot Junction	T_h	°F	1081	1079	1079	1079	1079	1084	1075	1014	1014	1009	1012	1015	1015	1015
Cold Junction	T_c	°F	192	190	192	188	194	192	189	184	187	188	185	187	189	189
Gross Power Input****	P_t	Watts (t)	1076	1105	1116	1118	1124	1139	1138	1038	1034	1028	1022	1022	1022	1014
Internal Gas Pressure	P_g	PSIG	11.1	11.9	12.7	13.0	12.7	13.0	12.5	11.8	11.6	11.7	11.7	11.4	11.4	11.3

* Data normalized to T_h 1080°F and T_c = 192°F

** Reading recorded on 30 September 1969

*** Converter input changed at 3534 hours to PMC-2 BOL Conditions (T_h = 1011°F and T_c = 187°F)

**** Watts-transducer was recalibrated at 5543 hours

Figure 3-3
 SNAP-23A Converter PMC-1B Performance History
 (BOL Conditions)

Table 3-10
SNAP-23A Converter PMC-1B Performance Data
(Ratio of Experimental-to-Theoretical Values)

Thermoelectric Designation	Time Evaluated in Hours	Seebeck Ratio		Resistance Ratio ⁽¹⁾	
		EOL	BOL	EOL	BOL
Thermopile ⁽²⁾	Initial EOL - 28	0.97	0.98	1.01	0.98
	Initial BOL - 127				
	1104	0.97		0.97	
	3457	0.98		0.96	
	5644	0.98		0.97	
	8061	0.97		0.98	
Typical N-Leg ⁽³⁾	Initial EOL - 28	1.00	1.00	0.97	0.95
	Initial BOL - 127				
	1104	1.00		0.97	
	3457	1.01		0.96	
	5644	1.01		0.98	
	8061	1.01		0.99	
Typical P-Leg ⁽⁴⁾	Initial EOL - 28	0.96	0.98	1.04	1.04
	Initial BOL - 127				
	1104	0.96		0.98	
	3457	0.96		0.96	
	5644	0.96		0.96	
	8061	0.94		0.97	

⁽¹⁾The theoretical resistance values include only T/E material resistance.

	Seebeck Ratio	Resistance Ratio
⁽²⁾ Design Value	0.98 - 0.99	0.97 - 1.08
⁽³⁾ Design Value	1.00	0.96 - 1.05
⁽⁴⁾ Design Value	0.95 - 0.98	0.97 - 1.11

3.2 PROTOTYPE MOCKUP CONVERTER NO. 2 (PMC-2)

Design analysis and development continued during fabrication and assembly of the SNAP-23A 60-watt converter PMC-2. Working drawings were issued and used for development work, manufacturing planning, and Quality Control planning.

As the manufacturing of the unit proceeded, the information obtained was used to revise prints prior to final release. These parallel activities allowed work to proceed on the unit and reduced paper work to a minimum. During this period, the activities of Design Engineering, Manufacturing, and Q. C. were well coordinated so that schedules could be met.

3.2.1 Design Analysis

3.2.1.1 Outer Case-Lower Cover Weld Stress

An analysis of the stresses was conducted in the weld area where the lower cover joins to the outer case. Stress in this weld would be caused by the lower cover expanding faster than the outer case during converter heat up. The lower cover expands faster because of difference in material thermal expansion rates. The lower cover is made of 304 SS and outer case of Inconel 625. The calculations (Appendix A) showed that a shrink fit would not be required prior to welding. This simplifies the assembly of the converter.

3.2.1.2 Outer Case-Header Ring Weld Stress

Another analysis was conducted to determine the dimensions in the weld area where the outer case joins the header ring. In this area, after the weld has been completed and the unit is heated up, the header ring will expand faster than the outer case causing a stress in the weld. The length of fit between the outer case and the header ring was increased to reduce the stress in the weld. The calculations in Appendix B show that this added length decreases the discontinuity stress to a safe level.

3.2.1.3 15 G Lateral Load

The enclosing support structure for PMC-2 was designed to withstand 10 G shock loads. This 10 G loading was based on the Westinghouse system support structure controlling the magnification of input loading to a value no greater than 2. During system dynamic testing, laterally imposed shock loads reached as high as 15 G. While Westinghouse could design a support system which would control the magnification factor to 2, it would be accompanied by an increase in extraneous heat loss. WANL requested that 3M analyze the converter structure to determine its capability to withstand 15 G lateral shock load. The analysis was conducted to the same depth and extent as the initial structural design calculations (reference Quarterly Report No. 1). The calculations for the 15 G lateral load (Appendix C) showed that the margin of safety was positive so the structure should carry this load. An analysis to determine if this additional load would contribute to a fatigue failure was included with the above analysis. The results indicated that fatigue failure should not occur. This conclusion is based on a structural analysis only and does not include the thermoelectrics. For the converter to be qualified for 15 G lateral shock load, a unit should be dynamically tested.

3.2.2 Design Development

3.2.2.1 Weld Program

The purpose of the weld program was two-fold:

- 1) Obtain data for determining configuration of the components in the weld area.
- 2) Establish the weld schedule for automatic welding of PMC-2 assembly.

Several general conclusions can be drawn from the weld development work which was completed during the period.

1. Proper design of weld joints having large mass differences is essential to high integrity welds. Proper attention to heat balance at the design stage can mean the difference

between a process which is very sensitive to parameter variations and one which provides a practical latitude for production applications.

2. Weld puddle geometry and weld microstructure can be greatly improved with the proper use of parameters when the two metals being joined have a significant weld temperature difference. The appropriate use of welding chills, speed, current, and proper design are necessary for producing acceptable welds.
3. Design considerations based on good engineering judgement allowed the most difficult welds (304 SS to Inconel 625) to be accomplished without any evidence of cracking or porosity.

The welding equipment used in the program consisted of a precision d-c power supply capable of controlling all modes of the welding cycle (Figure 3-4). A modified glass blower lathe (Figure 3-5) was used to turn the samples during the welding operations. The welding torch (Figure 3-6) is a standard heliarc torch held in an adjustable holder to control arc positions. The torch holder, providing excellent control and reproducibility of the arc gap, was used for all subsequent experiments in the welding program.

A qualitative type experiment to determine performance of the welding equipment and to obtain a feel for welding behavior of the SNAP-23A materials (Inconel 625 to 3D4SS) was conducted. Preliminary evaluation was done on sheet stock to metallurgically evaluate the microstructure of typical welds. The samples were evaluated and considered metallurgically sound.

Samples of the actual configurations and materials in the SNAP-23A PMC-2 Converter were prepared.

A sequential weld study, using weld parameters which bracketed the estimated weld sequence was developed.

Figures 3-7 through 3-25 are typical samples of the welds made during the development program.

Figure 3-4
Miller ES2-150 Automatic
Sequence Power Supply

Figure 3-5
Welding Lathe

Figure 3-6
Adjustable Welding Torch
Hot Frame to Upper Cover
Sample in Lathe

Figure 3-7
Lower Cover (304SS) to Outer Case
(Inconel 625) - Under Penetration
10x

Figure 3-8
Lower Cover to Outer Case -
Over Penetration. 10x

Figure 3-9
Lower Cover to Outer Case -
Proper Penetration. 10x

Figure 3-10
Lower Cover to Outer Case
Weld Structure of 304 to 625
Alloy. 50x

Figure 3-11
Lower Cover to Hot Frame
304 to 304
Over Penetration. 10x

Figure 3-12
Lower Cover to Hot Frame
304 to 304
Proper Penetration. 10x

Figure 3-13
Lower Cover to Hot Frame
304 to 304
Weld Structure. 50x

Figure 3-14
Hot Frame to Top Cover
304 to 304
Proper Penetration. 10x

Figure 3-15
Hot Frame to Top Cover
304 to 304
Weld Structure. 50x

Figure 3-16
Top Cover to Header Ring
304 to 304
Proper Penetration 10x

Figure 3-17
Top Cover to Header Ring
304 to 304
Weld Structure. 50x

Figure 3-18
Header Ring to Outer Case
304 to 625
Under Penetration. 10x

Figure 3-19
Header Ring to Outer Case
304 to 625
Weld Structure of Fig. 3-18. 50x

Figure 3-20
Header Ring to Outer Case
304 to 625
Proper Penetration. 10x

Figure 3-21
Header Ring to Outer Case
304 to 625
Weld Structure of Fig. 3-20. 50x

Figure 3-22
1000X Enlargement of Heat
Affect Zone
Header Ring to Outer Case

Figure 3-23
Outer Case to Rain Shield. 10x
625 to 625
Moderate Penetration

Figure 3-24
Outer Case to Rain Cover
625 to 625
Full Penetration Weld 10x

Figure 3-25
Outer Case to Rain Cover
625 to 625
Weld Structure of Fig. 3-24. 50x

After each sample weld was thoroughly examined, two sets of qualification welds were made using parameters identical to those which provided adequate sample welds. These qualification samples were approved for production by Engineering, Quality Control and Manufacturing.

This development effort information was used to complete the PMC-2 component design. In addition, weld development schedules for the automatic welding were prepared.

3.2.2.2 Power Lead Potting

The area where the power output leads exit from the converter was considered vulnerable to corrosive attack. To protect this area the wires and exposed surface of the hermetically sealed header were encapsulated. Tests were conducted to check out the acceptability of the selected potting material and to establish proper procedure. The material selected was Dow Corning silicone rubber compound No. 3120. This is a two-part material, a small amount of catalyst being added so the rubber will cure. The material was selected because of the properties it exhibited during the cable potting development work conducted in the last quarter. The procedure involved pouring the potting compound into the cavity created by the retaining sleeve. A vacuum was used to remove the air bubbles.

The cavity was overfilled and then trimmed to proper height after cure. The compression plate which fits on top with the attaching screws was used to compress the potting compound. The completed assembly is shown by Figure 3-26. This initial design and procedure provided adequate results during development assembly and no changes are anticipated for PMC-2.

3.2.3 Design of PMC-2 Hardware

3.2.3.1 PMC-2 Components

The design of all the converter components for the laboratory test and field service configurations except the top cover Min-K 2002 insulation blocks were completed. The drawings were completed from development, manufacturing, and Q.C. inputs. Priority of final design release was based on items most critical in the build schedule.

3.2.3.2 PMC-2 Assemblies

All assembly drawings have been completed except for the final configuration. The drawing for the final assembly will be completed when all inputs have been received from manufacturing and the design of the Min-K 2002 blocks is completed. Preliminary drawings of the final assembly and a master Bill of Materials were available to enable assembly of the unit to proceed. The other assembly drawings were first issued as working drawings for review and planning by Manufacturing and Q.C. After comments by Manufacturing and Q.C., the drawings were finalized. This procedure reduced the effort and paper work required and yet provided the design description necessary so work could proceed.

3.2.4 Interface with Westinghouse

3.2.4.1 Interface Drawing

The Westinghouse interface drawing for PMC-2 was subjected to detailed review. This was the three sheets of 914-E-462 which included all Westinghouse and 3M inputs which had been mutually agreed upon. The drawing is released under configuration control by WANL.

Figure 3-26
Converter Power Output Leads

3.2.4.2 FPMS - PMC-2 Mating

When PMC-2 converter is mated with the spud of FPMS, the spud will be at elevated temperatures. The converter could be damaged by thermal shock if the room temperature converter was placed on the hot spud. This had been the subject of several previous discussions with Westinghouse but had not been resolved for a fueled system. Westinghouse requested that 3M evaluate the technique of controlling thermal shock by slowly lowering the cold converter onto the hot spud. Initial evaluation resulted in approval of this technique so that Westinghouse could proceed with tool design. Subsequence detailed evaluation was conducted and limiting control factors for this procedure were established. The purpose of these factors is to limit the thermal shock on the converter so it will not be damaged. These control factors are discussed in Appendix D.

3.2.4.3 Thermal Insulation

The type and state of the thermal insulation material for two areas associated with the PMC-2 converter were resolved. The first area internal to the converter and adjacent to the support core will utilize a microquartz pad. This flexible pad will conform to the irregularities of the cone surface, routing of instrumentation wire and the Min-K 2002 insulation blocks.

The second area is external to the converter and is in the cavity of the hot frame (see Figure 3-27). The 3M supplied Min-K 2002 insulation blocks will fill this cavity to within one inch of the top of the hot frame web. When the converter is operated on the 3M test station, the volume below this plane will be filled with powder. When used on the Westinghouse system, this cavity will be filled with both block and powdered insulation. The difference in heat loss which will occur is less than 0.2 of a watt. The exact heat loss cannot be duplicated on the test station because of a different hardware configuration.

Figure 3-27
Upper Portion Hot Frame Insulation Interface Definition

3.2.5 Fabrication and Assembly of PMC-2

The balance of the component parts for the assembly of PMC-2 converter were machined and inspected during this report period. Various problems were encountered with several components but all the components have been accepted for use in the converter. The most serious deviations noted on any part were on the hot frame and the cold frame.

The diameter of the hot frame taper at the small end was oversized and the slope of the taper was low and out-of-round. The hot frame was placed on the plug of the assembly fixture which corrected the out-of-round condition. Since the system spud had not yet been machined, Westinghouse agreed to machine the spud to match the dimensions of the hot frame.

The cold frame as machined had two deviations from print specification. The first on the follower holes and the second on the outside diameter. The follower holes were elliptical at the cold frame inside diameter which caused some of the holes to be too large at their major diameter. Forty-two holes were inspected (Figure 3-28) and variable data recorded. From this data it was determined that increased thermal impedance could increase cold cap temperatures 5°F for EOL heat flux and 6°F for BOL heat flux from nominal hole size. Power output could decrease 0.23 watts at EOL conditions and 0.62 watts at BOL conditions. These values represent the worst case effect on converter performance. Cost and schedule were considered in making the decision to use the cold frame as machined. The deviated follower holes were acceptable and their use in PMC-2 will develop data for dimensioning follower holes for future converters. The cold frame outside diameter was undersize by less than 0.001 inch. This diameter was acceptable based on the reduction of the outer case wall thickness tolerance from 0.038/0.042 to 0.0385/0.042 which was necessary to maintain the proper outer case interface dimension.

After each row of thermoelectric couples (with the exception of the end couples) were assembled onto the insulation strip, the assembly was photographed for a permanent record. Figure 3-29 shows a row of assembled thermoelectric couples. Note that the "N" and "P" legs are very clearly defined. These assembled rows were further identified to each row within the converter. The top and bottom ends of the hot frame are shown in Figure 3-30 and 3-31 with the end couples in place.

Figure 3-28
Inspection of Follower Holes

Figure 3-30 shows the thermopile being visually inspected using a boroscope. The boroscope made it possible to inspect every couple for proper seating in the hot buttons, proper seating of the cold caps in the followers, cracked or broken jumper wires between cold caps, broken legs, or any foreign material in the thermopile.

All thermocouple instrumentation wires were brought out through the top end of the thermopile as shown by Figures 3-30 and 3-31.

After assembly and inspection of the thermopile assembly, the Inconel outer case was shrunk fit over the cold frame by heating the outer case to approximately 600° F.

During the welding of the header ring to the outer case, the power leads of the converter shorted to the cold frame and burned off. This was caused by a lack of proper grounding during welding. The converter design changes resulted in an assembly procedure change which required different grounding.

Figure 3-29
Assembled Row of T/E Couples

Figure 3-30
Top View of Cold Frame
T/E Couples and Hot Frame Assy

Figure 3-31
Bottom View of Cold Frame,
T/E Couples and Hot Frame Assy

Figure 3-32
Visual Inspection of Thermopile

Figures 3-33, 3-34, 3-35 and 3-36 show the sequence of the repair work that was accomplished on the power leads. The wires were rejoined by soldering and then fiber glass sleeved per the approved process procedure.

Figure 3-33
Power Leads Burned Through

Figure 3-34
One Lead Resoldered

Figure 3-35
Repaired Lead Being Fiberglass
Sleeved

Figure 3-36
Second Lead Wire Being Repaired

After repairing the power lead wires and obtaining the proper ground conditions, the header ring was welded to the outer case. This weld was satisfactory for approximately three-fourths of the total weld. On the remainder one-fourth of the two metals being welded, a discontinuous weld occurred giving the appearance as shown in Figure 3-37. The discontinuous weld was caused by a fit-up gap in the piece parts.

Figure 3-37
Defective Weld Area

This discontinuous weld area was repaired by hand TIG welding which produced an acceptable weld. (See Figure 3-38.)

The remainder of the converter assembly was completed with no major problems. Three instrumentation thermocouple wires were moved from their original header position, because of broken pin wires, to new locations.

Figure 3-38
Repair of Discontinuous Weld Area

Figures 3-39 through 3-43 show the assembly of the top end of the converter. Figure 3-43 shows the top support cone in place ready for welding. The top support was machined to fit the header ring which had been distorted during the repair weld mentioned earlier.

Figure 3-39
Insulation (Min-K) Packed around
Thermoelectric Couples

Figure 3-40
Powdered Insulation (Min-K)
Packed Around Thermopile

Figure 3-41
Shaped Insulation Block (Min-K)
Placed over Thermopile

Figure 3-42
Insulation Pad (Microquartz)
Placed into Position

Figure 3-43
Support Cone Placed into Position
and Ready for Welding

Figures 3-44 through 3-47 show the assembly of the bottom of the converter.
Figure 3-47 shows the heater block inserted to complete the converter.

Figure 3-44
Powdered Insulation (Min-K) Placed
and Packed in Position

Figure 3-45
Insulation Pad (Microquartz)
Placed in Position

Figure 3-46
Lower Cover Placed in Position
and Ready for Welding

Figure 3-47
Bottom End of Converter with Heater
Block and Heaters in Place

The top connectors were assembled into the processing configuration and instrumentation wires were connected. Figure 3-48 shows the top components in the final stages of assembly.

Figure 3-48
Top Connector Assembly

3.2.6 Summary of Computer Programs

The data presented in Westinghouse's July Progress Report was reviewed. There appeared to be some inconsistencies in the calculated power and current values. In conversations with Westinghouse, it was apparent these inconsistencies were caused by corrections made to values calculated with the computer code. To reconcile any differences in the method of calculation between 3M and Westinghouse a summary of computer programs and adjustments used was prepared and sent to Westinghouse. This summary is also included in Appendix E.

3.2.7 Fire-Safety Evaluation

The design details of the six-couple test module were completed and piece-parts are being either processed or fabricated as required. Joint review of the test stand design by 3M and WANL indicated that the original design concept presented in Quarterly Report No. 10 would probably not be capable of reproducing the latest cold side fire transients postulated by HAI. To reduce the cold end thermal mass and lag, the final design shown in Figure 3-49 incorporates the thermal conductivity

standards at the hot side of the module where the transient is relatively small. In late September, sufficient test stand design detail had been completed to initiate procurement and fabrication of piece parts.

The detailed test plan and procedures associated with the fire-safety evaluation was completed in September following appropriate review by WANL and HAI. The completed document was then submitted to RDT for approval near the end of the quarter.

Figure 3-49
Fire Module Test Stand

4.0 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 in support of the 60-watt converter development program through the five distinct approaches listed below.

- Post-test analysis of SNAP-23A and related devices.
- 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.
- Continuation testing of related devices.
- Thermoelectric degradation analysis of SNAP-23A and other related SNAP devices.

During this quarter, effort has been expended in all of the above areas, except bell jar testing and post-test analysis, and degradation analysis.

4.2 TEN-COUPLE MODULES

Long-term test of modules 1, 3 and 5 through 12 continued during this quarter.

4.2.1 Modules 1 and 3

Plots of average performance ratios (experimental-to-theoretical values) versus time for modules 1 and 3 are shown in Figures 4-1 through 4-5. Analysis of the recent data (10,000 hours to present) for modules 1 and 3 is summarized in Table 4-1.

Table 4-1
SNAP-23A Ten-Couple Module Performance Analysis
(Modules 1 and 3)

Module	Legs	Comments
1	Bonded N	Seebeck decreasing resistance stable; hence power down
	Simultaneously Pressed N	Seebeck decreasing, resistance stable; hence power down.
	Bonded P	Seebeck, resistance and power stable.
	Simultaneously Pressed P	Seebeck decreasing, resistance decreasing, power stable.
3	Bonded N	Seebeck stable, resistance up; hence power down.
	Simultaneously Pressed N	Seebeck stable, resistance up; hence power down.
	Bonded P	Seebeck down slightly, resistance up; hence power down.
	Simultaneously Pressed P	Seebeck down slightly, resistance up; hence power down.

As indicated by the data analysis, Module No. 1 (Min-K 1301 thermal insulation and 250 psi contact pressure) consistently outperforms Module No. 3 (micro-quartz insulation and 150 psi contact pressure) from a power standpoint. At this time, neither microquartz nor the lower contact pressure appear to be suitable alternates for the baseline (converter) program.

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

SNAP-23A TEN COUPLE MODULE NO. 1 - SEEBECK RATIO VS TIME

Thermal Insulation = MIN-K 1301
Contact Pressure = 250 psi
Hot Electrode = 1100°F
Cold Electrode = 190°F

○ P-Leg, Odd, Simul. Pressed, Hard Nose
□ N-Leg, Odd, Simul. Pressed, Hard Nose
△ P-Leg, Even, Bonded, Hard Nose
× N-Leg, Even, Bonded, Hard Nose

Figure 4-2
Resistance Ratio
versus
Elapsed Time

Thermal Insulation = MIN-K 1301

Contact Pressure = 250 psi

Hot Electrode = 1100°F

Cold Electrode = 190°F

○ P-Leg, Odd, Simul. Pressed, Hard Nose

□ N-Leg, Odd, Simul. Pressed, Hard Nose

△ P-Leg, Even, Bonded, Hard Nose

× N-Leg, Even, Bonded, Hard Nose

Figure 4-3
Power Ratio
versus
Elapsed Time
(Module 1)

SNAP-23A TEN COUPLE MODULE NO. 1 - POWER RATIO VS TIME

Thermal Insulation = Min-K 1301
Contact Pressure = 250 psi
Hot Electrode = 1100°F
Cold Electrode = 190°F

○ P-Leg, Odd, Simul. Pressed, Hard Nose
□ N-Leg, Odd, Simul. Pressed, Hard Nose
△ P-Leg, Even, Bonded, Hard Nose
× N-Leg, Even, Bonded, Hard Nose

Figure 4-4
Seebeck Voltage Ratio
versus
Elapsed Time
(Module 3)

SNAP-23A TEN COUPLE MODULE NO. 3 - SEEBECK RATIO VS TIME

Thermal Insulation = Microquartz	○ P-Leg, Odd, Simul. Pressed, Soft Nose
Contact Pressure = 150 psi	□ N-Leg, Odd, Simul. Pressed, Hard Nose
Hot Electrode = 1100°F	△ P-Leg, Even, Bonded, Soft Nose
Cold Electrode = 190°F	× N-Leg, Even, Bonded, Hard Nose

Figure 4-5
Resistance Ratio
versus
Elapsed Time
(Module 3)

Elapsed Time, hours

SNAP-23A TEN COUPLE MODULE NO. 3 - RESISTANCE RATIO VS TIME

Thermal Insulation = Microquartz	○ P-Leg, Odd, Simul. Pressed, Soft Nose
Contact Pressure = 150 psi	□ N-Leg, Odd, Simul. Pressed, Hard Nose
Hot Electrode = 1100°F	△ P-Leg, Even, Bonded, Soft Nose
Cold Electrode = 190°F	× N-Leg, Even, Bonded, Hard Nose

Figure 4-6
Power Ratio
versus
Elapsed Time
(Module 3)

SNAP-23A TEN COUPLE MODULE NO. 3 - POWER RATIO VS TIME

Thermal Insulation = Microquartz	○ P-Leg, Odd, Simul. Pressed, Soft Nose
Contact Pressure = 150 psi	□ N-Leg, Odd, Simul. Pressed, Hard Nose
Hot Electrode = 1100°F	△ P-Leg, Even, Bonded, Soft Nose
Cold Electrode = 190°F	× N-Leg, Even, Bonded, Hard Nose

4.2.2 Module 5 through 12

Statistical analyses of the data taken on 10-couple modules 5 through 12 at their respective 12,500-, 13,000-, 13,500-, and 14,000-hour points were completed during the quarter. Tables 4-2 through 4-3 present summaries of the statistical analyses completed thus far. Figures 4-7 through 4-19 graphically present the N- and P-leg average Seebeck, resistance, and power ratios versus time for both the microquartz modules and the Min-K 1301 modules; significant effects are shown on a second scale. Analysis of these graphs indicate the following:

- N-leg Seebeck Voltage – Microquartz Modules (Figure 4-7):

The average Seebeck ratio has remained stable, and none of the variables have a significant effect.

- N-leg resistance – Microquartz Modules (Figure 4-8):

Those legs with iron hot buttons (factor B+) exhibit a resistance ratio 0.088 higher than those with molybdenum buttons (factor B-). As a result of the first and second order interactions of hot junction temperature and hot contact pressure (factors C, D, and DC), the various combinations result in the following resistance ratios after 14,000 hours of operation.

Hot Junction Temperature, °F	Contact Pressure, psi	Resistance Ratio
1000 (C-)	150 (D-)	1.21
1000 (C-)	250 (D+)	1.08
1100 (C+)	150 (D-)	1.51
1100 (C+)	250 (D+)	1.14

Differences between the lower (0) and upper (+) levels of each of the significant effects are increasing with time, thus increasing their significance. The resistance of the C+, D- combination increased significantly more than that of the others during the past quarter.

- N-leg power – Microquartz Modules (Figure 4-9):

Those legs with iron hot buttons (factor B+) exhibit a power ratio 0.059 lower than those with molybdenum buttons (factor B-). The various combinations of hot junction temperature (factor C) and hot contact pressure (factor D) result in the following power ratios after 14,000 hours of operation:

<u>Hot Junction Temperature, °F</u>	<u>Contact Pressure, psi</u>	<u>Power Ratio</u>
1000 (C-)	150 (D-)	0.87
1000 (C-)	250 (D+)	0.97
1100 (C+)	150 (D-)	0.69
1100 (C+)	250 (D+)	0.92

Differences between the lower (-) and upper (+) levels of each of the significant effects are increasing with time, thus increasing their significance. The average power ratio continues to decrease with time.

- N-leg Seebeck voltage – Min-K 1301 Modules (Figure 4-10):

The Seebeck ratio of those legs with an 1100°F hot junction temperature continues to decrease and is now 0.024 lower than that of legs with a 1000°F hot junction temperature.

- N-leg resistance – Min-K 1301 Modules (Figure 4-11):

As a result of the first and second order interactions of hot junction temperature and hot contact pressure (factors C, D and CD) the various combinations result in the following resistance ratios after 14,000 hours of operation:

<u>Hot Junction Temperature, °F</u>	<u>Contact Pressure, psi</u>	<u>Resistance Ratio</u>
1000 (C-)	150 (D-)	1.02
1000 (C-)	250 (D+)	1.01
1100 (C+)	150 (D-)	1.11
1100 (C+)	250 (D+)	0.93

Resistance changes during the past quarter were relatively small.

- N-leg power – Min-K 1301 Modules (Figure 4-12):

The various combinations of hot junction temperature (factor C) and hot contact pressure (factor D) result in the following power ratios after 14,000 hours of operation:

<u>Hot Junction Temperature, °F</u>	<u>Contact Pressure, psi</u>	<u>Power Ratio</u>
1000 (C-)	150 (D-)	0.99
1000 (C-)	250 (D+)	1.04
1100 (C+)	150 (D-)	0.88
1100 (C+)	250 (D+)	1.04

Differences between the lower (-) and upper (+) level of each of the significant effects are increasing with time, thus increasing their significance. The average power ratio continues to decrease slightly with time.

- P-leg Seebeck voltage – Microquartz Modules (Figure 4-12):

The average Seebeck voltage ratio is decreasing slightly with simultaneously-pressed P-legs exhibiting a 0.16 higher ratio than their bonded counterparts.

- P-leg resistance – Microquartz Modules (Figure 4-14):

The resistance of the bonded type P-leg is increasing while that of the simultaneously-pressed type has stabilized. However, the resistance ratio of the bonded type is currently 0.70 lower than that of the simultaneously pressed variety.

- P-leg power – Microquartz Modules (Figure 4-15):

The power ratio of the simultaneously-pressed P-legs has stabilized while that of the bonded type is decreasing. However, the power ratio of the bonded type is currently 0.10 higher than that of the simultaneously-pressed variety.

- P-leg Seebeck voltage – Min-K 1301 Modules (Figure 4-16):

The simultaneously-pressed legs continue to exhibit a Seebeck ratio approximately 0.13 higher than their bonded counterparts. The Seebeck ratio of legs with an 1100°F hot junction temperature continues to decrease more rapidly than the ratio for 1000°F legs (the lower temperature legs now exhibit a 0.07 higher Seebeck ratio than the 1100°F legs).

- P-leg resistance – Min-K 1301 Modules (Figure 4-17):

The resistance of the simultaneously-pressed legs is decreasing while that of the bonded type is stable. However, the resistance ratio of the simultaneously-pressed type is still 0.30 higher than that of the bonded type legs. The 1100°F legs continue to exhibit a 0.06 higher resistance ratio than those with an 1100°F hot junction temperature. The resistance ratio of legs with a 250 psi contact pressure remains approximately 0.11 lower than that of the 150 psi legs.

- P-leg power – Min-K 1301 Modules (Figure 4-18):

The various combinations of leg manufacturing technique (factor A) and hot junction temperature (factor C) result in the following power ratios after 14,000 hours of operation:

<u>Leg Type</u>	<u>Hot Junction Temperature, °F</u>	<u>Power Ratio</u>
Simultaneously Pressed (A+)	1000 (C-)	0.92
Simultaneously Pressed (A+)	1100 (C+)	0.84
Bonded (A-)	1000 (C-)	0.94
Bonded (A-)	1100 (C+)	0.86

The power ratios of bonded legs at 1000°F and simultaneously pressed legs at 1100°F tend to be fairly stable, while those associated with bonded legs at 1100°F and simultaneously pressed legs at 1000°F are decreasing and increasing respectively (see Figure 4-19). The power ratio of legs with a 250 psi contact pressure remains approximately 0.07 higher than that of the 150 psi legs.

Table 4-2
SNAP-23A N-Leg Statistical Analysis Summary (Microquartz Modules)
(Seebeck Ratio)

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

Effect	Mean Effect and Test Hours									
	225	1000	2500	5500	8500	11500	12500	13000	13500	14000
AVERAGE	1.01750	1.01634	1.01468	1.01417	1.01948	1.02302	1.02001	1.02135	1.02198	1.02209
A	0.00375	0.00271	0.00104	0.00251	0.00271	0.00480	0.00209	0.00020	0.00104	-0.00292
B	-0.00125	-0.00354	-0.00021	0.00001	-0.00104	-0.00020	-0.00291	-0.00105	-0.00646	-0.00543
AB	0.00250	0.00644	0.00811	0.00584	0.00771	0.00605	0.00751	0.00645	0.00646	0.00917
C	-0.00168	0.00064	-0.00854	0.00041	-0.00894	-0.00727	-0.00584	-0.00522	-0.00604	-0.00375
AC	-0.00458	-0.00354	-0.00356	-0.00291	-0.00354	-0.00687	-0.00376	-0.00437	-0.00146	-0.00750
BC	-0.00458	0.00271	0.00269	0.00209	0.00521	0.00313	0.00124	0.00187	0.00104	0.00250
ABC	0.00082	0.00189	0.00771	0.00041	0.00231	-0.00228	0.00166	-0.00398	0.00146	0.00375
D	0.00165	0.00354	0.01271	0.00416	0.00436	0.00562	0.00291	0.00687	0.00311	0.00042
AD	0.00125	0.00271	0.01104	0.00334	0.00396	0.00352	0.00249	0.00437	0.00019	0.00583
BD	0.00125	0.00146	-0.00521	0.00084	-0.00229	-0.00147	-0.00001	-0.00187	0.00019	0.00083
ABD	-0.00085	-0.00271	-0.00354	0.00166	-0.00439	-0.00438	-0.00209	-0.00438	-0.00189	-0.00208
CD	0.01083	0.01229	0.01646	0.01209	0.01146	0.01230	0.01041	0.00895	0.00646	0.00585
ACD	0.00207	0.00396	0.00479	-0.00124	0.00271	-0.00145	-0.00001	-0.00020	0.00104	0.00460
BCD	0.00207	0.00021	-0.00396	-0.00124	-0.00104	-0.00145	-0.00251	0.00105	0.00104	0.00210
ABCD	-0.00168	-0.00146	-0.00229	-0.00291	-0.00479	-0.00270	-0.00459	-0.00480	-0.00354	-0.00415

Table 4-3
SNAP-23A N-Leg Statistical Analysis Summary (Microquartz Modules)
(Resistance Ratio)

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

Effect	Mean Effect and Test Hours									
	225	1000	2500	5500	8500	11500	12500	13000	13500	14000
AVERAGE	1.01104	1.01730	1.02625	1.08082	1.15843	1.17688	1.20709	1.22334	1.22354	1.23459
A	-0.00126	0.01542	0.01500	0.00707	-0.02646	-0.03126	-0.02500	-0.03625	-0.04000	-0.04460
B	0.02874	0.01293	0.01500	0.02708	0.02479	0.08874	0.08070	0.09375	0.09375	0.08790
AB	0.00209	0.01210	0.00750	-0.01085	0.02811	0.00376	0.00418	-0.01082	0.00082	-0.00083
C	0.01041	-0.03040	-0.03833	0.04210	0.11521	0.11374	0.15625	0.17750	0.17043	0.17625
AC	0.01041	-0.00793	-0.00917	0.00332	-0.03896	-0.03459	-0.03208	-0.03958	-0.02750	-0.03332
BC	-0.03459	0.00458	0.00082	0.01082	-0.00271	0.05541	0.04042	0.05542	0.05125	0.05168
ABC	-0.02459	-0.00790	0.00667	-0.01790	0.02646	0.00374	0.00875	-0.01000	0.00418	0.00375
D	0.03876	-0.00250	-0.03290	-0.10625	-0.16814	-0.17291	-0.22417	-0.23710	-0.23832	-0.25290
AD	0.02791	0.02167	0.03710	0.02667	0.04689	0.04541	0.04500	0.05082	0.04710	0.04918
BD	-0.02209	-0.00832	-0.02540	-0.00082	0.00314	-0.04459	-0.04500	-0.06167	-0.04915	-0.04583
ABD	0.00376	-0.00250	0.00460	-0.00175	-0.03189	-0.01291	-0.00917	-0.00210	-0.00457	-0.00540
CD	-0.01791	0.01500	0.00707	-0.01500	-0.06229	-0.05959	-0.08125	-0.10708	-0.10582	-0.11332
ACD	-0.04041	-0.01917	-0.00458	-0.01457	0.00689	-0.01126	-0.01232	-0.01500	-0.01625	-0.00875
BCD	0.03459	0.00082	-0.01208	0.00042	0.00314	-0.05126	-0.05043	-0.05750	-0.05250	-0.05625
ABCD	0.00209	-0.00500	-0.01043	-0.01250	-0.04104	-0.01959	-0.02875	-0.02708	-0.02707	-0.02332

Table 4-4
SNAP-23A N-Leg Statistical Analysis Summary (Microquartz Modules)
(Power Ratio)

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

Effect	Mean Effect and Test Hours									
	225	1000	2500	5500	8500	11500	12500	13000	13500	14000
<u>AVERAGE</u>	<u>1.02756</u>	<u>1.01639</u>	<u>1.00484</u>	<u>0.95561</u>	<u>0.90799</u>	<u>0.90014</u>	<u>0.87624</u>	<u>0.86967</u>	<u>0.87017</u>	<u>0.86302</u>
A	0.01202	-0.01020	-0.01382	-0.00425	0.01528	0.02681	0.01480	0.01739	0.02278	0.01931
B	-0.03430	-0.01975	-0.01342	-0.02408	-0.02685	-0.05964	-0.05390	-0.05469	-0.06665	-0.05961
AB	0.00055	0.00132	0.00838	0.02135	0.00005	0.00689	0.01067	0.01686	0.01007	0.01596
C	-0.01930	0.03125	0.02070	-0.03335	-0.09478	-0.08924	-0.11050	-0.11799	-0.11503	-0.11214
AC	-0.02395	0.00067	0.00205	-0.00838	0.01802	0.01294	0.01617	0.01831	0.01450	0.00784
BC	0.02828	0.00017	0.00450	-0.00600	0.00825	-0.02526	-0.01412	-0.01941	-0.01907	-0.01609
ABC	0.02918	0.01185	0.00905	0.01797	-0.00805	-0.00799	-0.00240	-0.00051	-0.00005	0.00379
D	-0.04062	0.00952	0.05740	0.10157	0.12982	0.13344	0.15743	0.16609	0.16115	0.16389
AD	-0.02812	-0.01555	-0.01430	-0.01885	-0.02242	-0.02524	-0.02610	-0.02411	-0.02877	-0.01989
BD	0.02830	0.01115	0.01410	-0.00102	-0.00505	0.01686	0.01740	0.02201	0.01675	0.01519
ABD	-0.00225	-0.00268	-0.01100	0.00695	0.00990	0.00419	0.00392	-0.00249	0.00132	0.00231
CD	0.04440	0.00955	0.02662	0.03330	0.05118	0.05081	0.05335	0.06406	0.06002	0.06216
ACD	0.04695	0.02627	0.01287	0.00972	0.00972	0.01179	0.01657	0.02021	0.02210	0.02219
BCD	-0.03427	-0.03077	0.00412	-0.00475	0.00055	0.02644	0.02227	0.02839	0.02638	0.03066
ABCD	-0.00848	0.00200	0.00527	0.00777	0.01520	0.01071	0.01235	0.01394	0.01335	0.00999

Table 4-5
SNAP-23A N-Leg Statistical Analysis Summary (Min-K 1301 Modules)
(Seebeck Ratio)

Effect	Effect Description	(+) Level	(-) Level
A B C D	Leg Soldering Technique Hot Contact Material Hot Junction Temperature Hot Contact Pressure	Simultaneous Press Iron 1100°F 250 PSI	Bonded Molybdenum 1000°F 150 PSI

Effect	Mean Effect and Test Hours									
	225	1000	2500	5500	8500	11500	12500	13000	13500	14000
AVERAGE	1.00386	1.01291	1.01218	1.01531	1.01114	1.00896	1.00469	1.00344	1.00177	1.00062
A	0.00814	0.00625	0.00104	0.00357	0.00311	0.00624	0.01062	0.01270	0.00979	0.00792
B	0.00189	-0.00125	0.00229	0.00232	-0.00314	-0.00876	-0.00563	-0.00355	-0.00896	-0.01207
AB	-0.00104	0.00083	0.00061	-0.00313	-0.00396	-0.00209	-0.00937	-0.00937	-0.00771	-0.00375
C	0.01644	0.00750	0.01271	0.01063	-0.00271	-0.01541	-0.02062	-0.01938	-0.01939	-0.02460
AC	0.00021	-0.00042	-0.00811	-0.00562	-0.00439	-0.00209	0.00063	-0.00105	0.00021	0.00292
BC	-0.00854	-0.00293	0.00314	0.00312	-0.00564	-0.01209	-0.00563	-0.00480	-0.01174	-0.01207
ABC	-0.00481	-0.00250	0.00396	0.01187	0.00104	-0.00041	-0.00937	-0.00812	-0.00314	0.00040
D	-0.00229	0.00250	0.00689	0.00188	0.00854	0.00541	0.00477	0.00395	0.00729	0.00625
AD	-0.01686	-0.00543	-0.01314	-0.01437	-0.00644	-0.01041	-0.00897	-0.00602	-0.00896	-0.00707
BD	0.00689	-0.00292	0.00311	0.00188	-0.00019	0.00459	0.00727	0.01022	0.00979	0.00793
ABD	0.00896	0.00750	0.00814	0.01063	0.00979	0.00041	-0.00148	-0.00480	-0.00146	-0.00375
CD	-0.00436	-0.00168	-0.00896	-0.00812	0.00104	-0.00541	-0.01102	-0.00980	-0.01479	-0.01040
ACD	0.00271	-0.00125	0.00021	-0.00687	-0.00314	-0.00624	-0.00147	-0.00397	-0.00269	-0.00458
BCD	-0.00104	0.00125	0.00146	-0.00062	0.00311	0.00876	0.00977	0.00978	0.00856	0.01043
ABCD	-0.00061	-0.00667	0.00229	0.00562	0.00729	-0.00741	-0.00227	-0.00605	-0.00174	-0.00540

Table 4-6
SNAP-23A N-Leg Statistical Analysis Summary (Min-K 1301 Modules)
(Resistance Ratio)

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

Effect	Mean Effect and Test Hours									
	225	1000	2500	5500	8500	11500	12500	13000	13500	14000
AVERAGE	0.98907	0.99249	0.98583	1.01479	1.01635	1.01948	1.02136	1.02240	1.02126	1.01844
A	0.01979	0.02084	0.01084	0.01959	0.01730	0.02104	0.02937	0.03187	0.03294	0.02730
B	0.00604	0.00084	0.01334	0.00459	-0.00395	-0.01521	-0.00937	-0.00437	-0.01456	-0.01895
AB	-0.01061	-0.00501	-0.00584	-0.01541	-0.01105	0.00021	-0.01103	-0.01895	-0.00749	-0.00187
C	0.00811	-0.01749	-0.00336	0.01334	0.01395	0.02479	0.02313	0.02062	0.02041	0.01437
AC	0.01896	0.00751	-0.00584	-0.00916	-0.00480	0.00771	0.01313	0.00770	0.00334	0.00645
BC	-0.02479	-0.01249	0.00666	0.00334	-0.00355	-0.02354	-0.00812	-0.00855	-0.01666	-0.02480
ABC	-0.01564	-0.01249	-0.00086	-0.00916	0.00270	0.00604	-0.01313	-0.00312	0.00291	0.01062
D	-0.01479	-0.03041	-0.03416	-0.05084	-0.04855	-0.08811	-0.10490	-0.10227	-0.10166	-0.09690
AD	-0.01564	0.00124	-0.01584	-0.01499	-0.02230	-0.00189	0.00135	0.00480	-0.00209	0.00437
BD	0.01311	-0.00626	0.00166	-0.00249	0.00395	0.00936	0.01730	0.02175	0.02041	0.02062
ABD	0.02396	0.01709	0.01834	0.02666	0.02520	-0.00436	-0.00855	-0.01353	-0.00666	-0.00815
CD	0.00104	-0.00709	-0.01834	-0.05374	-0.04395	-0.07564	-0.09105	-0.08980	-0.09626	-0.08855
ACD	0.01769	0.00541	-0.00166	-0.00709	-0.01105	-0.01856	-0.00855	-0.01602	-0.01749	-0.01563
BCD	0.00144	0.00291	0.01084	0.00291	0.01770	0.02769	0.03520	0.03023	0.03751	0.03062
ABCD	-0.00021	-0.00959	-0.00084	0.01626	0.02237	-0.00189	-0.00730	-0.01105	-0.00376	-0.00980

Table 4-7
SNAP-23A N-Leg Statistical Analysis Summary (Min-K 1301 Modules)
(Power Ratio)

SNAP-23A N-Leg Statistical Analysis Summary (MIN K 1301 Modules)
(Power Ratio)

Effect	Effect Description	() Level	() Level
A B C D	Leg Segmenting Technique Hot Contact Material Hot Junction Temperature Hot Contact Pressure	Simultaneous Press Iron 1100 F 250 PSI	Bonded Molybdenum 1000 F 150 PSI

Effect	Mean Effect and Test Hours									
	225	1000	2500	5500	8500	11500	12500	13000	13500	14000
AVERAGE	1.01985	1.04541	1.04049	1.01782	1.00902	1.00305	0.99389	0.99031	0.98825	0.98840
A	-0.00360	-0.00981	-0.00916	-0.01304	-0.01089	-0.00875	-0.00841	-0.00654	-0.01273	-0.01211
B	-0.00338	-0.00371	-0.01049	-0.00089	-0.00401	-0.00517	-0.00561	-0.00614	-0.00707	-0.00936
AB	0.00868	0.00706	0.00711	0.00834	0.00191	-0.00318	-0.00631	0.00196	-0.00670	-0.00384
C	0.02448	0.03381	0.03029	0.01089	-0.01646	-0.04808	-0.05426	-0.04974	-0.04911	-0.05441
AC	-0.01927	-0.00936	-0.01031	-0.00204	-0.00289	-0.01087	-0.01096	-0.00329	-0.00117	0.00061
BC	0.00895	0.00749	-0.00154	0.00246	-0.00886	-0.00285	-0.00656	-0.00364	-0.00888	-0.00244
ABC	0.00655	0.00811	0.00891	0.01154	-0.00254	-0.00620	-0.00456	-0.01234	-0.00835	-0.00926
D	0.01102	0.03769	0.05059	0.05401	0.06416	0.09470	0.10839	0.10416	0.10955	0.10316
AD	-0.01792	-0.01284	-0.01006	-0.01376	-0.01076	-0.02095	-0.02121	-0.01894	-0.01793	-0.01991
BD	-0.00010	0.00066	0.00386	0.00649	-0.00369	0.01177	-0.00096	0.00066	0.00147	-0.00261
ABD	-0.00700	-0.00306	-0.00294	-0.00489	-0.00556	0.00467	0.00574	0.00411	0.00290	-0.00084
CD	-0.01025	0.00529	0.00209	0.03741	0.04496	0.06072	0.05329	0.06471	0.06010	0.06734
ACD	-0.01375	-0.00949	0.00179	-0.00711	0.00404	0.00392	0.00309	0.00551	0.00997	0.00431
BCD	-0.00293	-0.00024	-0.00909	-0.00451	-0.01154	-0.00900	-0.01486	-0.00944	-0.01853	-0.00839
ABCD	-0.00038	-0.00281	0.00596	-0.00374	-0.00691	0.00095	0.00354	-0.00139	0.00157	-0.00156

Table 4-8
SNAP-23A P-Leg Statistical Analysis Summary (Microquartz Modules)
(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	Contact Type	Hard Nose	Soft Nose

Effect	Mean Effect and Test Hours									
	225	1000	2500	5500	8500	11500	12500	13000	13500	14000
AVERAGE	0.96125	0.95984	0.96500	0.95734	0.95547	0.95641	0.95125	0.95016	0.94906	0.94844
A	0.11500	0.13594	0.15187	0.15844	0.15844	0.16344	0.15875	0.16426	0.16437	0.16562
B	0.01125	0.01219	0.00563	0.01094	0.00844	0.00594	0.01000	0.01156	0.01063	0.01187
AB	-0.00625	0.00094	0.00125	0.00469	0.00594	0.00281	0.00125	0.00031	0.00188	0.00063
C	0.01000	0.01219	0.00813	0.00656	-0.00281	0.00344	0.00125	0.00031	0.0	-0.00062
AC	0.00125	-0.00406	-0.01000	-0.01594	-0.01531	-0.01219	-0.01625	-0.01719	-0.01500	-0.01562
BC	-0.00250	-0.00031	-0.00125	-0.00844	-0.00531	-0.00719	-0.01000	-0.00969	-0.00625	-0.00687
ABC	0.00125	0.00594	0.00437	0.00656	0.00719	0.00594	0.01000	0.01031	0.01125	0.01063
D	-0.00313	-0.00281	0.00625	0.00406	0.00656	0.01594	0.01563	0.01719	0.01563	0.01812
AD	0.00438	0.00344	0.00687	0.00531	0.00156	0.00406	0.00063	-0.00031	0.00313	0.00062
BD	0.00063	-0.00531	-0.01187	-0.01219	-0.01594	-0.01594	-0.01562	-0.01531	-0.01562	-0.01562
ABD	0.00812	0.00844	0.01000	0.00906	0.00906	0.01344	0.01688	0.01969	0.01934	0.01938
CD	-0.00563	-0.00531	-0.00437	-0.00156	-0.00469	-0.00719	-0.00188	-0.00781	-0.00250	-0.00438
ACD	-0.00188	-0.00156	-0.00125	-0.00156	0.00031	-0.00281	0.00437	0.00094	-0.00125	-0.00062
BCD	-0.00063	-0.00281	0.0	0.00094	0.00281	-0.00031	0.00312	0.00094	0.00250	0.00062
ABCD	0.00062	-0.00156	-0.00062	-0.00156	-0.00719	-0.00719	-0.01062	-0.01031	-0.01125	-0.01063
E	-0.00250	-0.00906	-0.00563	-0.00656	-0.01031	-0.01156	-0.00875	-0.00844	-0.00813	-0.00688
AE	0.02250	0.01719	0.01250	0.01469	0.01219	0.01031	0.01500	0.01031	0.01312	0.00937
BE	-0.00125	0.00344	0.00625	-0.00031	0.00219	0.00031	-0.00125	0.00281	0.00188	0.00063
ABE	0.00375	-0.00281	-0.00438	-0.00906	-0.01031	-0.00906	-0.00750	-0.00844	-0.00687	-0.00812
CE	-0.00375	-0.00906	-0.00750	-0.00844	-0.00656	-0.00469	-0.00625	-0.00219	-0.00500	-0.00313
ACF	0.00250	-0.00031	0.00062	-0.00594	-0.00406	-0.00656	-0.00875	-0.00719	-0.00750	-0.00813
BCE	-0.00625	-0.00156	-0.00063	-0.00094	0.00094	0.00094	0.00020	0.00031	-0.00125	-0.00437
ABCE	0.00750	0.00469	0.00875	0.01406	0.01344	0.01531	0.01500	0.01281	0.00875	0.01313
DE	0.00187	0.00344	0.00437	0.00781	0.01031	0.01156	0.00562	0.00469	0.00812	0.00552
ADE	0.01187	0.00469	0.00375	0.00156	0.00031	0.00094	-0.00437	-0.00031	-0.00187	-0.00187
BDE	-0.00688	-0.00906	-0.01000	-0.00844	-0.00719	-0.00656	-0.00313	-0.00531	-0.00312	-0.00312
ABDE	0.01312	0.01469	0.01312	0.01531	0.01781	0.01656	0.01437	0.01219	0.01438	0.01188
CDE	0.00313	-0.00156	-0.00875	-0.01156	-0.01344	-0.01781	-0.01313	-0.01656	-0.01375	-0.01563
ACDE	-0.00312	0.00219	-0.00187	-0.00156	-0.00344	-0.00469	-0.00437	-0.00281	-0.00250	-0.00062
BCDE	-0.00188	0.00094	0.00437	0.00344	0.00406	0.00531	0.00187	0.00219	0.00375	0.00067
ABCDE	-0.00562	-0.00281	-0.00000	-0.00406	-0.00594	-0.00531	-0.00438	-0.00290	-0.00500	-0.00638

Table 4-9
SNAP-23A P-Leg Statistical Analysis Summary (Microquartz Modules)
(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	Contact Type	Hard Nose	Soft Nose

Effect	Mean Effect and Test Hours									
	225	1000	2500	5500	8500	11500	12500	13000	13500	14000
AVERAGE	1.26515	1.36344	1.43359	1.52531	1.77922	1.73578	1.77000	1.79437	1.82656	1.87078
A	0.47219	0.76187	0.89406	0.89812	1.13844	0.85031	0.77437	0.77125	0.71437	0.69656
B	-0.08656	-0.09687	-0.10719	-0.13938	-0.43781	-0.19219	-0.19062	-0.23750	-0.20063	-0.21969
AB	-0.01344	-0.02938	-0.05406	-0.07437	-0.37281	-0.16594	-0.15250	-0.14000	-0.17687	-0.21469
C	0.03406	-0.04687	-0.10656	-0.13938	-0.42406	-0.23906	-0.21875	-0.22375	-0.29875	-0.32781
AC	0.05469	0.04062	0.01406	0.01938	-0.20156	0.08094	0.09812	0.13375	0.10250	0.11094
BC	0.00594	0.06687	0.10281	0.14688	0.43969	0.20094	0.21063	0.23250	0.28250	0.28469
ABC	0.02531	0.01187	0.01219	-0.01437	0.22719	0.31594	-0.04375	-0.01500	-0.01875	-0.04406
D	-0.10906	-0.10688	-0.09156	-0.08687	-0.13219	-0.22969	-0.22437	-0.22900	-0.24937	-0.25719
AD	0.04031	-0.02188	-0.04469	-0.06563	-0.06844	0.00281	0.03500	0.03125	0.04937	0.05156
BD	0.01656	0.01938	0.00406	-0.03812	-0.05469	-0.04719	-0.08000	-0.10250	-0.11063	-0.13219
ABD	0.04219	0.08187	0.10719	0.11312	0.16656	0.20031	0.18312	0.20625	0.21063	0.23406
CD	-0.00781	-0.00687	-0.01531	-0.02563	-0.04219	0.03594	0.01187	-0.01750	-0.00375	-0.01531
ACD	-0.02219	-0.01812	0.03281	0.03687	0.03906	-0.02531	-0.03375	-0.06125	-0.06000	-0.06281
BCD	0.06406	0.06438	0.05656	0.11937	0.16531	0.15219	0.21375	0.24250	0.25500	0.27844
ABCD	-0.07156	-0.06312	-0.06156	-0.06562	-0.11594	-0.14656	-0.11813	-0.15375	-0.14375	-0.16906
E	0.19969	0.21062	0.19406	0.16687	0.45844	0.30406	0.26812	0.31250	0.29437	0.32531
AE	-0.01969	-0.00437	-0.00531	-0.02313	0.20094	-0.07469	-0.13375	-0.20250	-0.19437	-0.20969
BE	-0.10844	-0.10563	-0.07906	-0.11813	-0.38031	-0.13969	-0.11875	-0.09875	-0.10938	-0.14094
ABE	0.03594	0.01687	0.00031	0.00937	-0.21281	-0.00594	0.06562	0.07125	0.10937	0.10906
CE	-0.01781	-0.09063	-0.15094	-0.22687	-0.57406	-0.41531	-0.42313	-0.45500	-0.52500	-0.55281
ACE	0.08406	0.07687	0.08594	0.11187	-0.04906	0.24969	0.31750	0.35000	0.36625	0.41844
BCE	-0.01469	0.03562	0.07219	0.08688	0.33219	0.07719	0.04000	0.07625	0.06125	0.04219
ABCE	0.09344	0.07562	0.06531	0.06062	0.31219	0.09719	0.07187	0.04625	0.08500	0.08594
DE	-0.04219	-0.01562	0.01531	0.08062	0.08406	-0.00594	0.02625	0.04500	0.03688	0.03531
ADE	0.07594	0.03437	-0.01406	-0.03313	-0.02219	0.03656	0.06438	0.07125	0.09063	0.09656
BDE	-0.01281	-0.02688	-0.05781	-0.10813	-0.15844	-0.17094	-0.22062	-0.25000	-0.26937	-0.29219
ABDE	0.02406	0.05562	0.08156	0.11312	0.16781	0.20656	0.19375	0.19875	0.22187	0.23656
CDE	0.03031	0.04938	0.04781	0.01313	0.05406	0.15094	0.12250	0.12250	0.13500	0.13844
ACDE	0.00219	0.07437	0.09719	0.11812	0.12531	0.07219	0.06062	0.06875	0.05375	0.06594
BCDE	0.00344	0.00313	-0.01156	0.03312	0.03656	0.03219	0.06812	0.10000	0.09375	0.11719
ABCDE	-0.09844	-0.10937	-0.09094	-0.12937	-0.16969	-0.18906	-0.17750	-0.20125	-0.20500	-0.22031

Table 4-10
SNAP-23A P-Leg Statistical Analysis Summary (Microquartz Modules)
(Power Ratio)

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

Effect	Mean Effect and Test Hours									
	225	1000	2500	5500	8500	11500	12500	13000	13500	14000
AVERAGE	0.76083	0.72632	0.70748	0.65519	0.59553	0.58580	0.56735	0.56413	0.55358	0.54382
A	-0.12598	-0.22724	-0.24813	-0.20768	-0.19787	-0.14946	-0.13071	-0.12867	-0.10901	-0.10359
B	0.06267	0.05492	0.03953	0.04181	0.06654	0.04353	0.05079	0.06026	0.04659	0.04889
AB	-0.00988	-0.00053	0.01096	0.02839	0.06331	0.03824	0.03464	0.03034	0.04304	0.05054
C	-0.00547	0.04134	0.05596	0.05312	0.06188	0.04911	0.03587	0.05977	0.04474	0.04655
AC	-0.01894	-0.03059	-0.03307	-0.03379	-0.00721	-0.02893	-0.02341	-0.03414	-0.01759	-0.01670
BC	-0.01279	-0.03645	-0.04728	-0.06873	-0.09524	-0.07742	-0.08751	-0.08709	-0.09636	-0.09402
ABC	-0.00397	0.02030	0.02192	0.03381	0.01277	0.03212	0.04892	0.04042	0.04269	0.04730
D	0.05614	0.05386	0.05932	0.05718	0.07137	0.10442	0.11033	0.11111	0.11430	0.11892
AD	-0.02538	-0.01051	-0.00703	-0.00721	-0.02567	-0.03764	-0.05064	-0.05081	-0.05020	-0.05465
BD	0.00102	-0.00800	-0.00812	-0.00124	0.00127	-0.00568	-0.00444	-0.00483	-0.00423	-0.00195
ABD	-0.01641	-0.01760	-0.02029	-0.01563	-0.01737	-0.01907	-0.00972	-0.00677	-0.00510	-0.00779
CD	-0.00422	0.00209	0.00996	0.00284	0.01073	-0.00641	-0.00044	-0.00004	0.00633	0.00889
ACD	0.01193	-0.00599	-0.01162	-0.00454	-0.00061	0.00626	0.01031	0.01502	0.00598	0.00579
BCD	-0.04817	-0.04930	-0.03858	-0.05041	-0.05837	-0.05006	-0.05329	-0.06053	-0.05592	-0.06061
ABCD	0.04978	0.03725	0.03182	0.02881	0.02689	0.02948	0.02061	0.02941	0.01990	0.02481
E	-0.12354	-0.13111	-0.10814	-0.07593	-0.10297	-0.09639	-0.08531	-0.08842	-0.08220	-0.08244
AE	0.07368	0.07349	0.06338	0.04963	0.02324	0.04904	0.06032	0.06422	0.06387	0.05821
BE	0.07091	0.06525	0.04329	0.04119	0.06656	0.04486	0.03814	0.03114	0.03695	0.04209
ABE	-0.03312	-0.03637	-0.02141	-0.02364	-0.00873	-0.02673	-0.03278	-0.02894	-0.04095	-0.04134
CE	0.01817	0.04399	0.07704	0.09966	0.14827	0.13903	0.13567	0.13996	0.15012	0.15073
ACE	-0.05203	-0.05766	-0.07501	-0.09283	-0.09407	-0.12751	-0.13488	-0.13583	-0.13730	-0.14420
BCE	0.00709	0.00747	-0.00627	-0.00889	-0.02031	0.00133	0.01219	0.00652	0.00820	0.01058
ABCE	-0.04156	-0.03455	-0.01634	-0.00838	-0.03414	-0.00823	-0.01236	-0.00989	-0.02035	-0.01682
DE	0.02463	0.01534	-0.00717	-0.02506	-0.02167	0.00002	-0.00802	-0.01636	-0.00934	-0.01210
ADE	-0.02697	-0.01921	0.00751	0.01658	0.00269	-0.00664	-0.01442	-0.00874	-0.01554	-0.01630
BDE	-0.00129	0.00730	0.02507	0.03682	0.05438	0.05769	0.06616	0.06103	0.07121	0.07015
ABDE	0.00506	-0.00302	-0.01963	-0.02539	-0.03176	-0.04389	-0.04604	-0.04003	-0.04776	-0.04808
CDE	-0.01588	-0.01594	-0.01643	-0.00874	-0.02048	-0.04583	-0.03289	-0.03578	-0.03391	-0.03449
ACDE	0.00369	-0.02159	-0.03373	-0.03721	-0.02602	-0.01957	-0.02267	-0.02444	-0.02041	-0.02226
BCDE	-0.00343	-0.01180	0.00646	-0.01059	-0.00513	0.00369	-0.00424	-0.00579	-0.00134	0.00199
ABCDE	0.03739	0.04323	0.02408	0.03149	0.02043	0.02243	0.02253	0.01747	0.02044	0.01519

Table 4-11
SNAP-23A P-Leg Statistical Analysis Summary (Min-K 1301 Modules)
(Seebeck Ratio)

Effect	Effect Description	() Level	() Level
A B C D E	Leg Segmenting Technique Hot Contact Material Hot Junction Temperature Hot Contact Pressure Contact Type	Simultaneous Press Iron 1100 F 250 PSI Hard Nose	Bonlel Molybdenum 1000 F 150 PSI Soft Nose

Effect	Mean Effect and Test Hours									
	225	1000	2500	5000	7500	11500	12500	13000	13500	14000
AVERAGE	0.96922	0.99531	1.00719	1.00375	0.98516	0.97562	0.97016	0.96484	0.96250	0.95797
A	0.09219	0.12875	0.14062	0.14625	0.13031	0.13250	0.12400	0.12344	0.12062	0.12469
B	0.00469	0.00375	0.00687	0.00625	0.00031	0.00375	0.00531	0.00719	0.00312	0.00344
AB	-0.00156	-0.00188	-0.00188	-0.00250	0.00031	0.00250	0.00156	0.00344	0.00500	0.00469
C	0.01156	0.01437	0.01750	-0.00937	-0.03531	-0.05625	-0.06719	-0.06344	-0.06250	-0.07156
AC	0.00031	-0.00375	-0.01125	-0.02187	-0.02531	-0.01875	-0.02344	-0.01844	-0.02437	-0.01906
BC	0.00031	0.00125	0.00250	0.00562	0.00719	0.01250	0.01031	0.01281	0.01062	0.01219
ABC	-0.00094	-0.00313	-0.00125	0.00312	0.00719	0.01000	0.00656	0.00781	0.01000	0.00969
D	0.00094	0.00688	0.00312	-0.00875	-0.00656	-0.00813	-0.00344	-0.00344	-0.00438	-0.00594
AD	-0.00156	-0.00375	-0.00313	-0.00625	-0.00531	-0.00312	-0.00094	0.00156	0.00250	0.00406
BD	-0.00406	0.00125	-0.00188	0.00125	-0.00731	-0.00687	-0.00469	-0.00969	-0.00500	-0.01219
ABD	0.00094	-0.00063	0.00187	-0.00125	-0.00156	-0.00188	-0.00219	0.00031	-0.00437	-0.00219
CD	0.00531	0.00312	-0.00250	-0.00812	-0.00094	0.00312	0.00406	0.00344	-0.00437	0.00241
ACD	0.00281	0.00125	0.00375	-0.00188	0.00031	0.00187	0.00656	0.00469	0.01000	0.00656
BCD	0.00281	0.00125	-0.00250	-0.00188	-0.00219	-0.00187	-0.00469	-0.00406	0.00000	-0.00719
ABCD	-0.00219	-0.00438	-0.00125	-0.00313	-0.00344	-0.00562	-0.00219	-0.00031	-0.00688	-0.00094
E	0.00719	0.01125	0.01312	0.01750	0.02156	0.01875	0.01916	0.01719	0.01687	0.01344
AE	0.00844	-0.00187	-0.00313	-0.00375	-0.00344	-0.00500	-0.00469	-0.00406	-0.00625	-0.00531
BE	0.00344	-0.00187	0.00063	-0.00125	0.00156	0.00875	0.01156	0.00719	0.00625	0.00844
ABE	0.00469	0.00375	-0.00062	-0.00000	0.00156	0.00250	0.00031	-0.00156	0.00187	0.00219
CE	0.00031	-0.00625	-0.00375	-0.00313	-0.00156	-0.00250	-0.00094	-0.00469	0.00187	0.00219
ACE	0.00156	0.00187	-0.00000	0.00187	-0.00156	-0.00250	-0.00469	-0.00219	-0.00875	-0.00031
BCE	-0.00594	-0.00313	-0.00375	-0.00313	0.00094	0.00125	0.00006	0.00656	0.00625	0.00594
ABCE	0.00531	0.00625	-0.00500	-0.00313	-0.00406	-0.00375	-0.00219	-0.00594	-0.00625	-0.00656
DE	0.00344	0.00875	0.00687	0.00500	0.00844	0.00812	0.00656	0.00781	0.00625	0.00781
ADE	0.00094	-0.00063	-0.00188	-0.00000	0.00719	0.00562	0.00406	0.00531	0.00688	0.00281
BDE	-0.00096	-0.00062	-0.00313	-0.00500	-0.00781	-0.01063	-0.01469	-0.01844	-0.01563	-0.01344
ABDE	0.01094	0.00625	0.00912	0.01000	0.00844	0.01188	0.00781	0.00916	0.00625	0.00656
CDE	0.00281	0.00375	0.00375	0.00188	0.00656	0.00813	0.00656	0.00594	0.00375	0.00781
ACDE	-0.00469	0.00063	-0.00250	-0.01187	0.00031	0.00187	0.00406	0.00219	0.00188	-0.00094
BCDE	-0.00219	0.00063	-0.00625	-0.00937	-0.00719	-0.01437	-0.01719	-0.01906	-0.01312	-0.01469
ABCDE	0.00281	0.00625	0.00250	-0.00062	0.00406	0.00688	0.00531	0.00969	0.00125	0.00906

Table 4-12
SNAP-23A P-Leg Statistical Analysis Summary (Min-K 1301 Modules)
(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	Contact Type	Hard Nose	Soft Nose

Effect	Mean Effect and Test Hours									
	225	1000	2500	5000	8500	11500	12500	13000	13500	14000
AVERAGE	1.08515	1.13234	1.14141	1.13922	1.09312	1.07344	1.06647	1.06281	1.05719	1.04859
A	0.37469	0.51344	0.51344	0.46531	0.34125	0.33812	0.32062	0.30812	0.30687	0.29844
B	-0.05781	-0.04281	-0.03156	-0.04219	-0.05500	-0.05437	-0.06063	-0.05052	-0.05937	-0.06406
AB	-0.01719	-0.01906	-0.01969	-0.03156	-0.03000	-0.03312	-0.03250	-0.03562	-0.03437	-0.03031
C	-0.00719	-0.05406	-0.06844	-0.06781	-0.26938	-0.05937	-0.06500	-0.05688	-0.06063	-0.06344
AC	0.02594	-0.03406	-0.09031	-0.12719	-0.10938	-0.10187	-0.09937	-0.08812	-0.09187	-0.08594
BC	0.04094	0.02719	0.01219	-0.00219	-0.01312	0.00562	-0.00312	0.00062	-0.00063	-0.00094
ABC	-0.02219	-0.02531	-0.01344	-0.01531	-0.02412	-0.01938	-0.02875	-0.03063	-0.02687	-0.01844
D	-0.11531	-0.11469	-0.10344	-0.11969	-0.10250	-0.12437	-0.11250	-0.11125	-0.10542	-0.10719
AD	-0.05719	-0.07344	-0.06656	-0.07031	-0.05875	-0.05937	-0.05312	-0.05000	-0.05312	-0.03844
BD	0.02031	0.02281	0.03844	0.01469	0.01000	0.00562	0.01063	0.00125	0.01063	-0.00094
ABD	-0.00781	-0.00094	0.00906	0.00781	0.01125	0.01812	0.01625	0.02250	0.01563	0.01031
CD	0.03469	0.01906	0.00156	-0.04344	-0.02187	-0.01312	-0.01875	-0.01625	-0.02062	-0.02156
ACD	0.00156	-0.00094	-0.00406	-0.02781	-0.01313	-0.00438	-0.00312	0.00125	0.00062	-0.00406
BCD	-0.04344	-0.03219	-0.02156	-0.01031	-0.00187	-0.00437	-0.00688	0.0	0.00187	0.00094
ABCD	0.03469	0.03031	0.01156	0.01656	0.01938	0.01438	0.01750	0.01500	0.01312	0.01844
E	0.06344	0.02844	0.00219	0.01031	0.00875	0.00312	0.00187	0.00313	-0.00187	-0.00781
AE	0.00656	0.00719	-0.01344	-0.00656	-0.01125	-0.01062	-0.01750	-0.01687	-0.01687	-0.01656
BE	-0.03594	-0.02906	-0.00844	-0.00656	0.00000	-0.00062	0.01125	-0.00063	-0.00312	0.00094
ABE	0.00094	0.00469	0.00969	0.00281	0.00000	0.01063	0.01062	0.00688	0.00938	0.01969
CE	-0.02031	-0.03406	-0.01656	-0.00969	-0.01187	-0.00438	-0.00062	-0.00812	-0.00062	-0.00719
ACE	0.01906	-0.00156	-0.00469	-0.01031	-0.00188	0.00562	-0.00375	0.00062	0.00813	0.01231
BCE	0.00906	0.00969	-0.00219	-0.00781	-0.00812	-0.00937	0.00250	-0.00563	-0.00063	-0.00219
ABCE	-0.05531	-0.03031	-0.03156	-0.01469	-0.01312	-0.02187	-0.00938	-0.01688	-0.00688	-0.01719
DE	-0.01594	0.00656	0.01469	0.01219	0.02125	0.01812	0.01062	0.01500	0.01063	0.01781
ADE	0.05344	0.05781	0.04781	0.03281	0.04250	0.04062	0.03375	0.04125	0.03563	0.03656
RDE	0.01094	-0.00094	-0.00719	-0.00469	-0.00625	-0.01188	-0.00750	-0.01750	-0.01563	-0.01094
ABDE	-0.00344	-0.00969	-0.00281	0.00219	-0.01250	-0.01187	-0.02063	-0.01125	-0.01312	-0.01469
CDE	0.00781	0.00906	0.00219	0.00719	0.01188	0.01062	0.00812	0.00125	-0.00063	0.00219
ACDE	-0.02656	-0.01844	-0.00719	-0.00844	-0.00687	-0.00063	0.00000	-0.00375	-0.00437	-0.01231
BCDE	0.01344	0.03031	0.00531	0.00656	0.01687	0.00688	0.00125	-0.00500	0.00188	-0.00281
ABCDE	0.04781	0.03531	0.01219	-0.00031	-0.00438	-0.00937	-0.00563	-0.00750	-0.01187	-0.00781

Table 4-13
SNAP-23A P-Leg Statistical Analysis Summary (Min-K 1301 Modules)
(Power Ratio)

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

Effect	Mean Effect and Test Hours									
	225	1000	2500	5500	8500	11500	12500	13000	13500	14000
AVERAGE	0.88781	0.90578	0.91612	0.90581	0.90355	0.90015	0.89488	0.88737	0.88769	0.88618
A	-0.14286	-0.18169	-0.15714	-0.10444	-0.07458	-0.03811	-0.03922	-0.02886	-0.03330	-0.02082
B	0.04612	0.03369	0.03392	0.04072	0.04301	0.04821	0.05636	0.05099	0.05076	0.05622
AB	0.00495	0.00354	0.00410	0.01213	0.01726	0.02298	0.02051	0.02762	0.02888	0.02559
C	0.02564	0.06134	0.07054	0.02161	-0.01649	-0.06139	-0.07419	-0.07313	-0.06840	-0.08169
AC	-0.02149	0.00532	0.03544	0.05764	0.04418	0.05537	0.04573	0.04494	0.03734	0.04286
BC	-0.03200	-0.02269	-0.00595	0.00986	-0.01889	0.01358	0.01578	0.01692	0.01423	-0.01817
ABC	0.01947	0.02278	0.01380	0.01992	0.03639	0.03651	0.03758	0.04097	0.04186	0.03432
D	0.08146	0.08981	0.07820	0.07309	0.06616	0.08314	0.08181	0.08036	0.07383	0.07478
AD	0.02734	0.02481	0.02378	0.02553	0.02318	0.02702	0.02741	0.03016	0.03499	0.02661
BD	-0.01745	-0.01248	-0.00559	-0.00556	-0.00416	-0.01083	-0.01049	-0.01137	-0.01135	-0.01536
ABD	0.01062	0.00407	-0.00026	-0.00209	-0.00666	-0.01171	-0.00987	-0.01164	-0.01339	-0.00618
CD	-0.01299	-0.00298	-0.00080	0.02156	0.01764	0.01717	0.02258	0.01933	0.00876	0.02176
ACD	0.00099	0.00599	0.01635	0.01884	0.01152	0.00974	0.01493	0.00841	0.01825	0.01511
BCD	0.04155	0.03421	0.01514	0.01046	0.00316	0.00311	0.00166	-0.00434	0.00234	-0.01038
ABCD	-0.03627	-0.03837	-0.01556	-0.01878	-0.01929	-0.01910	-0.01492	-0.00879	-0.01928	-0.01213
E	-0.03601	-0.00074	0.01957	0.02212	0.02916	0.02910	0.03024	0.02587	0.02942	0.02813
AE	0.01426	-0.00512	0.00023	-0.00377	0.00083	-0.00384	0.00277	0.00389	0.00054	0.00098
BE	0.02960	0.02044	0.01304	0.00547	0.00457	0.02089	0.01504	0.01722	0.01720	0.01949
ABE	0.00483	-0.00068	-0.01011	-0.00269	0.00477	-0.00368	-0.00626	-0.00748	-0.00409	-0.01186
CE	0.01561	0.01324	0.00588	-0.00109	0.00697	-0.00051	-0.00178	-0.00103	0.00624	0.01161
ACE	-0.00841	0.00234	0.00335	0.01217	-0.00116	-0.00698	-0.00296	-0.00253	-0.00203	-0.00992
BCE	-0.02572	-0.02074	-0.01099	-0.00104	0.00786	0.00692	0.01329	0.01552	0.01116	0.01182
ABCE	0.04970	0.03511	0.01689	0.00559	0.00286	0.01214	0.00384	0.00364	0.00440	0.00354
DE	0.02056	0.02166	0.01331	0.00639	0.00467	0.00606	0.00847	0.00811	0.00794	0.00538
ADE	-0.04211	-0.04807	-0.04054	-0.02514	-0.02031	-0.02232	-0.01888	-0.02282	-0.01585	-0.02322
BDE	-0.02055	-0.00088	-0.00210	-0.00666	-0.01244	-0.01067	-0.02353	-0.01992	-0.01619	-0.01631
ABDE	0.02072	0.01419	0.01335	0.01398	0.02356	0.02796	0.02929	0.02313	0.01983	0.02089
CDE	-0.00024	-0.00393	-0.00266	-0.00629	-0.03164	0.00273	0.00227	0.00726	0.00467	0.00983
ACDE	0.00874	0.01487	-0.00066	0.00537	0.00768	0.00461	0.00897	0.00791	0.00661	0.00956
BCDE	-0.01170	-0.01939	-0.01328	-0.02154	-0.02823	-0.03261	-0.03226	-0.03112	-0.02590	-0.02501
ABCDE	-0.02258	-0.00579	-0.00040	0.00284	0.01517	0.02440	0.01627	0.02616	0.01444	0.02447

Figure 4-7
N-Leg Statistical Analysis (Microquartz Modules)
Average And Main Effects For Seebeck Ratio

Figure 4-8
N-Leg Statistical Analysis (Microquartz Modules)
Average And Main Effects For Resistance Ratio

Figure 4-9
N-Leg Statistical Analysis (Microquartz Modules)
Average And Main Effects For Power Ratio

Figure 4-10
N-Leg Statistical Analysis (Min-K-1301 Modules)
Average and Main Effects For Seebeck Ratio

Figure 4-11
N-Leg Statistical Analysis (Min-K-1301 Modules)
Average And Main Effects For Resistance Ratio

Figure 4-12
N-Leg Statistical Analysis (Min-K-1301 Modules)
Average and Main Effects for Power Ratio

Figure 4-13
P-Leg Statistical Analysis (Microquartz Modules)
Average And Main Effects For Seebeck Ratio

Figure 4-14
P-Leg Statistical Analysis (Microquartz Modules)
Average And Main Effects For Resistance Ratio

Figure 4-15
P-Leg Statistical Analysis (Microquartz Modules)
Average And Main Effects For Power Ratio

Figure 4-16
P-Leg Statistical Analysis (Min-K-1301 Modules)
Average And Main Effects For Seebeck Ratio

Figure 4-17
P-Leg Statistical Analysis (Min-K-1301 Modules)
Average And Main Effects For Resistance Ratio

Figure 4-18
P-Leg Statistical Analysis (Min-K-1301 Modules)
Average And Main Effects For Power Ratio

Figure 4-19
Comparison of Power Ratio for Various Combinations of P-Legs and Hot
Junction Temperatures (Min-K 1301 Modules)

4.3 CONTINUATION TESTING ON RELATED DEVICES

4.3.1 Module 23A3

Long-term test of six-couple module 23A3 continued during the quarter. N-leg performance data for the module is summarized in Table 4-14 and shown graphically in Figure 4-20.

Analysis of recent data indicates that both Seebeck voltage and internal resistance are decreasing with time.

4.3.2 Converter 23P-2

Long-term test of converter 23P-2 continued during the quarter. Performance data is summarized in Table 4-15. Normalized performance curves are shown in Figure 4-21; data is normalized to $T_h = 1070^\circ\text{F}$, $T_c = 200^\circ\text{F}$. Initial and current 23P-2 experimental-to-theoretical performance ratios are presented in Table 4-16. Analysis of recent data indicates that:

- The Seebeck voltage and resistance of the simultaneously-pressed P-legs appear to be stabilizing.
- The Seebeck voltage and resistance of the simultaneously-pressed N-legs are decreasing with time (about one percent each per 2,000 hours). This trend is the same as that observed on comparable N-legs in ten-couple module no. 1. The voltage decrease is similar to what has been experienced in the past when copper contamination of the N-leg has occurred.
- Normalized converter power output has decreased slightly as a result of the thermoelectric changes. These trends will be continually observed and data recorded periodically for long term evaluation of thermoelectric performance.

Table 4-14
Six-Couple Module 23A3 N-leg Performance Data
(Start of Test: 3/4/65: Current Reading: 10/1/69)

Hours	T _h , °F	T _c , °F	E, mv	R, mo	I, Amps
90	1102	190	114.2	18.8	2.84
481	1104	197	114.3	18.9	2.58
1,034	1100	194	114.5	19.6	2.55
1,655	1100	197	114.3	19.8	2.64
5,065	1100	191	114.5	21.3	2.58
11,252	1100	190	114.5	24.4	2.48
17,732	1095	193	114.0	26.0	2.35
23,000	1095	190	112.5	25.4	2.36
29,136	1100	191	111.5	25.6	2.38
35,694	1096	193	111.0	30.3	2.26
37,779	1103	184	110.5	27.7	2.33
39,262	1100	193	108.5	28.4	2.29
40,101	1100	196	106.0	26.4	2.29

Key

- T_h - Average hot electrode temperature
- T_c - Average cold electrode temperature
- E - Average N-leg open circuit voltage
- R - Average N-leg resistance
- I - Load current

Figure 4-20
 SNAP-23 Six-couple Module A3 N-Leg Performance History
 ($T_h=1100^\circ\text{F}$, $T_c=200^\circ\text{F}$)

Table 4-15
Converter 23P-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	49.6	8.66	71.0
8/2/65	288	1070	201	50.0	2.70	9.25	67.6	50.0	9.24	67.8
8/16/65	624	1080	202	50.8	2.67	9.51	67.8	50.2	9.39	67.2
Installed into System No. 1										
9/3/65	1,030	1075	200	51.0	2.62	9.73	66.8	50.7	9.68	66.3
10/5/65	1,805	1040	201	49.0	2.58	9.59	63.2	51.1	9.90	66.4
11/30/65	3,065	1030	203	48.5	2.56	9.47	62.1	51.0	9.87	66.8
2/2/66	4,679	1030	200	48.3	2.60	9.30	62.8	51.0	9.73	66.9
5/14/66	7,095	1023	204	47.6	2.60	9.15	61.9	51.0	9.60	67.5
8/12/66	9,183	1008	203	46.8	2.57	9.11	60.1	51.2	9.74	67.1
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	50.7	9.86	65.2
6/28/68	12,600	1066	199	50.6	2.73	9.34	68.3	50.8	9.39	68.5
10/1/68	14,884	1076	201	50.9	2.78	9.32	69.5	50.5	9.25	69.1
12/31/68	17,069	1073	201	50.6	2.79	9.18	69.8	50.4	9.14	69.7
3/31/69	19,232	1075	205	50.8	2.79	9.25	69.7	50.7	9.14	70.2
6/26/69	21,316	1078	205	50.6	2.78	9.23	69.5	50.3	9.10	69.6
10/1/69	23,640	1078	207	50.3	2.74	9.23	68.6	50.1	9.08	69.1

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 4-21
 SNAP-23 Prototype P-2 Converter BQL Performance History
 (Normalized Data $T_H=1070^{\circ}\text{F}$ $T_C=200^{\circ}\text{F}$)

Table 4-16
SNAP-23 Converter P-2 BOL Performance Data
(Ratio of Experimental-to-Theoretical Values)

	Time Evaluated in Hours	Seebeck Ratio	Resistance Ratio
Thermopile	48	0.97	1.00
	14,884	0.99	1.07
	19,232	0.99	1.06
	21,316	0.99	1.05
	23,640	0.98	1.05
Typical N-Leg	48	1.03	1.00
	14,884	1.01	0.95
	19,232	1.01	0.95
	21,316	1.00	0.94
	23,640	0.99	0.93
Typical P-Leg	48	0.95	1.10
	14,884	0.98	1.25
	19,232	0.98	1.21
	21,316	0.97	1.19
	23,640	0.97	1.19

*Theoretical resistance values include only T/E material resistance.

APPENDIX A
OUTER CASE - LOWER CASE WELD STRESS

The preliminary analysis of this dissimilar metal weld joint was presented in the Ninth Quarterly, Appendix B. It was shown that although the basic restrained movement (due to thermal expansion differences) would cause only a 9,000 psi hoop stress, the flange configuration with its offset weld resulted in excessive bending stresses.

As suggested in the preceding quarterly, an interim configuration was developed based on an interference fit wherein all stresses were acceptable. However, trial development assembly work encountered problems of simultaneous interfacing on both the I.D. and O.D.

A further configuration change was designed wherein the lower cover weld flange thickness was reduced to provide the required deflection at acceptable stress levels and yet provide a gap interface.

The initial configuration is shown in Figure A-1 and the final configuration in Figure A-2. The only basic change reduced the 0.366 inch long flange from 0.045 inch thickness to 0.025 inch thickness over 0.23 inches of length.

The analysis was accomplished by limiting the 0.366 inch long flange "fixed" support bending moment to a value below the weld bead support level while the flange deflected the required 0.0015 inch expansion difference.

INITIAL OUTER CASE - LOWER COVER CONFIGURATION
(SEE QUARTERLY #9)

FIGURE A-1

FIGURE A-2

FINAL OUTER CASE - LOWER COVER CONFIGURATION

1. Weld Bead

As the weld bead supports the flange on the side rather than the end, the flange bending loads concentrated or distributed are carried in direct bearing compression, whereas any resulting moment rapidly overstresses the weld because it lacks depth for establishing a force acting distance.

The following calculations express the maximum moment for the established weld bead of .034 inches.

$$M = \frac{2}{3} w F$$

$$\text{where } = \frac{2}{3} w \left(\frac{1}{2} S_m \times \frac{1}{2} w b \right)$$

$$M = \text{inch pounds}$$

$$w = 0.034 \text{ (weld penetration)}$$

$$F = \frac{1}{2} S_m \times \frac{1}{2} w \times b$$

$$b = 1.0 \text{ inch}$$

$$S_m = 30,000 \text{ lbs/in}^2$$

solving for M

$$M = 0.67 \times 0.034 \times 0.5 \times 30,000 \times \frac{0.034}{2} \times 1.0$$

$$= 5.8 \text{ in-lbs per inch of circumference.}$$

This is the maximum bending stress which allows for no direct load stresses. The direct load which the weld bead could carry is:

$$W = b \omega s$$

$$= 1.0 \times 0.034 \times 30,000$$

$$= 1020 \text{ lbs}$$

where

$$b = 1.0 \text{ inch}$$

$$\omega = 0.034 \text{ inch}$$

$$s = 30,000 \text{ lbs/in}^2$$

thus, the bending moment is far more restrictive.

2. Weld Flange

The weld flange configuration shown in Figure A-2 has maximum flexibility for the overall dimensions. The 0.020/0.025 thickness is minimal for fabrication purposes and the length (l) is maximum at 0.230 inch. The major thermal expansion load is supplied by the radial disc portion of the lower cover. The flexible flange allows the disc to expand rather than supporting its load if restrained; therefore, it is necessary to determine if the flange can deflect 0.0015 inch at the disc end. This is done by assuming a 1.0 inch wide section of the flange as a beam with one end fixed (weld bead end) and the other end guided (disc end) and loaded (to give 0.0015 inch deflection) then

$$Y = \frac{Wl^3}{12EI}$$

$$M = \frac{Wl}{2}$$

where

Y = deflection 0.0015 inch

M = moment in-lbs

W = load lbs

ℓ = length of thin wall 0.23 inch

E = material modulus 28×10^6 lbs/in²

I = cross section moment of inertia (in⁴)

$$I = \frac{b d^3}{12}$$

b = width of beam 1.0 inch

d = depth of beam 0.023 inch

Solving for W

$$Y = \frac{W \ell^3}{12 EI}$$

$$W = \frac{12 EI Y}{\ell^3} = \frac{12 E b d^3 Y}{\ell^3} = \frac{E b d^3 Y}{\ell^3}$$

$$= \frac{28 \times 10^6 \times 1.0 \times 0.023^3 \times 0.0015}{0.23^3}$$

$$= 42 \text{ lbs}$$

Solving for M

$$M = \frac{W \ell}{2}$$

$$= \frac{42 \times 0.23}{2}$$

$$= 4.83 \text{ in lbs}$$

Note: that moment is less than maximum set.

One further check on the flange bending stress is needed:

$$S_b = \frac{W \ell}{2Z}$$

where

$$W = 42 \text{ lbs}$$

$$\ell = 0.23 \text{ inch}$$

$$Z = \frac{b d^2}{6}$$

$$b = 1.0 \text{ inch}$$

$$d = 0.023 \text{ inch}$$

$$\begin{aligned} S_b &= \frac{42 \times 0.23 \times 6}{2 \times 1.0 \times 0.023^2} \\ &= 54,800 \text{ lbs/in}^2 \end{aligned}$$

This is considerably above the 30,000 limit and appears more restrictive than the weld; therefore, calculations were made for a restraint of 0.00075 inch.

Calculate load W from disc if restrained 0.00075 inch.

$$\text{Strain} = \frac{\text{Restraint}}{\text{Radius}} = \frac{0.00075}{4.625} = 162 \times 10^{-6}$$

$$\text{Stress} = E \text{ Strain} = 28 \times 10^6 \times 162 \times 10^{-6} = 4540 \text{ lb/in}^2$$

$$\begin{aligned} \text{Load} &= \frac{2F}{D} = \frac{2 \times \text{Stress} \times t \times d}{9.25} = \frac{2 \times 4540 \times 0.020 \times 1.0}{9.25} \\ &= 19.6 \text{ pound per inch circumference} \end{aligned}$$

The bending stress in the flange thin wall is then

$$\begin{aligned} S_b &= \frac{W \ell}{2Z} \\ &= \frac{19.6 \times 0.23 \times 6}{2 \times 1.0 \times 0.023^2} \\ &= 25,400 \text{ lbs/in}^2 \end{aligned}$$

This is satisfactory.

The bending moment at the flange support is then

$$\begin{aligned} M &= \frac{W \ell}{2} \quad \text{where } \ell \text{ is really } 0.36, \text{ i. e., full flange length} \\ &= \frac{19.6 \times 0.36}{2} \\ &= 3.5 \text{ in/lbs} \end{aligned}$$

This is satisfactory.

Therefore the lower cover with its revised flange is a satisfactory configuration for a loose fit weld flange.

APPENDIX B
OUTER CASE – HEADER RING WELD ANALYSIS

The basic preliminary analysis of this dissimilar metal weld joint was presented in the Ninth Quarterly, Appendix B. The basic analysis is reviewed in Section 1, followed by discontinuity stresses in the outer case in Section 2, and the weld stresses in Section 3. Figure B-1 shows the preliminary configuration (Ninth Quarterly) and Figure B-2 shows the final configuration.

The properties of the metals are listed below:

Metal	<u>OUTER CASE</u>	<u>HEADER RING</u>
	Inconel 625 Alloy	304 Stainless Steel
Operating Temperature	200 °F	200°F
Modulus of Elasticity (E) Tensile-psi	29.2×10^6	28.2×10^6
Yield Stress-Typical (0.2% Tension - psi)	56,000	42,000
Mean Coefficient of Expansion (in/in per °F)	7.1×10^{-6}	9.6×10^{-6}

Section 1

All of the deflection occurs in the thin wall of the outer case flange. The required deflection is:

1. 0.003 inch on 9.25 inch diameter assembly interference
2. 0.003 inch on 9.25 inch diameter thermal interference

304 STN	9.6×10^{-6}	in/in per °F
625 Alloy	7.1×10^{-6}	in/in per °F
Difference	2.5×10^{-6}	in/in per °F

then

$$(200^{\circ}\text{F} - 70^{\circ}\text{F}) (9.25 \text{ dia}) (2.5 \times 10^{-6} \text{ in/in} - ^{\circ}\text{F})$$

gives

$$3000 \times 10^{-6} \text{ in or } 0.003 \text{ inch.}$$

The total strain (deflection) of 0.006 inch on a 9.25 diameter gives a stress of 18,950 psi.

Stress = strain x modulus

$$= 0.006 \text{ in}/9.25 \text{ in times } 29.2 \times 10^6 \text{ psi}$$

$$= 18,950 \text{ psi}$$

The 18,950 psi stress is less than 50 percent of the typical yield stress for Inconel 625 alloy (56,000 psi) and thus assures a sound design. This basic stress is the same for both the preliminary (Figure B-1) and final (Figure B-2) weld flanges.

Section 2

The thin flange (0.045 inch wall thickness) was lengthened to the extent possible (0.500 inch) and still retain the overall PMC-2 configuration. The added length was necessary to reduce bending stresses in the transition length of the outer case wall below the header ring interface.

Based on thin wall pressure vessel analysis (Formulas for Stress and Strain; Roark, 4th Edition - Table XIII, Case 13, 14 & 15) the discontinuity stressed are:

1. Maximum Bending Stress -

Assuming sufficient cylindrical length that discontinuities do not conflict:

For Rigid Support

$$M_o = \frac{P}{2\lambda^2} \quad V_o = \frac{P}{\lambda}$$

(Case 13) Maximum Bending Stress = $\frac{-6 M_o}{t}$

where

t = wall thickness = 0.045 inch

R = cylinder radius = 4.625 inch

$$\lambda = \sqrt[4]{\frac{3(1-\nu^2)}{R^2 t^2}} = \frac{1.285}{\sqrt{Rt}}$$

when

$\nu = 0.3$ (Poisson's Ratio)

$$= \frac{1.285}{\sqrt{4.625 \times 0.45}} = \frac{1.285}{0.456} = \underline{\underline{2.82}}$$

P = Interface Pressure (psi)

Half Shell

then

9.25 inch dia, 1 inch long, 0.045 inch thick
stress (partial) = 18,950 psi

$$\begin{aligned} F &= \text{stress} \times \text{area} \\ &= 18950 \text{ psi} \times 0.045 \text{ inch} \\ &= 853 \text{ lbs per inch length} \end{aligned}$$

and

$$\begin{aligned} P &= \frac{2F}{D} = \frac{2 \times 853 \text{ lbs/in}}{9.25 \text{ inch}} \\ &= \underline{\underline{185 \text{ lbs/in}^2}} \end{aligned}$$

$$M_o = \frac{P}{2\lambda^2} = \frac{185}{2 \times (2.82)^2} = 11.6 \text{ lbs/in circumference}$$

and

$$\text{Max bending stress} = \frac{-6 M_o}{t^2} = \frac{-6 \times 11.6}{(0.045)^2} = -34,400 \text{ lbs/in}^2$$

Note numerical value correct but for actual flange all forces reversed making

2. Spacing and Conflict of Adjacent Discontinuities

- a) A review of literature shows the discontinuities need to be spaced at distance

$$x \text{ of } \frac{4}{\lambda} = \frac{4}{2.82} = 1.4.$$

For PMC-2 the 0.5 inch flange results in a distance

$$x = 0.500 - 0.218 = 0.282 \text{ inch}$$

- b) To define the degree of conflict and to check the preceding calculations, the reference "Theory of Plates and Shells," (Timo Shenko) was used in conjunction with "Formulas for Stress and Strain," (Roark). The decay of the discontinuity stresses and strain with distance is given by formula and the decay factors tabulated.

The Deflection δ (at interface)

$$\delta = -\frac{1}{2\lambda^3 D} \left[\lambda M_o + V_o \right]$$

where

$$D = \frac{E t^3}{12 (1 - \nu^2)} = \frac{29.2 \times 10^6 \times 0.045^3}{12 (1 - 0.3^2)} = 244$$

$$V_o = P/\lambda = \frac{185}{2.82} = 65.7 \text{ lbs per inch of circumference}$$

then

$$\begin{aligned}\delta &= -\frac{1}{2 \times 2.82^3 \times 244} \left[2.82 \times -11.6 + 65.7 \right] \\ &= -\frac{1}{10,700} (-32.7 + 65.7) \\ &= \frac{33}{10,700} = -0.00309\end{aligned}$$

This is the outward deflection (on radius)

the deflection δ (at $x = 0.282$ inch)

$$\delta = -\frac{1}{2\lambda^3 D} \left[\lambda M_o x F' + V_o F^2 \right]$$

where

F' is 0.0093 from Table 84 (Timo Shenko)

for

$$e^{-\lambda x} (\cos \lambda x + \sin \lambda x)$$

when

$$\lambda x = 2.82 \times 0.282 = 0.8$$

Similarly

$$F^2 \text{ is } 0.3131$$

for

$$e^{-\lambda x} \cos Bx$$

Then

$$\begin{aligned}\delta &= -\frac{1}{10,700} \left[-32.7 \times -0.0093 + 65.7 \times 0.3131 \right] \\ &= -\frac{1}{10,700} \left[0.306 + 20.55 \right] = -\frac{20.86}{10,700} \\ &= -0.00195\end{aligned}$$

Thus, the outward deflection is nearly 2/3 of original (0.003 inch).

The hoop stress which is directly related to the deflection was also checked to verify that the deflection was considerable at the 0.282 inch distance where the outer case wall increases in thickness to 0.125 inches. As the added thickness greatly increases the rigidity, the 0.045 inch by 0.282 inch long flange must of necessity be deformed the full 0.003 inch.

As the formulas and calculations for conflicting discontinuities in pressure vessels are very complex; a reasonable substitute calculation was accomplished to evaluate the stresses in the 0.282 inch long segment of the outer case.

A one inch slice through the 0.282 inch long by 0.045 inch thick ring is assumed to act as a beam. The load conditions for matching at the outer case discontinuities are:

- One end fixed
- Other end guided and loaded
- Deflection as required - 0.003 inch

(Ref. Machinery's Handbook, 13th Edition, Table on Page 394, case 17).

$$\text{Stress at Supports} = \frac{w\ell}{2Z}$$

$$\text{Deflection } (\delta) = \frac{W\ell^3}{12EI}$$

where beam is:

$$0.045 \text{ inch thick} = d$$

$$1.000 \text{ inch wide} = b$$

$$0.282 \text{ inch long} = \ell$$

and

$$E = 29.2 \times 10^6$$

$$I = \frac{bd^3}{12}$$

$$Z = \frac{I}{d/2} = \frac{2I}{d} \text{ or } \frac{bd^2}{6}$$

The needed relationship is stress (S_b) with respect to deflection (S) by transforming the above formulas to remove the third unknown (W).

$$\begin{aligned}
 S &= \frac{W\ell}{2Z} & \delta &= \frac{W\ell^3}{12EI} \\
 &= \frac{W\ell}{\frac{2bd^2}{6}} & &= \frac{W\ell^3}{12E\frac{bd^3}{12}} \\
 &= \frac{3W\ell}{bd^2} & &= \frac{W\ell^3}{Ebd^3}
 \end{aligned}$$

$$\begin{aligned}
 \frac{Sbd^2}{3\ell} &= W & \frac{\delta Ebd^3}{\ell^3} &= W
 \end{aligned}$$

$$\frac{Sbd^2}{3\ell} = \frac{\delta Ebd^3}{\ell^3}$$

$$S = \frac{\delta Ebd^3 \ell}{bd^2 \ell^3} = \frac{3\delta Ed}{\ell^2}$$

$$S = \frac{3 \times 29.2 \times 10^6 \times 0.045}{0.282^2} \quad \delta = 49.5 \times 10^6 \delta$$

1. A check on the beam compared to actual .

$$\left[\text{Substitute } S = 0.00105 \text{ (0.003 - 0.00195) see Section 2.2. b} \right]$$

$$\begin{aligned}
 S &= 49.5 \times 10^6 \times 0.00105 \\
 &= 52,000 \text{ lbs/in}^2
 \end{aligned}$$

This is 50 percent higher than actual maximum bending stress of $34,400 \text{ lbs/in}^2$, indicating a conservative substitution.

2. Calculate stress for full deflection of 0.003

$$S = 49.5 \times 10^6 \times 0.003 = 147,000 \text{ lbs/in}^2$$

will cause yielding on the inner (compression) and outer (tension) fibers to satisfy deflection.

3. A degree of yielding under bending stresses is not detrimental to outer case service life if the thermal cycling deflection gives less than full "yield to yield" stress reversal. The total thermal deflection is 0.0015, thus a 0.00075 deflection ($\frac{0.0015}{2}$) will be used to calculate the bending stress.

$$\begin{aligned} S &= 49.5 \times 10^6 \times 0.00075 \\ &= 37,200 \text{ lbs/in}^2 \end{aligned}$$

This stress is sufficiently below the 56,000 typical yield stress of Inconel 625 Alloy to assure long life - even with thermal cycling.

4. The discontinuity parameters for the 0.282 length bent to yield ($S = 56,000$) are

- a) deflection

$$\begin{aligned} S &= 49.5 \times 10^6 \delta \\ 56,000 &= 49.5 \times 10^6 \delta \\ 0.00113 \text{ inch} &= \delta \end{aligned}$$

- b) V_o (i.e. W)

$$\begin{aligned} S &= \frac{w \ell}{2Z} \quad \text{or} \quad w = \frac{2 S Z}{\ell} = \frac{2S}{\ell} \times \frac{bd^2}{6} \\ V_o = w &= \frac{2 \times 56,000 \times 1.0 \times 0.045^2}{0.282 \times 6} = 134 \text{ lbs} \end{aligned}$$

- c) M_o (i.e. $\frac{w \ell}{2}$)

$$M_o = \frac{134 \times 0.282}{2} = 18.9 \text{ in/lbs}$$

Section 3

The portion of the outer case flange which is expanded around the header ring was assumed to provide a fixed support during analysis in Section 2. The loading and supports on this portion are

The header ring will give fixed bearing support over the 0.218 inch length.

The weld bead 0.020 inch minimum thickness will be stressed as needed

Note that the loading (P) results from deflecting the outer case, setting up tensile hoop stress. In Section 1, this was 18,900 lb/in at operate temperature.

Of particular interest is the ability to transfer or sustain the discontinuity loads V_O and M_O .

1. The V_O load as shown will transfer in direct bearing to the header ring and as such does not cause concern.
2. The M_O load as shown will be sustained (i.e., flange head fixed) by the "P" bearing loads as follows. Assuming that over a short length of 0.218 the ring does not bend. Then the moment M_P developed by P is

$$P \times \text{area} \times \frac{0.218}{2} = 185 \times (0.218 \times 1.0) \times \frac{0.218}{2}$$

$$M_P = 4.4 \text{ in/lbs}$$

The M_O load will not be controlled by P loading thus M_O will not be developed and the assumption that the discontinuity has a rigid interface is erroneous - at least prior to welding (i.e., during press fit).

3. The other method for M_o load being sustained is by the weld (weld in shear). The moment M_w that can be developed by the weld is (use S_s - 40,000 yield)

$$M_w = S_s \times t \times x = 40,000 \times 0.020 \times 0.218$$

giving

$$M_w = 175 \text{ in/lbs}$$

indicating that after welding (i. e., during thermal expansion) the discontinuity will act like a fixed support to the transition lengths.

The preceding analysis shows a need for re-calculating the transition length loading during the press fit (0.001 to 0.003 on dia.). The recalculation using beam formulas for Cantilever beam (with beam extending beyond load to give determination of 0.218 section) is as follows:

Comparing back to prior case 17 (guided at load section 2.2.0) the deflection for a given load is four times as great under case 12 load conditions and the stress is doubled; therefore, the load will be one fourth and the stress could be one half of the prior calculations.

The overhanging end deflection can be given as a ratio of the deflection at the load. For our conditions, the distances are fixed.

$$\text{The deflection at load} = \frac{Wl^3}{3EI}$$

The deflection at the end = $\frac{W\ell^2}{6EI} (2\ell + 3b)$

$$\frac{W\ell^2}{6EI} (2\ell + 3b) = \frac{W\ell^3}{3EI} + \frac{W\ell^2 b}{2EI} = \frac{W\ell^2}{EI} \left(\frac{\ell}{3} + \frac{b}{2} \right)$$

for a ratio of $\frac{\ell}{3}$ to $b/2$

giving

$$\frac{0.282}{3} \text{ to } \frac{0.218}{2}$$

and 0.094 to 0.109.

Thus the 0.218 length bears on the header ring at the discontinuity and gaps at weld line by $\frac{0.109}{0.094}$ or 1.16 times the radial interference fit of 0.0005 to 0.0015. The gap can then range from 0.00058 inch to 0.00174 inch.

The load conditions at assembly can now be calculated (use maximum interference fit) and the thermal loading can be added to complete analysis.

$$\text{then } 0.0015 \text{ deflection} = \frac{W\ell^3}{3EI}$$

where

$$\ell = 0.282 \text{ and } \ell^3 = 0.0224$$

$$E = 29.2 \times 10^6$$

$$I = \frac{bd^3}{12} = \frac{1.0 \times 0.045^3}{12} = 7.6 \times 10^{-6}$$

$$W = V_o$$

$$V_o = (0.0015) \frac{3EI}{l^3} = \frac{0.0015 \times 3 \times 29.2 \times 10^6 \times 7.6 \times 10^{-6}}{0.0224}$$

$$= 44.6 \text{ lbs per inch circumference}$$

Bending stress (thick wall)

$$= \frac{V_o l}{Z}$$

where

$$Z = \frac{bd^2}{6} = \frac{1.0 \times 0.045^2}{6} = 0.338 \times 10^{-3}$$

$$\text{Stress} = \frac{44.6 \times 0.282}{0.338 \times 10^{-3}} = 37,300 \text{ lb/in}^2$$

The pressure load (P), proportional to the cylinder expansion results in an additional bearing load V_p . Prior calculations show $P = 185 \text{ psi}$ when deflection is 0.003 with a resulting force load of 40 pounds per inch of circumference.

The thermal loading will be per the prior beam analysis resulting in bending stresses to the yield point at the thick wall (fixed end) and at the discontinuity (guided end). The V_o of 134 pounds and M_o of 18.9 in/lbs will be sustained; V_o by direct bearing, M_o by shear stress in the weld.

The weld loading (M_o) is then $M_o / 0.218 \text{ lbs per linear inch}$.

$$\text{Weld shear load} = \frac{18.9}{0.218} = 86.5 \text{ lbs per inch and the}$$

$$\text{weld shear stress} = \frac{\text{load}}{\text{thickness}} = \frac{86.5}{0.020 \text{ in}} = 4,330 \text{ psi.}$$

The loading for thermal heat-up is satisfactory. A further analysis of loading during thermal cool down is needed since V_o and M_o loading reverse direction as a result of yielding out during heat-up. From Part B, the deflection associated with loading to the yield stress is 0.0011, thus the reversed deflection is $0.0015 - 0.0011 = 0.0004 \text{ inch}$ or approximately one third that required to cause yielding.

It is shown that through the analysis of this appendix that the outer case-header ring weld and flange is an acceptable configuration.

APPENDIX C
STRENGTH ANALYSIS FOR 15-G TRANSVERSE LOADING

Based on Westinghouse test and analysis for the system support structure which resulted in a 15-g load factor, the new load will be:

$$\frac{15}{10} \times 2400 = 3600 \text{ lbs.}$$

For transverse loads, the bottom closure is stiffer than the cone but we will assume 50 percent of the load supported by the cone.

$$0.5 \times 3600 = 1800 \text{ lbs.}$$

Cone Stress

Moment at top of cone = 1.6×1800

$$f = \frac{My}{I} = \frac{1.6 \times 1800 \times 2.01}{3.1416 (2.01)^3 (0.025) 0.707} = 12,800 \text{ psi}$$

$$r_i = 2.01$$

$$\alpha = 45^\circ$$

$$f_B = 12,800 \text{ psi}$$

$$t = 0.025 \text{ inch}$$

Equivalent axial load to produce 12,800 psi all around small end of cone will be:

$$P = \frac{\pi D t f_B}{0.707} = \frac{3.1416 (2 \times 2.01) (0.025) (1.28 \times 10^4)}{0.707} = 5,720 \text{ lb.}$$

Cone Buckling

Next calculate critical buckling load for cone if loaded axially. From Figure A-2 in 3M Quarterly Report No. 1, May 22, 1967, with:

$$t \frac{r}{\cos \alpha} = \frac{2.01}{0.025 \times 0.707} = 113.6,$$

$$C = 0.35 \text{ and } P_{cr} = 2\pi C E^1 t^2 \cos^2 \alpha$$

$E^1 = \sqrt{E_T E_S}$ where E_T = tangent modulus and E_S = secant modulus, both evaluated at the existing stress level and temperature. Assume a maximum stress level of 0.2 percent yield at 500°F. If the actual stress corresponding to P_{cr} is greater than the yield value, then the critical load will be the one for yield stress. At 500°F the yield stress is 65 percent of the room temperature value giving $0.65 \times 30,000 = 19,500$ psi. At this stress level, $E_T = 20.4 \times 10^6$ and $E_S = 26.3 \times 10^6$. At 500°F the moduli will be approximately 93 percent of their room temperature values giving:

$$E^1 = (0.93 \times 20.4 \times 10^6 \times 0.93 \times 26.3 \times 10^6)^{1/2}$$

$$= 21.6 \times 10^6 \text{ psi}$$

$$P_{cr} = 2 \times 3.1416 \times 0.35 \times 21.6 \times 10^6 (0.025)^2 (0.707)^2$$

$$= 14,900 \text{ lb.}$$

Since this equivalent axial load produces a meridional stress of

$$f = \frac{14,900 \times 0.707}{\pi D t} = \frac{14,900 \times 0.707}{3.1416 \times 4.02 \times 0.025} = 33,400 \text{ psi}$$

which is greater than the 19,500 psi yield allowable, the critical condition is actually for yield stress. Therefore, the critical equivalent axial load will be:

$$P_{cr}^1 = \frac{3.1416 \times 4.02 \times 0.025 \times 19,500}{0.707} = 8,700$$

$$M.S. = \frac{8700}{5720} - 1 = +0.52$$

Upper Portion Hot Frame

$$(r = 1.87 \text{ inch, } t = 0.020 \text{ inch})$$

Maximum moment at the top = 1.6×1800

$$f = \frac{My}{I} = \frac{Mr}{\pi r^3 t} = \frac{M}{\pi r^2 t} = \frac{1.6 \times 1.8 \times 10^3}{3.1416 (1.87)^2 (2 \times 10^{-2})} = 13,100 \text{ psi}$$

There is a "Gradient Factor" of 1.3 associated with the comparison of critical stress for bending versus direct axial load to produce buckling of circular cylinders. We will conservatively neglect the factor and use data and formulas for compressive buckling as found in Appendix A of NACA TN 3783, August 1957.

$$\frac{L^2}{rt} = \frac{(2.5)^2}{1.87 (0.020)} = 167$$

Since this is greater than 100, the problem is in the "long-cylinder" category and:

$$f_{cr} = \eta CET/r$$

where η is a plasticity reduction factor to be used if stress level is above the proportional limit. We will limit f_{cr} to yield stress, for which " η " very nearly equals 1; therefore $\eta = 0.95$ will be used for analytical calculations.

From Figure 7 of the referenced Technical Note with

$$\frac{r}{t} = \frac{1.87}{0.020} = 93.5, C = 0.43$$

$$f_{cr} = 0.95 \times 0.43 \left(\frac{25.6 \times 10^6}{@ 500^\circ F} \right) \downarrow \frac{0.025}{1.87} = 139,500 \text{ psi}$$

Since this is far above yield allowable, the value of

$$f_{cr} = 19,500 \text{ psi (for } 500^\circ F \text{ temperature)}$$

will be used as the limiting strength

$$M.S. = \frac{19,500}{13,100} - 1 = +0.49$$

SNAP-23A 15-G LATERAL SHOCK LOAD

The material of both the cone and the inner cylinder is 304 stainless steel. A 600°F temperature is assumed at the juncture of cone and cylinder. From the International Nickel Company publication "Nickel Alloy Steels", second edition, section 7, data sheet A, page 64, the following information on Endurance Limit, is available.

The room temperature value for the material used in test was 40,000 psi. This value is greater than the minimum yield strength of 30,000 psi in tension and consequently we will establish our design curve as $\frac{30,000}{40,000} \times 100 = 75$ percent of the test values reported above. The solid line on the above figure shows the design values of endurance limit.

At 600°F the endurance limit is 25,000 psi.

Stress due to bending at the top of the cone is 12,800 psi.

$$\text{M. S. for Fatigue} = \frac{25,000}{12,800} - 1 = +0.95$$

Stress due to bending at the top of the inner cylinder is 13,100 psi.

$$\text{M. S. for Fatigue} = \frac{25,000}{13,100} - 1 = +0.91$$

Based on the results of this analysis the structure could safely withstand a 15-G lateral load. The structure is able to carry this 15-G lateral load because both the support cone and lower cover carry a portion of the load. Loading in the vertical direction is carried entirely by the support cone. Thus, the cone loading for the 15-G lateral load is $50 \times \frac{15}{10} = 75$ percent of what it is for a 10-G vertical load.

APPENDIX D
PROCEDURE RESTRICTIONS FOR MOUNTING PMC-2 CONVERTER
TO FUELED PROTOTYPE MOCK-UP SYSTEM

These procedure restrictions apply to mating of a room temperature converter to the spud of the system at elevated temperature. The concern is to control thermal shock so the converter is not damaged. The threshold of thermal shock which would cause damage to a converter is not known. However, from previous experience with thermoelectric power generators, judgement can be applied to limit the thermal shock.

The procedure restrictions are as follows:

1. The initial step in mating the converter should position the top of system head spud 1/4" from lower cover-outer case weld. The spud should be held in this position for ten minutes or until the hot junction temperature at the lower end of the converter reaches 250°F.
2. Lower converter onto spud in increments of time and movement such that the rate of temperature rise of any hot junction shall not be greater than 400°F per hour and the hot junction differential from top to bottom shall not exceed 500°F.
3. When the temperature differential between the coldest hot junction and the spud temperature is less than 400°F, the converter can be seated into position on the spud.
4. The spud temperature, prior to mating with the converter, must be low enough so the hot junction temperature does not exceed 1040°F.

APPENDIX E

THERMOELECTRIC ANALYSIS FOR SNAP-23A PMC-1 AND PMC-2

Calculations used for the analysis of SNAP-23A converters involve several adjustments. Seebeck voltage and resistance ratios are entered as part of the computer program input whereas delta adjustment to heat input and sometimes power output are made to the output. The purpose of these adjustments is to match the parametric analysis program to converter performance and to normalize the parametric analysis program (PRAM-01) to the design program (LEG-02).

PMC-1a

PMC-1a analysis is currently being performed by WANL to evaluate converter and system long-term performance. Predictions are made with WANL's parametric analysis program which closely matches PRAM-01. The following adjustments are necessary to match converter performance:

Thermoelectric adjustment factors determined from thermopile resistance and Seebeck voltage measured at 3792 hours of operation and split between the N and P legs are:

	<u>Resistance Ratio</u>	<u>Seebeck Ratio</u>
N Leg	0.95	1.00
P Leg	0.92	0.95

Converter heat requirement includes losses through the converter insulation and other shunt paths which are calculated by:

$$Q_{\text{Loss 1 (Watts)}} = 0.1714 \times (T_h - T_c) - 53.31$$

In addition, an experimental to theoretical heat input bias has been determined through comparison studies. The comparison shows that seven watts should be added to PRAM-01 heat requirement to match PMC-1a converter requirements. The total heat requirement of PMC-1a is then given as:

$$Q_{\text{PMC-1a}} = Q_{\text{PRAM-01}} + Q_{\text{Loss 1}} + 7 \text{ Watts}$$

A power adjustment to PRAM-01 is not necessary to match PMC-1a performance. The resistance and Seebeck voltage ratios from PMC-1a force a match of experimental and predicted resistance and Seebeck voltage. With equal load voltage the predicted and experimental power are forced to match.

The power adjustment in practice is quite small being of the same order (0.5 percent) as the accuracy of resistance and Seebeck voltage ratios. The only advantage of using this adjustment is to match design calculations and parametric analysis. Therefore, it is recommended that this adjustment be dropped when the PRAM-01 program is normalized to a specific operational unit and be retained for parametric analysis before actual performance data is measured.

PMC-2

Parametric analysis of PMC-2 presents a different situation in that the unit has not yet been tested. As a result, the analysis is made for the range in Seebeck voltage and resistance ratios observed in operating SNAP-23A units. In addition, an adjustment is made to the predicted heat input to account for the calculational bias observed in comparing the parametric analysis model to experimental results. (A difference does exist between heat input calculated by the design model, LEG-02, and that calculated by the parametric analysis model, PRAM-01, but these differences are eliminated by normalization of both models to experimental results.) Finally a small power adjustment is made to normalize the parametric analysis results to the design model.

Seebeck voltage and resistance ratios for PMC-2 analysis are listed below.

THERMOELECTRIC ADJUSTMENT FACTORS

Resistance Ratios

	<u>Design</u>	<u>Nominal</u>	<u>Best</u>
N Leg	1.00	0.98	0.96
P Leg	1.03	0.99	0.96

Seebeck Voltage Ratios

	<u>Design</u>	<u>Nominal</u>	<u>Best</u>
N Leg	1.00	1.00	1.00
P Leg	0.96	0.97	0.98

Predictions of PMC-2 heat requirement are made with a shunt heat loss equation of:

$$Q_{\text{Loss 2 (Watts)}} = 0.1670 \times (T_h - T_c) - 45.97$$

The calculational bias for heat input is + 6 watts for the parametric analysis results, PRAM-01, and + 20 watts for the design program, LEG-02. The 14 watts difference between the two programs is due to small differences in the theoretical models.

The heat input requirement for PMC-2 is then calculated as follows:

$$Q_{\text{PMC-2 (Watts)}} = Q_{\text{PRAM-01}} + Q_{\text{Loss 2}} + 6$$

or

$$Q_{\text{PMC-2 (Watts)}} = Q_{\text{LEG-02}} + Q_{\text{Loss 2}} + 20$$

The power adjustment for PMC-2 to normalize PRAM-01 to the design program is -0.30 watts. Power output predictions for PMC-2 are therefore:

$$P_{\text{PMC-2 (Watts)}} = P_{\text{PRAM-01}} - 0.30$$

or

$$P_{\text{PMC-2 (Watts)}} = P_{\text{LEG-02}}$$