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**SNAP-23A PROGRAM, PHASE 1
THERMOELECTRIC CONVERTER
DEVELOPMENT PROGRAM
QUARTERLY REPORT NO. 9**

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AEC RESEARCH AND DEVELOPMENT REPORT

This report has been prepared under Contract AT(30-1)-3824
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SNAP-23A PROGRAM, PHASE I
THERMOELECTRIC CONVERTER
DEVELOPMENT PROGRAM

QUARTERLY REPORT NO. 9

January 1, 1969 through March 31, 1969

Prepared by
SNAP-23A
Technical Staff

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FOREWORD

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

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

The SNAP-23A development effort is directed toward the design, fabrication, and test of a thermoelectric converter design to be used as a component in the 60-watt SNAP-23A Terrestrial Radioisotope Power Supply System. This document reports progress for this effort from the period 1 January 1969 through 31 March 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

The design base criteria selected to control design selections and trade-offs for the PMC-2 converter were established on the premise that PMC-2 would be integrated into a fueled PMS. Under the consideration that a fueled system would be representative of an advanced operational unit, design emphasis was directed toward operational environmental requirements. Areas of design investigation were:

- Effects of ambient temperature increase upon converter performance.
- Effects of potential T/E degradation upon converter performance.
- Enclosure structure suitability to operational environment.

The extent of the design investigation was to

- Select converter operational design point (BOL and EOL conditions).
- Select enclosure materials suitable to operational criteria.
- Provide a design for an operational type of converter which is adapted for laboratory test by incorporation of additional instrumentation and termination provisions.

The result of these design investigations produced a series of design changes and an evolution of the converter from the prior PMC-1 design to one that includes an integral top rain cover.

The effects of ambient temperature increase and degradation analysis produced a change in converter operating temperature. Thermoelectric couple design was only changed in respective segment lengths while overall couple length remained the same; the number of couples was increased to 280. The suitability of the structure to an operational environment was improved by redesign of the outer case assembly as follows:

- Selection of Inconel 625 for superior corrosion resistance in a salt environment.
- Relocation of exterior instrumentation headers to an interior header ring under the converter top cover.
- Removal of upper bolt flange and incorporation of a welded upper rain cover extension.
- Redesign of lower bolted flange interface with lower rain cover.
- Relocation and redesign of the power header and associated transition terminal.
- Redesign of converter internal pinning structures to compensate for the change in thermal properties of the outer case material (Inconel 625 vs. 304 stainless steel as formerly used).
- Relocation and redesign of the gas fill port.
- Removal of the pressure gage.
- Redesign of top cone.
- Redesign of bottom cover.

The resultant PMC-2 concept was coordinated with the SNAP-23A systems contractor, Westinghouse. Near the close of the quarter, 3M Company proceeded to implement the design concept into definitive engineering drawings.

Long-term operation testing of the following devices are continuing

- 10-couple modules 1, 3, and 5 through 12
- Converter 23P2
- Six-couple module 23A-3
- Converters EMC-2, EMC-3, PMC-1B

Measurement of end-of-life performance was conducted on EMC-2, EMC-3, and PMC-1B and is shown in Table 1-1.

Table 1-1
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	891	851	849	893
Power Output	P_o	Watts (e)	50.9	63.6	64.1	69.4	70.1
Efficiency	η	Percent	6.08	7.14	7.53	8.16	7.85
Open Circuit Voltage	E_o	Volts	40.9	42.8	41.5	41.8	41.9
Load Voltage	V_l	Volts	23.0	24.0	24.0	24.0	24.0
Load Current	I_l	Amps	2.21	2.65	2.67	2.89	2.92
Internal Resistance	R_g	Ohms	8.10	7.08	6.56	6.16	6.14
Temperatures							
Hot Junction	T_h	$^{\circ}F$	900	905	901	919	922
Cold Junction	T_c	$^{\circ}F$	173	175	176	177	175
Heat Loss	P_I	Watts (t)	27	28	28	28	28
Gross Power	P_t	Watts (t)	864	919	879	880	921
Internal Gas Pressure	P_g	PSIG	9.4	6.2	8.8	10.0	10.9
Test Time	Hrs	Hours	43	7142	9539	507	3457

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

2.0 PROGRAM MANAGEMENT

2.1 LIAISON

Engineering evaluation investigations and analysis consistent with criteria for the fueled Prototype Mockup System were implemented during the quarter.

On 16 January 1969, 3M Company attended a meeting at Westinghouse to examine corrosion problems associated with a fueled PMS. The meeting was attended by Metallurgical Engineers from the Huntington Alloys Division of International Nickel Company. The recommendation of the meeting (related to the converter only and subject to additional 3M engineering investigation) was a change of the exposed outer case materials from 304SS to Inconel 625.

On 22 January an abbreviated interface meeting was held at Westinghouse. Based upon the lack of compatibility of the thermal expansion characteristics between the copper heat source accumulator and Inconel 625, Westinghouse recommended the retention of 304SS for the hot frame.

3M Company continued design evaluation of the proposed change to the enclosure materials. At the 11 February 1969 interface meeting, 3M Company presented a preliminary design concept for the PMC-2 converter. The concept incorporated an outer case of the same general outer diameter configuration as PMC-1A, i.e., bolted flange interface with the system upper and lower rain covers. The interior diameter configuration featured an additional flange in the same plane as the top cone. This flange was designed to accommodate the

hermetic headers previously welded to the outer case just above the radiator base. 3M Company recommended consideration of a welded extension to the converter wall which would replace the outer wall of the upper rain cover. The 3M Company recommendation included the internal routing of the output power cable from the hermetic feedthrough to a feedthrough located on the wall of the upper extension, utilizing a transition terminal mounted on the interior wall of the upper extension.

All instrumentation can be removed if the fueled PMS should be utilized for field operation.

After Westinghouse review of the 3M Company concept, concurrence was received on 14 February 1969, but decisions relating to the upper rain cover insulation and top cover were deferred to the next interface meeting. Westinghouse reserved the prerogative to approve the power cable selection, and eliminated pin-type connectors from consideration because of potential reliability problems.

With Westinghouse concurrence to the change in design responsibility of interfacing components, the 3M Company proceeded to develop a definitive design from the agreed-to concept. The design was presented by 3M Company at the 19 March 1969 interface meeting. This design featured a redesigned top cone, header ring, outer case, and power header. 3M Company presented concept designs for a stuffing gland (cable feedthrough) and top cover. An agreement was reached for 3M to assume design responsibility for the top cover and insulation block. Westinghouse presented general criteria for the selection of the power cable to 3M Company.

The concurrence on the design approach between Westinghouse and 3M Company, which was accomplished during the quarter, resolved outstanding interface problems and should result in a converter/system design which approaches an operational configuration. The design of the enclosing structure of the converter should present a configuration which is suitable to the SNAP-23A operational environment.

2.2 DOCUMENTATION AND REPORTS

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

- Quarterly Report No. 8 (MMM 3824-0030)
- November 1968 Monthly Report (MMM 3824-0029)
- January Monthly Report (MMM 3824-0031)
- 10-Couple Module Data for the month of December 1968 (MMM 3824-1021)
- 10-Couple Module Data for the month of February 1969 (MMM 3824-1072)

2.3 WORK FORECAST FOR EFFORT PLANNED NEXT QUARTER

Major effort scheduled for next reporting period includes:

- Complete design and release drawings for SNAP-23A converter PMC-2
- Fabricate and procure piece parts for SNAP-23A converter PMC-2
- Prepare manufacturing flow plans for assembly of SNAP-23A converter PMC-2
- 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 P-2

Module 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 reevaluated at EOL design conditions; the results are presented in Table 3-1. EMC-2 BOL performance history 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 resistance of the simultaneously pressed P-legs decreased slightly during the past quarter. This agrees well with performance trends observed for similar legs in ten-couple module No. 1 (see Figure 4-2).
- N-leg performance remains quite stable and is typical of that observed in the ten-couple modules under similar conditions of spring pressure, thermal insulation, and test time.
- The output of the pressure transducer continues to yield erroneous data (as it has ever since the shock and vibration tests were completed).

- Converter EOL efficiency increased slightly during the quarter as a result of the resistance decrease and of a slight decrease in thermal input required to maintain constant temperature conditions.

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**
Net Power Input	P_{in}	Watts (t)	832	852	860	896	891
Power Output	P_o	Watts (e)	57.6	57.6	57.1	63.2	63.6
Efficiency	η	Percent	6.92	6.16	6.64	7.05	7.14
Open Circuit Voltage	E	Volts	41.1	42.4	42.9	43.2	42.8
Load Voltage	V_l	Volts	23.0	23.0	24.0	24.0	24.0
Load Current	I_l	Amps	2.50	2.50	2.38	2.63	2.65
Internal Resistance	R_g	Ohms	7.23	7.76	7.94	7.28	7.08
Temperatures							
Hot Frame	T_{hf}	$^{\circ}F$	931	926	934	933	935
Hot Junction	T_h	$^{\circ}F$	901	898	904	903	905
Cold Junction	T_c	$^{\circ}F$	173	172	176	171	175
Outer Case	T_{oc}	$^{\circ}F$	128	129	125	119	119
Gross Power Input*	P_t	Watts (t)	860	880	888	924	919
Internal Gas Pressure	P_g	PSIG	8.5	10.3	7.7	7.9	6.2

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

**Reading recorded on 18 March 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	2146	3009	3827	4469	5288	6010	6657	7349***
Power Output	P_o	Watts (e)	79.5	79.0	79.7	78.3	78.8	81.0	84.0	84.8	85.2	85.7	86.2	85.5	86.2
Normalized Power Output	P_N^*	Watts (e)	79.6	79.1	79.9	78.9	80.7	82.6	83.8	83.8	84.1	84.4	84.6	85.4	84.6
Open Circuit Voltage	E	Volts	53.7	54.2	54.5	54.1	54.2	55.1	55.2	55.4	55.6	55.2	55.3	55.2	55.3
Normalized O. C. Voltage	E_N^*	Volts	53.8	54.3	54.8	54.7	55.0	55.6	55.5	55.3	55.2	55.1	55.0	55.0	55.0
Internal Resistance	R_g	Ohms	9.03	9.24	9.26	9.30	9.27	9.29	8.99	8.96	8.99	8.80	8.79	8.82	8.77
Norm. Int. Resistance	R_N^*	Ohms	9.04	9.25	9.31	9.42	9.33	9.27	9.12	9.02	8.98	8.88	8.83	8.78	8.81
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
Load Current	I_l	Amps	3.18	3.16	3.19	3.13	3.15	3.24	3.36	3.39	3.41	3.43	3.45	3.42	3.45
Temperatures															
Hot Junction	T_h	° F	1084	1084	1081	1076	1076	1082	1078	1084	1089	1083	1086	1088	1086
Cold Junction	T_c	° F	191	191	190	189	195	197	186	186	188	184	185	192	185
Gross Power Input**	P_t	Watts (t)	1104	1112	1120	1132	1128	1144	1156	1170	1179	1176	1175	1162	1153
Internal Gas Pressure	P_g	PSIG	11.0	11.5	11.6	9.5	10.0	9.7	9.5	9.5	9.2	9.0	8.5	8.2	6.2

*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 26 March 1969

Figure 3-1
 SNAP-23A Converter EMC-2 Performance History
 (BOL 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
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
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

(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.

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

EMC-3 long-term test continued during the quarter. Converter performance was reevaluated 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:

- Bonded-type P-leg performance remains quite stable and is typical of that observed for similar legs in the ten-couple module with insulation the same as that in this converter.
- Thermal performance remains relatively stable over the period of 1107 to 7349 hours.
- Converter EOL efficiency has decreased apparently as a result of the N-leg degradation.

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
Net Power Input	P_{in}	Watts (t)	824	860	864	848	866	851
Power Output	P_o	Watts (c)	61 2	65 3	66 5	66 2	67 2	64 1
Efficiency	η	Percent	7 43	7 59	7 70	7 81	7 76	7 53
Open Circuit Voltage	I	Volts	40 7	41 5	41 3	41 5	41 6	41 5
Load Voltage	V_l	Volts	23 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
Internal Resistance	R_g	Ohms	6 65	6 43	6 25	6 34	6 30	6 56
Temperatures								
Hot Frame	T_{hf}	$^{\circ}F$	928	931	925	930	928	930
Hot Junction	T_h	$^{\circ}F$	900	903	899	900	898	901
Cold Junction	T_c	$^{\circ}F$	172	172	174	175	171	176
Outer Case	T_{oc}	$^{\circ}F$	151	150	151	151	146	151
Gross Power Input	P_t	Watts (t)	852	888 0	892	876	894	879
Internal Gas Pressure	P_g	PSIG	8 4	9 4	9 6	9 4	9 1	8 8

*Watts-transducer was recalibrated at 3507, 5907, and 8837 hours.

**Reading recorded on 18 March 1969

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

Parameter	Symbol	Units	Measured Values at Specified Hours												
			123	392	681	1107	1800	2863	4014	6223	6846	7687	8407	9052	9746**
Power Output	P_o	Watts (e)	88.0	87.8	89.3	91.0	91.5	92.0	92.3	92.9	92.5	92.0	90.8	90.5	91.0
Normalized Power Output	P_N^*	Watts (e)	88.2	90.1	91.2	92.6	92.9	93.0	93.3	91.7	91.6	90.5	91.0	90.1	90.0
Open Circuit Voltage	E	Volts	54.1	53.6	53.7	54.1	53.9	54.2	54.3	54.8	54.5	54.6	54.5	54.4	54.4
Normalized O. C. Voltage	E_N^*	Volts	54.4	54.6	54.6	54.6	54.7	54.9	54.9	54.5	54.5	54.4	54.7	54.4	54.3
Internal Resistance	R_g	Ohms	8.27	8.15	8.04	7.99	7.90	7.93	7.94	8.02	7.96	8.03	8.11	8.12	8.08
Norm. Int. Resistance	R_N^*	Ohms	8.34	8.24	8.14	8.01	8.02	8.05	8.03	8.03	8.02	8.10	8.14	8.17	8.14
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
Load Current	I_l	Amps	3.52	3.51	3.57	3.64	3.66	3.68	3.69	3.71	3.70	3.68	3.63	3.62	3.64
Temperature~															
Hot Junction	T_h	° F	1080	1074	1074	1080	1074	1075	1077	1087	1083	1084	1083	1083	1084
Cold Junction	T_c	° F	189	195	193	195	191	190	191	187	186	184	191	188	186
Gross Power Input**	P_t	Watts (t)	1096	1100	1108	1120	1124	1128	1112	1140	1132	1130	1122	1120	1122
Internal Gas Pressure	P_g	PSIG	10.4	10.9	11.2	11.1	11.0	11.0	11.0	10.9	10.4	9.9	10.3	10.1	10.2

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

**Watts-transducer was recalibrated at 3507, 5907, and 8837 hours

***Reading recorded on 26 March 1969

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

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
	7687		0.99		1.00		0.98
	9746		0.99		1.00		0.98
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
	7687		0.99		0.99		0.99
	9746		0.99		1.00		0.99
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
	7687		0.97		1.00		0.94
	9746		0.97		1.00		0.94

(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.

3.1.2 Prototype Mockup Converter

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

PMC-1B long-term test continued during the quarter. Converter performance was reevaluated at EOL design conditions; the results are presented in Table 3-7. PMC-1B BOL performance history is presented in Table 3-8 and shown graphically in Figure 3-3. The last data point reflects the change to PMC-2 BOL conditions initiated near the end of the quarter. Initial and current PMC-1B experimental-to-theoretical performance ratios are presented in Table 3-9. Analysis of recent PMC-1B data indicates that:

- The resistance of the bonded-type P-legs continued to decrease. This is similar to the early P-leg performance trend noted on EMC-3 (refer to Quarterly Report No. 6).
- N-leg performance remains quite stable and is typical of that observed in the ten-couple modules under similar conditions of spring pressure, thermal insulation, and test time.
- Converter EOL efficiency increased slightly since the increase in power was proportionately larger than the increase in thermal input required.

Table 3-7
 SNAP-23A Converter PMC-1B Performance Data
 (End-of-Life Conditions)

Parameter	Symbol	Units	Measured Value at Specified Hours		
			28	1104	3457
Net Power Input	P_{in}	Watts	824	870	893
Power Output	P_o	Watts	63.8	67.2	70.1
Efficiency	η	Percent	7.74	7.72	7.85
Open Circuit Voltage	E	Volts	41.2	41.4	41.9
Load Voltage	V_l	Volts	24.0	24.0	24.0
Load Current	I_l	Amps	2.66	2.80	2.92
Internal Resistance	R_g	Ohms	6.47	6.21	6.14
Temperatures					
Hot Frame	T_{hf}	$^{\circ}F$	965	961	962
Hot Junction	T_h	$^{\circ}F$	920	921	922
Cold Junction	T_c	$^{\circ}F$	176	177	175
Outer Case	T_{oc}	$^{\circ}F$	145	149	148
Gross Power Input	P_t	Watts	852	898	921
Internal Gas Pressure	P_g	PSIG	9.6	11.3	10.9

*Estimated values based on PMC-1A test station losses.
 Reading recorded on 21 March 1969

Table 3-8
 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**
Power Output	P_o	Watts (e)	86.2	89.0	90.2	90.0	90.5	91.2	91.2	83.2
Normalized Power Output	P_N^*	Watts (e)	86.1	88.7	90.3	89.2	91.1	90.7	91.1	90.0
Open Circuit Voltage	E	Volts	52.4	52.6	52.6	52.3	52.7	52.6	52.5	48.2
Normalized O. C. Voltage	E_N^*	Volts	52.4	52.4	52.7	52.2	52.8	52.3	52.7	52.6
Internal Resistance	R_g	Ohms	7.94	7.76	7.66	7.58	7.64	7.55	7.54	6.96
Norm. Int. Resistance	R_N^*	Ohms	7.93	7.79	7.67	7.63	7.53	7.51	7.53	7.66
Load Voltage	V_l	Volts	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
Temperatures***										
Hot Junction	T_h	$^{\circ}\text{F}$	1081	1079	1079	1079	1079	1084	1075	1014
Cold Junction	T_c	$^{\circ}\text{F}$	192	190	192	188	194	192	189	184
Gross Power Input	P_t	Watts (t)	1076	1105	1116	1118	1124	1139	1138	1038
Internal Gas Pressure	P_g	PSIG	11.1	11.9	12.7	13.0	12.7	13.0	12.5	11.8

*Data normalized to PMC-1 BOL Conditions ($T_h = 1080^{\circ}\text{F}$ and $T_c = 192^{\circ}\text{F}$)

**Readings recorded on 1 April 1969

***Converter input changed at 3534 hours to PMC-2 BOL Conditions ($T_h = 1011^{\circ}\text{F}$ and $T_c = 187^{\circ}\text{F}$)

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

Table 3-9
 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	
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	
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		0.94	

(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

3.1.3 Overtemperature Incident

A twelve-hour overtemperature excursion of approximately 200°F at the hot junction occurred on converters 23P2, EMC-2, EMC-3 and PMC-1B. The cause for this overtemperature was a component malfunction in the laboratory regulated power supply. The test hours for each converter at the time of the incident is as follows:

<u>Device Designation</u>	<u>Test Hour</u>
23P2	17,710
EMC-2	5,950
EMC-3	8,350
PMC-1B	2,200

No significant short-term effects have been observed on the above converters.

As the long-term testing continues, the performance of each converter will be analyzed (with this incident taken into consideration).

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

The design analysis and development of the SNAP-23A 60-watt converter PMC-2 has progressed to the point where 1) the majority of the interface requirements can be defined and 2) the specific component drawings can be completed. The effort conducted during this quarter that led to this progress is listed as follows:

3.2.1 Design Analysis

Different thermal expansion and stresses occur on the cold frame, weld joints, and support cone as a result of changing the outer case material from 304 stainless steel to Inconel 625. Calculations were made to determine the effect of these different thermal expansions and stresses to assure mechanical reliability of the SNAP-23A converter.

3.2.1.1 Cold Frame Stress

The assembly of the fin base and outer case onto the cold frame is shown schematically in Figure 3-4. The outer case is a shrink fit onto the cold frame and develops the hoop force (F_a) shown in Figure 3-5. The outer case is stressed beyond its elastic limit (yield stress).

During system assembly, the fin base is then bolted-on over the outer case. This develops a second hoop force (F_b) on the cold frame.

The two hoop forces (F_a and F_b) are counteracted by cold frame forces (F_w) which as noted in Figure 3-5 is a series of webs between the row of holes.

As shown in Appendix A, the frame webs between the holes have a maximum stress of 8,450 psi and a maximum strain (distortion) of 0.000114 inch (reduction in follower hole diameter). These values are within reasonable limits and correspond to PMC-1 values.

3.2.1.2 Weld Joint Stress

The additional stresses in the weld bead and the adjacent flanges were analyzed as dissimilar metal joints. In Figure 3-6, stainless steel (high expansion) was selected for the high temperature hot frame and Inconel 625 alloy (low expansion) for the low temperature outer case. The joining members of the lower cover or support cone and header ring cover (see Figure 3-6) could be made from either Inconel 625 or 304 stainless steel. However, the analysis indicated that the only feasible dissimilar metal joint were 304SS parts jointed to the Inconel 625 outer case. This conclusion is based in part on the following:

The higher temperature at the hot frame would greatly aggravate the stress build-up due to the thermal expansion variance acting over a larger temperature change. The stress levels would cause considerable yielding of the thin walled hot frame. Further, several heat/cool cycles are necessary for producing the unit, thus giving cyclic yielding. Even with the dissimilar metal joint at the

Figure 3-4
PMC-2 Cold Frame Interface

Figure 3-5
PMC-2 Cold Frame Force Loading

relatively cool outer case region, special consideration must be given to the mating weld flange configuration. In Appendix B several stress analyses are shown, which indicate that normal close fitting flanges joined by direct fusion will be generally overstressed. The depth of weld penetration is only equal to the thickness of the thinner member and is not sufficient to keep flanges from bending (cantilevering) due to thermal expansion; thus the weld bead will yield. The characteristics of the weld bead alloy (304-625 mix) may have "hot short", brittle-like characteristics which would prevent weld bead flexing of any degree. Support of the final design development effort is in progress, the purpose of which is to study the dissimilar metal weld joints, as well as check out characteristics of Inconel 625 alloy (machining, finishing, welding). In the development effort, the first selection of weld configuration will be the straight flange fusion weld (ring and girth) as indicated on Figure 3-6. The mating interfaces are to be a press fit joint. This style of assembly is shown to give low stress levels and no weld flexing by preliminary calculations; see Appendix B. The filler metal weld depicted in Figure 3-7 is the prime back-up configuration which will likely require a separate weld on bolt flange to provide space for the welding machine head.

3.2.1.3 Support Cone Stress

The support cone for PMC-2, has a steeper angle, 45° instead of 35° , and a small OD, 7-1/2" instead of 9-1/4", than the support cone of the previous converters (see Figure 3-8). Calculations were made to determine the effect of these changes on the structural strength of the converter load support system. The results of this analysis as shown in Table 3-10 show a higher margin of safety for every type of loading over the previous design. For this reason the new support cone is considered structurally adequate; shock and vibration test verification is not required.

Figure 3-6
SNAP-23A Converter PMC-2 Configuration

Figure 3-7
 SNAP-23A Converter PMC-2
 Outer Case - Lower Cover Conceptual Weld

Configuration shown for a MIG Fillet Weld of Inconel 625.
 Shaded area shows increased material from PMC-1.
 TIG Weld (X) of lower cover at dash line may be required to gain clearance for MIG Weld.

NOTE: 32° angle at Westinghouse request exact DIM's pending MIG Fillet Weld per Inconel suggestion.

Figure 3-8
Support Cone Stress Definition

Table 3-10
SNAP-23A Converter Support Cone Stresses

Item	Hoop Stress**			Meridional Stress**			Combined Stress**	Failure Mode	M. S. ***
	Down Load	Up Load	Pressure Load	Down Load	Up Load	Pressure Load			
Support cone adjacent to its outer thickened ring	---	---	+ 5,530*	+ 6,000*	---	+ 2,765*	+ 8,200*	Tens. Yield	2.00*
	---	---	+11,220	+ 6,140	---	+ 5,610	+11,500	Tens. Yield	1.19
	---	---	+ 5,530*	---	- 6,000*	+ 2,765	---	Tens. Yield	2.28*
Support cone adjacent to its inner thickened ring	---	---	+11,220	---	- 6,140	+ 5,610	---	Tens. Yield	1.20
	---	---	+ 3,880*	+10,750*	---	+ 1,940*	+10,130*	Tens. Yield	0.925*
	---	---	+ 4,520	+15,280	---	+ 2,260	+15,750	Tens. Yield	0.16
Outer thickened ring of support cone	---	---	+ 3,880*	---	-10,750*	+ 1,940*	---	Comp. Yield****	1.29*
	---	---	+ 4,520	---	-15,280	+ 2,260	---	Comp. Yield****	0.42
	Up Load Not as Critical as Down Load						---		
Inner thickened ring of support cone	- 6,220*	---	---	---	---	---	- 6,220*	Buckling	5.83*
	-12,800	---	---	---	---	---	-12,800	Buckling	1.09
	---	+ 7,900*	---	---	---	---	- 7,900*	Comp. Yield****	2.20*
	---	-14,900	---	---	---	---	-14,900	Comp. Yield****	0.60
	+ 9,650*	---	---	---	---	---	+ 9,650*	Tens. Yield	1.08*
	+17,050	---	---	---	---	---	+17,050	Tens. Yield	0.07

*Values with support cone for PMC-2 at 45 angle. All other values are for previous converters with a 35° support cone angle

**(+) Indicates tension, (-) indicates compression, all stresses in psi.

***M. S. (Margin of Safety) = (allowable stress/design stress) - 1.

****Not critical in buckling.

NOTE All stress values in psi.

3.2.2 PMC-2 Instrumentation

The instrumentation requirements for PMC-2 were evaluated during this reporting period. This evaluation was based on 1) the need for additional detailed thermoelectric data on the thermopile, 2) predictability of test station heat losses, 3) data available on the temperature drop from the hot frame to the hot junction, and 4) data available on the temperature drop from the cold junction to the outer case. Also considered in the evaluation are the instrumentation needs required by the SNAP-23A systems.

3.2.2.1 Thermoelectric Evaluation of the Thermopile

Data from the SNAP-21 and -23A converters and test units have been analyzed to determine the variations in Seebeck voltage and resistance ratios. The data summarized in Table 3-11 shows the simultaneously pressed N-leg electrical properties to be consistent, while the bonded P-leg data exhibits a wide spread in resistance ratio. These resistance ratios of SNAP-23A module and EMC-3 are the main reason for this wide spread, but further confirmation is required before a smaller P-leg resistance variation is incorporated into the thermopile design; therefore, additional N- and P-leg data are essential.

3.2.2.2 Test Stations Heat Losses

Data from EMC-1, 2, 3 and PMC-1A and 1B were statistically analyzed to determine how closely test station heat loss and hot junction temperature can be predicted from hot frame instrumentation. The analysis was made for two pairs of hot frame thermocouples - one pair interior to the hermetic enclosure at mid-thermopile elevations, and the second pair exterior to the hermetic enclosure near the upper support cone. Using external hot frame instrumentation gives the advantage of eliminating a penetration in the hermetic seal. However, internal hot frame thermocouples are centrally located and thereby give closer predictions of the average hot junction temperature. With internal hot frame instrumentation, test station heat losses can be predicted to within ± 2.3 watts. Results from the statistical analysis are presented in Figure 3-9

where test station heat losses are plotted versus hot frame temperature internal to the hermetic enclosure. The mean line is the equation of relationship between Q loss and hot frame temperature. The equation of relationship is defined as the least square fit linear relationship between the two variables. The line at ± 2 (two standard errors from the mean) represents expected extreme deviations from the mean since $\sim 95\%$ of the data points will normally fall within this band.

With external hot frame instrumentation, test station heat losses can be predicted to within ± 2.5 watts. Figure 3-10 presents the results from the statistical analysis of test station heat losses versus hot frame temperatures external to the hermetic enclosure. The equation of relationship and $\pm 2\sigma$ lines represent the predicted test station heat losses and maximum deviations from prediction.

This data indicates that internal instrumentation is not required for determining test station heat losses of a PMC-1 design; but since significant changes to the upper cone and cover are in progress for PMC-2, instrumentation should be retained for detailed heat loss calculations.

3.2.2.3 Hot Frame to Hot Junction Temperature Drop

Analysis of the hot end ΔT data from EMC-1, 2, 3, PMC-1A and PMC-1B indicates the average hot junction temperature can be predicted to within $\pm 8^\circ\text{F}$ from internal thermocouple readings. End-of-life, beginning-of-life and processing temperature conditions were included in the statistical analysis as shown in Figure 3-11. This figure also shows the mean line and the $\pm 2\sigma$ deviations.

With external hot frame instrumentation, the predictability of average hot junction temperature is quite poor as illustrated in Figure 3-12. The $\pm 2\sigma$ deviation from the mean line is greater than 22°F . The reason for the poor correlation is the chronological increase in external temperature indication from EMC-1 to PMC-1b. This trend is quite clear in Figure 3-12 where the hot frame temperatures are identified by converter. It is noted that the data

presented in Figure 3-12 does not include processing temperatures. The only hot frame temperatures recorded during processing of the first five converters were internal. External readings should be included in the future to expand the data base.

3.2.2.4 Cold Junction to Outer Case Temperature Drop

Data for determining the ΔT for the PMC-2 cold end design configuration consists of six data points measured on PMC-1B. The ΔT values measured were $27^{\circ}\text{F} \pm 9^{\circ}\text{F}$ at EOL, and $30^{\circ}\text{F} \pm 10^{\circ}\text{F}$ at BOL. Data on cold end ΔT from other SNAP-23A converters are not applicable because the cold end design is different; therefore, PMC-2 should be instrumented to obtaining additional ΔT data.

Cold frame temperature data for the first five SNAP-23A converters were evaluated. This data is in Table 3-12 and consists of two sets of cold frame-outer case temperatures measured at locations diametrically opposite each other. Evaluation of this data indicates the following:

- The average temperature drop through the cold frame is approximately 10°F and ranges from 4°F to 20°F .
- Cold frame thermocouples do not accurately indicate the temperature drop from the cold frame to the outer case for converters using water cooling. This is indicated by the negative temperature drop from the cold frame to the outer case.
- Cold frame temperature readings from unit to unit are inconsistent.

As a result of this evaluation, it appears that cold frame instrumentation is of little value; therefore, it will be eliminated from the PMC-2 converter.

3.2.2.5 Conclusions

Based upon the instrumentation evaluation and analysis, the instrumentation listed in Table 3-13 will be incorporated into the PMC-2 design.

Table 3-11
Thermoelectric Data
for
SNAP-23A Converter

N-Leg Simultaneously Pressed

<u>Device</u>	<u>R_x/R_c</u>	<u>E_x/E_c</u>
SNAP-23A Mod. 1	0.99	1.00
EMC-1	0.96	0.99
EMC-2	0.97	1.00
EMC-3	1.00	1.01
PMC-1A	0.96	1.01
PMC-1B	0.97	1.00

P-Leg Bonded

<u>Device</u>	<u>R_x/R_c</u>	<u>E_x/E_c</u>
SNAP-23A Mod. 1	0.90	0.95
EMC-3	1.03	0.96
PMC-1A	0.96	0.98
PMC-1B	0.98	0.97
SNAP-21 A10D6	0.97	0.98
SNAP-21 A10D8	1.00	0.96

Figure 3-9
Test Station Heat Loss Versus
Hot Frame Temperature Interior
to Hermetic Enclosure

Figure 3-10
Test Station Heat Loss Versus
Hot Frame Temperature Exterior
to Hermetic Enclosure

Figure 3-11
Hot Frame to Hot Junction ΔT
Hot Frame TC Interior to Hermetic Enclosure

Figure 3-12
 Hot Frame to Hot Junction ΔT
 Hot Frame TC Exterior to Hermetic Enclosure

Table 3-12
SNAP-23A Converter Cold Frame Data

Converter	Cooling	Time	Cold Frame		Outer Case		Cold Frame		Outer Case		Cold Frame		Outer Case		Cold Frame		Outer Case	
			ID TC35	OD TC37	TC40	TC47	LT TC35-37	LT TC37-49	ID TC36	OD TC38	TC48	TC50	LT TC36-38	LT TC38-48	ID TC36	OD TC38	TC48	TC50
EMC-1	Water	19 ^a EOI	107	95	105	105	12	-10	120	109	107	109	11	2				
	Water	66 ^b BOI	134	110	134	134	15	-15	153	143	138	140	10	5				
EMC-2	Water	628 EOL	134	118	128	128	16	-10	142	130	126	126	12	4				
	Water	820 BOI	138	118	130	130	20	-12	145	131	127	127	14	4				
	Air	533 ^c 7 BOL	160	151	154	152	9	-3	161	150	154	153	11	-4				
EMC-3	Water	2816 EOI	147	136	151	154	11	-15	166	162	157	185	4	5				
	Water	4131 BOL	160	146	162	164	14	-16	179	173	168	196	6	5				
PMC-1a	Water	707 EOL	132	-	140	141			158	153	152	151	5	1				
	Water	195 BOL	135	-	145	147			165	158	154	153	7	4				
	Air		158	150	149	149	8	1	154	148	150	151	6	-2				
PMC-1b	Water	1104 FOI	151	--	148	150	-	---	171	161	151	148	10	10				
	Water	1540 BOL	162	-	155	157		---	190	178	166	162	12	12				

NOTE All values in °F
TC indicates thermocouple location

Table 3-13
Recommended Instrumentation for
SNAP-23A Converter PMC-2

<u>Thermocouple*</u>	<u>Location</u>
1, 2, 5, 6, 7, 8	Hot Frame
11, 12, 13, 14, 15, 16	Hot Junction
17, 18, 19, 20, 21, 22	Hot Junction
23, 24, 25, 26, 27, 28	Cold Junction
29, 30, 31, 32, 33, 34	Cold Junction
47, 49	Outer Case
48, 50	Outer Case
39, 40, 41, 42, 43, 44, 45, 46	Cone and Header Ring

*Thermocouple location identified in Westinghouse Interface Control Drawing.

3.2.3 Thermoelectric Parametric Analysis

A parametric study of PMC-2 thermoelectric performance was completed. The study evaluated the effects on performance of ambient air temperature varying from 70°F to 100°F, thermoelectric adjustment factors ranging from minimum to maximum expected performance, and heat input to the converter ranging about a BOL reference value by ± 31 watts.

Results of the parametric study are presented in Tables 3-14, 3-15 and 3-16. Thermoelectric adjustment factors, nominal heat sink characteristics, and leg geometries used in the analysis are listed in Tables 3-17, 3-18 and 3-19. It should be noted that EOL results do not include thermoelectric degradation effects.

The performance calculations for the parametric study were made with the PRAM-03 computer program. A calculation bias on the heat requirement was determined by comparing the PRAM-03 computer program to EMC-2, EMC-3, PMC-1a and PMC-1b performance data. At the initial stabilized condition (which occurs after 600 to 1000 hours of operation), the converters required an average of 20 watts more heat input than predicted with PRAM-03 using nominal N- and P-leg geometry. Analysis of EMC-3 indicates most of the 20-watt bias is due to the difference between nominal and as-built leg geometry. This bias was included in the parametric study.

Table 3-14
SNAP-23A Converter PMC-2 Parameter Study
Minimum Heat Input Case*

	Design Adjustment Factors		Nominal Adjustment Factors		Best Adjustment Factors	
	<u>70° F Ambient</u>	<u>100° F Ambient</u>	<u>70° F Ambient</u>	<u>100° F Ambient</u>	<u>70° F Ambient</u>	<u>100° F Ambient</u>
<u>BOL TEMPERATURES (°F)</u>						
Average Hot Frame	1040	1069	1033	1062	1027	1056
Maximum Hot Junction	1008	1037	1001	1030	995	1024
Average Hot Junction	990	1019	983	1012	977	1006
Average Cold Junction	185	215	185	215	185	215
Outer Case	150	180	150	180	150	180
<u>EOL TEMPERATURES (°F)</u>						
Average Hot Frame	886	914	881	909	877	905
Average Hot Junction	841	869	836	864	832	860
Average Cold Junction	168	198	167	198	167	197
Outer Case	138	168	137	168	137	167
<u>BOL PERFORMANCE</u>						
Efficiency (%)	7.74	7.44	7.95	7.64	8.14	7.83
Power Output (watts, e)	78.4	75.4	80.5	77.4	82.5	79.3
Resistance (ohms)	8.47	9.11	8.16	8.78	7.89	8.49
Open Circuit Voltage (volts)	51.7	52.6	51.4	52.3	51.1	52.1
<u>EOL PERFORMANCE</u>						
Efficiency (%)	7.39	7.25	7.58	7.43	7.75	7.61
Power Output (watts, e)	58.4	57.3	59.9	58.7	61.2	60.1
Resistance (ohms)	6.73	7.26	6.50	7.01	6.30	6.80
Open Circuit Voltage (volts)	40.4	41.3	40.2	41.2	40.1	41.0

*Load Voltage = 24V, Q Input BOL = 1013 watts (t), Q Input EOL = 790 watts (t)

Table 3-15
SNAP-23A Converter PMC-2 Parameter Study
Reference Heat Input Case*

	Design Adjustment Factors		Nominal Adjustment Factors		Best Adjustment Factors	
	70°F Ambient	100°F Ambient	70°F Ambient	100°F Ambient	70°F Ambient	100°F Ambient
<u>BOL TEMPERATURES (°F)</u>						
Average Hot Frame	1061	1090	1054	1083	1048	1076
Maximum Hot Junction	1029	1058	1022	1051	1016	1044
Average Hot Junction	1011	1040	1004	1033	998	1026
Average Cold Junction	187	217	187	217	187	217
Outer Case	152	182	152	182	152	182
<u>EOL TEMPERATURES (°F)</u>						
Average Hot Frame	902	930	897	925	892	920
Average Hot Junction	857	885	852	880	847	875
Average Cold Junction	169	199	169	199	169	199
Outer Case	139	169	139	169	139	169
<u>BOL PERFORMANCE*</u>						
Efficiency (%)	7.70	7.39	7.92	7.61	8.11	7.80
Power Output (watts, e)	80.4	77.2	82.7	79.4	84.7	81.4
Resistance (ohms)	8.74	9.39	8.42	9.05	8.14	8.75
Open Circuit Voltage (volts)	53.3	54.2	53.0	53.9	52.7	53.7
<u>EOL PERFORMANCE*</u>						
Efficiency (%)	7.52	7.35	7.70	7.54	7.87	7.70
Power Output (watts, e)	61.2	59.8	62.7	61.4	64.1	62.7
Resistance (ohms)	6.89	7.44	6.65	7.18	6.44	6.95
Open Circuit Voltage (volts)	41.6	42.5	41.4	42.3	41.2	42.2

*Load Voltage = 24V, Q Input BOL = 1044 watts (t), Q Input EOL = 814 watts (t)

Table 3-16
SNAP-23A Converter PMC-2 Parameter Study
Maximum Heat Input Case*

	Design Adjustment Factors		Nominal Adjustment Factors		Best Adjustment Factors	
	70 F Ambient	100 F Ambient	70 F Ambient	100 F Ambient	70 F Ambient	100 F Ambient
<u>BOL TEMPERATURES (F)</u>						
Average Hot Frame	1082	1111	1075	1104	1068	1097
Maximum Hot Junction	1050	1079	1043	1072	1036	1065
Average Hot Junction	1032	1061	1025	1054	1018	1047
Average Cold Junction	189	219	188	219	188	219
Outer Case	154	184	153	184	153	184
<u>FOL TEMPERATURES (F)</u>						
Average Hot Frame	917	945	912	940	907	935
Average Hot Junction	872	900	867	895	862	890
Average Cold Junction	170	200	170	200	170	200
Outer Case	140	170	140	170	140	170
<u>BOL PERFORMANCE</u>						
Efficiency (%)	7.66	7.33	7.87	7.54	8.07	7.74
Power Output (watts, e)	82.3	78.8	84.6	81.1	86.8	83.2
Resistance (ohms)	9.02	9.68	8.68	9.32	8.39	9.02
Open Circuit Voltage (volts)	54.9	55.8	54.6	55.5	54.3	55.2
<u>FOL PERFORMANCE</u>						
Efficiency (%)	7.61	7.42	7.80	7.61	7.98	7.79
Power Output (watts, e)	63.8	62.2	65.4	63.8	66.9	65.3
Resistance (ohms)	7.06	7.61	6.81	7.34	6.59	7.11
Open Circuit Voltage (volts)	42.8	43.7	42.6	43.5	42.4	43.4

Load Voltage 24V Q Input BOL 1075 watts (t) Q Input FOL 838 watts (t)

Table 3-17
SNAP-23A Converter PMC-2
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
	0.96	0.97	0.98

Table 3-18
SNAP-23A Converter PMC-2
Heat Sink Characteristics

<u>Q Rejected</u>	Fin Base Temperature	
	<u>70° F Ambient</u>	<u>100° F Ambient</u>
720 Watts	138° F	168° F
925 Watts	151° F	181° F

Table 3-19
SNAP-23A Converter PMC-2
Thermoelectric Couple Geometry

Number of Couples	280
N-Leg Length	.466 Inches
N-Leg Cold Segment Length	.163 Inches
P-Leg Length	.355 Inches
P-Leg Cold Segment Length	.138 Inches
N- and P-Leg Diameter	.1875 Inches

3.2.4 Design Development

3.2.4.1 Weld Development

A weld development plan was prepared for those joints of 304SS to Inconel 625. The sizes of components required for this weld development were defined by sketch so that raw material could be ordered. Initial design of some of the flanges to be welded has been completed. Some edge welds of Inconel 625 to 304SS have been conducted and evaluated. This effort will continue into next quarter so that final configuration in the weld areas can be completed.

3.2.4.2 Power Cable Sealing Development

Power cable and potting compounds have to be ordered for sealing the end of the electric power cable which terminates within the top rain cover area. This development will result in the selection of potting materials and a technique for sealing the end of the cable.

3.2.5 Design of PMC-2

3.2.5.1 General Structure Modification

The revisions to the structure and enclosure of PMC-2 are shown in Figures 3-6, 3-7, 3-13, 3-14 and 3-15. The components shown by these sketches are new designs or extensive modification to the PMC-1 designs.

3.2.5.2 Specific Components

3.2.5.2.1 Outer Case (Figure 3-6) -- The material was changed from PMC-1 material of 304SS to Inconel 625, solution annealed. A procurement specification was prepared for the Inconel 625 material. In addition, acceptance criteria for flaws in the outer case raw material was prepared.

Figure 3-13
Conceptual Pinch-Off

Figure 3-14
Power Header Concept

Figure 3-15
Cut-Away View of
Power Output Termination

The wall thickness was reduced from 0.047" nominal to 0.040" nominal to keep the stress low enough in the cold frame so that follower holes will not be deformed excessively.

The upper bolt flange was removed and the lower bolt flange was changed in configuration. Where the upper bolt flange was on PMC, a weld will be made to the rain cover shell.

The weld flange configurations as shown in Figure 3-6 do not appear significantly different from those of PMC-1. However, the weld joint between the outer case and both the lower cover and header ring are now dissimilar metal welds of Inconel 625 to 304SS. The exact detail dimensions and configurations of these weld flanges will be determined by a weld development program. A backup design configuration for the outer case to lower cover weld is shown in Figure 3-7. A change to this configuration will require that a portion of the lower bolt flange be welded to the outer case after the outer case-lower case weld has been completed.

The location of the feed-through headers for internal instrumentation and power output wires was moved from the upper exposed cylindrical portion of the outer case to an enclosed flat header ring. The seal-off tube will also be mounted to this ring. In this location these fittings will be enclosed by the top cover and will not be exposed to corrosive moisture.

3.2.5.2.2 Rain Shield Ring (Figure 3-6) -- The rain shield ring was changed in configuration to match the revised configuration of the lower bolt flange. The material was also changed to Inconel 625.

3.2.5.2.3 Lower Cover (Figure 3-6) -- The outside diameter was increased to match the inside diameter change of the outer case. The exact dimension of this diameter will allow for press fit into outer case of a change to configuration as shown by Figure 3-7. This will be determined based on results of the weld development program.

3.2.5.2.4 Cold Frame (Figure 3-6) -- The outer diameter was increased to match the change in outer case diameter.

3.2.5.2.5 Header Ring (Figure 3-6) -- This ring made of 304SS will be the mounting location for power headers, instrumentation headers, and seal-off tube. This new design is a thick section to withstand the dissimilar metal thermal expansion stress, provide attachment to cold frame, simplify machining of outer case, and minimize stresses on the support cone.

3.2.5.2.6 Support Cone (Figure 3-6) -- The configuration was revised to a smaller outer diameter and steeper cone angle to fit with the header ring and provide space in the top cover area. This change in configuration does increase the load carrying capacity, thus providing greater margin of safety during dynamic loading (see Table 3-10 for summary and Appendix C for detailed calculation). The heat loss will also be increased. Preliminary calculation (details in Appendix D) shows this increased loss will be 2.6 watts at BOL temperature conditions. The change of the cone angle also required a change in location for pinning the hot side insulation strips (details in Appendix E).

3.2.5.2.7 Hot Frame (Figure 3-6) -- The location of the holes for pinning the hot side insulation strips was changed. This change in the pinning hole location required that the mounted holes for instrumentation points 5 and 6, exterior web of hot frame, be relocated.

3.2.5.2.8 Hot Junction Electrode -- No change in configuration was made but the base material procurement was a problem. The concern with the base copper material is that some of the constituents appear to prevent blistering of the plating which may expose the base copper during service. Information indicated that a low oxygen content with high silver is a probable constituent. The problem was to find an acceptable standard for material which could be procured. Oxygen free specification copper has been received for blister testing and chemical analyzing. A back-up material (oxygen free) with silver specification has been ordered because of lead-time considerations.

3.2.5.2.9 Thermoelectric Legs and Couple -- The components for the thermoelectric couples were revised to accommodate the calculated leg configuration of the thermopile design determined at the interface meeting of 16 December 1968.

3.2.5.2.10 Disk -- An indium foil disk will be used between the ball of the cold cap and the socket of the follower to improve heat transfer.

3.2.5.2.11 Insulation Block, Thermal (Figure 3-6) -- The configuration was changed to match the revised support cone configuration. The effect on extraneous heat loss will be calculated next quarter.

3.2.5.2.12 Seal-Off Tube (Figure 3-14) -- The use of Inconel 625 for the seal-off tube was investigated. This will not be incorporated in this design because a proven technique is not available for this application. A copper tube will be used for the pinch-off seal. This copper tube will in turn be enclosed in a 304SS cover which will be welded into place. This whole assembly will be enclosed within the top cover area.

3.2.5.2.13 Power Header (Figure 3-15) -- The power output header design was changed from a four-pin feedthrough with soldered-in leads to a preassembled brazed single pin and flexible lead. The exposed copper pin is intended to be covered over with a potting compound (in compression) for corrosion protection.

3.2.5.2.14 Top Cover Assembly -- PMC-2 converter has been designed with a top extension which will serve as a rain cover. The design of the top extension (top cover assembly) is a new design responsibility for 3M. The top cover assembly consists of four major parts; the shell, ring, cover plate, and "O" ring. The shell, ring and cover plate are designed of Inconel 625. The "O" ring groove in this shell was designed to keep out moisture by using vacuum seal criteria. Preliminary designs have been prepared for the "O" ring, power output header potting arrangement, terminal block, and top cover plate. Additional development and design work is being directed toward arriving at final designs. A power cable has been selected to extend from within the top rain cover enclosure to the Westinghouse power conditioner. This cable is of watertight construction according to the requirements of MIL-C-2194/E and is described specifically as to type and size by DSGA-3. Preparations are being made to develop additional sealing for the end of the cable which terminates within the rain cover enclosure. The cable entrance to the rain cover enclosure will be sealed with a stuffing tube patterned according to the stuffing tube described by MIL-S-19622. The packing assembly for sealing will be the same, but the nylon structure will be replaced by parts made from Inconel 625.

In addition to the Inconel 625 cover plate, another cover plate will be designed as part of the instrumentation. This design will provide a two layer gasket for the instrumentation wires to pass through between the cover plate and the top cover ring. MS connectors will be mounted on the cover plate to make connections for diagnostic instrumentation to the 3M test station and Westinghouse test set up. An access port will be provided in the center of the cover plate so that the converter can be removed from the 3M test station and mounted on the system without disturbing instrumentation wiring.

3.2.6 Interface Drawing

The preliminary Westinghouse issue of interface drawing 914-E-166 was reviewed. The review was based on the previous issue of Westinghouse interface drawing 914-E-166 issue of 10 March 1969, agreements at the 20 March 1969 3M/Westinghouse interface meeting, and 3M design and manufacturing practices. The proposed revisions to the interface drawing were minor in nature. No difficulty is anticipated in resolving these differences or is it delaying the design of PMC-2 at this time.

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.

4.2 TEN-COUPLE MODULES

Long-term test of modules 1, 3 and 5 through 12 continued during the quarter. During this period, the last of the 10-couple modules put on test exceeded one year of operation.

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 4-6. Analysis of the recent data 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 stable, resistance up slightly, hence power down since 5000 hours.
	Simultaneously Pressed N	Resistance stable, Seebeck down slightly, hence power down since 5000 hours.
	Bonded P	Seebeck stable, resistance up slightly, hence power down slightly.
	Simultaneously Pressed P	Seebeck stable, resistance down, hence power up.
3	Bonded N	Seebeck stable, resistance up, hence power down.
	Simultaneously Pressed N	Seebeck stable, resistance up, hence power down.
	Bonded P	Seebeck stable, resistance up, hence power down.
	Simultaneously Pressed P	Seebeck stable, resistance up, hence power down.

With respect to the P-legs, results of the data analysis indicate that the use of bonded P-legs, 250 psi contact pressure, and Min-K 1301 thermal insulation yields significantly higher power output than their respective alternates (simultaneously pressed legs, 150 psi contact pressure, and microquartz insulation), with the difference between them becoming larger with time.

With respect to the N-legs, results of the data analysis indicate that the use of 250 psi contact pressure and Min-K 1301 thermal insulation yields significantly higher power output than their respective alternates (150 psi contact pressure and microquartz insulation), with the difference between them becoming larger with time.

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
Δ P-Leg, Even, Bonded, Hard Nose
× N-Leg, Even, Bonded, Hard Nose

Figure 4-2
Resistance Ratio
versus
Elapsed Time
(Module 1)

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

Thermal Insulation = MIN-K 1301	○ P-Leg, Odd, Simul. Pressed, Hard Nose
Contact Pressure = 250 psi	□ N-Leg, Odd, Simul. Pressed, Hard Nose
Hot Electrode = 1100° F	△ P-Leg, Even, Bonded, Hard Nose
Cold Electrode = 190° F	× N-Leg, Even, Bonded, Hard Nose

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

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	O 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)

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

Thermal Insulation = Microquartz

Contact Pressure = 150 psi

Hot Electrode = 1100°F

Cold Electrode = 190°F

P-Leg, Odd, Simul. Pressed, Soft Nose

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

P-Leg, Even, Bonded, Soft Nose

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
Contact Pressure = 150 psi
Hot Electrode = 1100°F
Cold Electrode = 190°F

P-Leg, Odd, Simul. Pressed, Soft Nose
N-Leg, Odd, Simul. Pressed, Hard Nose
P-Leg, Even, Bonded, Soft Nose
N-Leg, Even, Bonded, Hard Nose

4.2.2 Modules 5 through 12

Statistical analyses of the data taken on 10-couple modules 5 through 12 with their respective 8000-, 8500-, 9000-, 9500- and 10,000-hour points were completed during the quarter. A general discussion of the test design and Yates analysis technique was presented in Quarterly Report No. 5; hence, in this and subsequent reports the discussion will be concerned primarily with the results. Tables 4-2 through 4-7 present summaries of the N- and P-leg statistical analysis completed thus far. The results indicated by the analyses are summarized in Table 4-8. Figures 4-7 through 4-12 graphically present the N- and P-leg average Seebeck, resistance, and power ratios versus time. Any significant effects (as indicated in Table 4-8) are shown on a second scale. By analyzing these graphs from a stability standpoint, the following conclusions can be drawn:

- a. The rate of N-leg performance degradation (resistance increase) generally appears to be lessening; however, the difference between 150 psi and 250 psi N-legs continues to increase with time (see Figure 4-13).
- b. N-leg performance in a microquartz environment continues to degrade more rapidly than that in a Min-K 1301 thermal insulation environment (see Figure 4-14).
- c. A Min-K 1301 environment for P-legs tends to increase the Seebeck ratio slightly, stabilize the resistance ratio, and hence stabilize the power ratio as a function of time (refer to Figure 4-15).
- d. A microquartz environment for P-legs tends to stabilize the Seebeck ratio, increase the resistance ratio, and hence decrease the power ratio as a function of time (refer to Figure 4-15).
- e. Compared to bonded-type P-legs, the simultaneously pressed variety exhibits:

1. A higher Seebeck ratio which tends to increase more rapidly with time during the first 2000 hours.
2. A considerably higher resistance ratio which tends to increase, more rapidly with time during the first 2000 hours.
3. A lower power ratio which tends to offer about the same net degree of stability (refer to Figure 4-15).

The results observed thus far in modules 5 through 12 agree quite well with those observed on comparable thermoelectric configuration in the other ten-couple modules and the SNAP-23A converters.

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

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

Effect	Mean Effect and Test Hours									
	225	1000	2500	3500	5500	8000	8500	9000	9500	10,000
Average	1.01068	1.01463	1.01343	1.01839	1.01474	1.01615	1.01531	1.01828	1.01745	1.02001
A	0.00594	0.00448	0.00104	0.00073	0.00304	-0.00166	0.00291	0.00197	0.00218	0.00333
B	0.00032	-0.00239	0.00104	-0.00115	0.00117	-0.00041	-0.00209	-0.00366	-0.00094	-0.00667
C	0.00738	0.00407	0.00209	0.00928	0.00552	0.00021	-0.00583	0.00093	-0.00448	-0.00562
D	-0.00032	0.00302	0.00980	0.00490	0.00302	0.00687	0.00645	0.00698	0.00384	0.00686
E	-0.01364	-0.00343	-0.00250	-0.01219	0.00114	-0.00585	-0.00834	-0.00657	-0.00261	-0.00937
AB	0.00073	0.00363	0.00436	0.00115	0.00136	-0.00021	0.00188	0.00093	0.00052	0.00251
AC	-0.00218	-0.00198	-0.00584	-0.00677	-0.00427	-0.00834	-0.00396	-0.00448	-0.00387	-0.00479
AD	-0.00781	-0.00136	-0.00105	-0.00365	-0.00552	-0.00291	-0.00124	-0.00468	-0.00427	-0.00437
AE	0.00219	0.00177	-0.00000	0.00134	0.00053	0.00021	0.00020	0.00177	-0.00282	0.00311
BC	-0.00656	-0.00011	0.00291	0.00135	0.00261	0.00291	-0.00021	-0.00136	-0.00074	-0.00604
BD	0.00407	-0.00073	-0.00105	0.00322	0.00136	0.00084	-0.00124	0.00219	-0.00114	-0.00063
BE	0.00157	0.00114	0.00125	0.00071	0.00116	0.00021	-0.00105	0.00261	0.00156	-0.00314
CD	0.00323	0.00531	0.00375	-0.00303	0.00198	0.00478	0.00625	0.00511	0.00114	0.00375
CE	0.00906	0.00343	0.01063	0.00114	0.00511	0.00417	0.00311	0.00031	0.00219	-0.00209
DE	-0.00197	0.00052	-0.00291	-0.00489	-0.00114	0.00208	0.00209	0.00343	0.00719	0.00542
ABC	-0.00199	-0.00031	0.00584	-0.00135	0.00114	0.00021	0.00168	0.00094	-0.00261	0.00063
ABD	0.00406	0.00239	0.00230	0.00302	0.00614	0.00187	0.00270	0.00136	0.00322	0.00061
ABE	-0.00177	-0.00281	-0.00375	-0.00406	-0.00448	-0.00459	-0.00584	-0.00344	-0.00448	-0.00312
ACD	0.00239	0.00136	0.00250	-0.00073	-0.00406	0.00126	-0.00021	-0.00073	-0.00364	-0.00416
ACE	0.00239	0.00156	-0.00228	-0.00199	-0.00136	-0.00188	-0.00042	-0.00218	-0.00469	-0.00043
ADE	-0.00906	-0.00407	-0.01209	-0.00551	-0.00886	-0.00604	-0.00520	-0.00781	-0.00677	-0.00584
BCD	0.00052	0.00073	-0.00125	0.00365	-0.00093	0.00001	0.00104	0.00239	0.00073	0.00334
BCE	-0.00198	-0.00282	0.00022	-0.00261	0.00052	-0.00438	-0.00542	-0.00281	-0.00407	-0.00543
BDE	0.00282	-0.00219	0.00416	0.00261	0.00052	0.00146	0.00105	0.00282	-0.00114	-0.00084
CDE	-0.00759	-0.00698	-0.01271	-0.00449	-0.01011	-0.00876	-0.00521	-0.00594	-0.00468	-0.00896
ABCD	-0.00114	-0.00407	-0.00000	0.00260	0.00136	0.00228	0.00125	0.00073	0.00177	0.00125
ABCE	-0.00282	-0.00219	-0.00187	0.00426	0.00073	0.00042	-0.00064	0.00218	-0.00343	0.00041
ABDE	0.00491	0.00511	0.00584	0.00699	0.00448	0.00583	0.00709	0.00406	0.00407	0.00543
ACDE	0.00032	-0.00261	-0.00229	-0.00261	-0.00282	-0.00313	-0.00292	-0.00136	-0.00532	-0.00355
BCDE	-0.00156	-0.00052	0.00271	-0.00199	0.00031	0.00187	0.00208	0.00052	0.00156	0.00270
ABCDE	0.00053	-0.00261	0.00229	-0.00011	0.00427	0.00499	0.00604	0.00093	0.00344	0.00229

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

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

Effect	Mean Effect and Test Hours									
	225	1000	2500	3500	5000	8000	8500	9000	9500	10,000
Average	1 00006	0 99910	1 00604	1 01301	1 04781	1 08432	1 08739	1 09844	1 09521	1 10052
A	0 00126	0 01813	0 01212	0 01188	0 01333	-0 00824	0 00458	0 00063	-0 01229	0 00793
B	0 01731	0 00688	0 01417	0 00563	0 01583	0 01364	0 01042	0 01188	0 03521	0 03083
C	0 00926	-0 02334	0 02084	0 01416	0 02772	0 06906	0 06458	0 08188	0 07147	0 06959
D	0 01199	0 01646	0 03333	0 03875	0 07854	0 10864	-0 10834	-0 11272	0 12292	-0 11854
E	-0 02197	0 03481	0 04042	0 05125	0 06603	-0 12824	-0 14208	-0 13167	0 12958	-0 14791
AB	0 00426	0 00354	0 00083	0 00523	0 01313	0 00676	0 00853	0 00063	0 00417	0 00105
AC	0 01463	0 00021	0 00751	0 01041	0 00292	0 02531	-0 02188	0 01937	-0 02334	-0 02479
AD	0 00614	0 01146	0 01063	0 01082	0 00584	0 02281	0 02229	0 01063	0 02312	0 02291
AE	0 01052	0 00271	-0 00208	0 00250	0 00626	0 01366	0 02188	0 01458	0 01813	0 02979
BC	0 02963	0 00336	0 00374	0 00041	0 00708	0 00656	0 00313	0 00188	0 01541	0 01021
BD	-0 00449	-0 00729	0 01187	0 00418	0 00166	0 00156	0 00354	-0 00062	-0 01688	-0 01834
BE	-0 01135	0 00604	-0 00083	0 01000	-0 01124	-0 01071	-0 01437	-0 02292	-0 02937	-0 04271
CD	-0 00844	-0 00396	0 00563	0 02896	0 03437	0 05531	0 05312	-0 05229	0 06104	-0 05915
CE	-0 00115	0 00646	0 01748	0 01646	0 01438	-0 03281	-0 05063	0 03834	0 03563	-0 04145
DE	-0 02678	0 01336	0 00063	0 00063	0 02771	0 04656	0 05979	0 04958	0 05168	0 05250
ABC	-0 02011	0 01013	0 00211	0 01334	0 01353	0 00219	0 01458	0 00563	-0 00103	0 00834
ABD	0 01386	0 00723	0 01147	0 01375	0 01271	0 00176	-0 00334	-0 00397	0 00417	-0 00104
ABE	0 00635	-0 00856	0 00667	0 01125	0 00228	0 01886	-0 01958	0 01167	-0 01333	-0 00416
ACD	0 01136	0 00688	0 00312	0 00896	0 01083	-0 00551	0 00208	0 00979	0 00876	-0 00895
ACE	0 00427	0 00772	0 00167	0 00229	0 00624	0 01074	0 01708	0 00876	0 01833	0 02500
ADE	-0 02177	-0 01022	-0 02647	-0 01395	0 02083	-0 01906	-0 02459	-0 02292	0 02771	-0 02937
BCD	0 01801	0 00187	-0 00062	0 00729	0 00167	0 00761	0 01042	0 00646	0 00251	-0 00895
BCE	0 00490	0 00853	0 00212	0 00354	0 00374	-0 00364	-0 00042	-0 00374	0 01542	-0 02875
BDE	0 01760	-0 00103	0 01333	0 00730	0 00083	0 00281	0 00041	0 00708	0 01479	0 01812
CDE	0 00947	-0 01104	-0 01271	0 00834	0 01937	0 00426	0 00917	0 00083	-0 00854	-0 00939
ABCD	0 00094	0 00723	-0 00563	0 00729	0 00188	0 01094	-0 00937	-0 01167	-0 01354	-0 01290
ABCE	0 00448	0 00229	-0 00377	0 00729	0 00437	0 00344	-0 01188	0 00166	-0 01313	-0 00145
ABDE	0 01010	0 00979	0 00687	0 01062	0 01396	0 02219	0 02854	0 01458	0 01543	0 01375
ACDE	0 02905	0 01229	0 00146	0 00791	0 00374	0 00261	-0 00897	0 00167	0 01333	-0 01666
BCDE	0 01657	0 00104	0 01146	0 00041	0 00124	0 00699	0 00728	0 00583	0 02792	0 02959
ABCDE	-0 00115	-0 00229	0 00479	0 00166	0 01438	0 02886	0 03167	0 02333	0 02646	0 02311

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

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

Effect	Mean Effect and Test Hours									
	225	1000	2500	3500	5500	8000	8500	9000	9500	10,000
Average	1.02371	1.03090	1.02267	1.02572	0.98671	0.96110	0.95800	0.95268	0.95525	0.95596
A	0.00421	-0.01001	-0.01149	-0.01107	-0.00864	-0.00106	0.00219	-0.00092	0.00912	0.00660
B	-0.01884	-0.01173	-0.01196	-0.00734	-0.01248	-0.01323	-0.01543	-0.01598	-0.02888	-0.03324
C	0.00259	0.03253	0.02549	0.00615	-0.01123	-0.05157	-0.05562	-0.06064	-0.06027	-0.05980
D	-0.01480	0.02361	0.05399	0.04873	0.07779	0.10164	0.09699	0.10308	0.10588	0.10646
E	-0.00771	0.02902	0.03566	0.02710	0.06221	0.09616	0.10003	0.09536	0.10136	0.10350
AB	0.00461	0.00419	0.00774	0.00717	0.01484	-0.00339	0.00098	0.00361	-0.00136	0.00366
AC	-0.02116	-0.00434	-0.00413	-0.00266	-0.00521	0.00462	0.00757	0.00762	0.01001	0.00932
AD	-0.02302	-0.01419	-0.01218	-0.01801	-0.01631	-0.02289	-0.01659	-0.01561	-0.02464	-0.02394
AE	-0.00781	0.00019	0.00233	0.00026	-0.00439	-0.00828	-0.01308	-0.00626	-0.01597	-0.01455
BC	0.01861	0.00383	0.00148	0.00343	-0.00177	-0.00158	-0.00031	-0.00417	-0.01202	-0.01436
BD	0.01410	0.00591	0.00898	0.01030	0.00273	0.00286	-0.00437	0.00318	0.00748	0.00840
BE	0.01546	0.00802	0.00147	0.01035	0.01159	0.00869	0.01142	0.01301	0.02181	0.02371
CD	0.01708	0.00742	0.01436	0.02311	0.03536	0.05007	0.04807	0.04629	0.04687	0.04974
CF	0.02189	0.00128	0.00479	0.01931	0.02212	0.02843	0.03916	0.02432	0.02634	0.02200
DE	0.02582	0.01408	-0.00341	-0.00699	0.02378	-0.02418	-0.03283	-0.02331	-0.01718	-0.01954
ABC	0.01786	0.00998	0.00898	0.01324	0.01476	0.00141	-0.00529	-0.00488	-0.00159	-0.00596
ABD	-0.00462	-0.00287	-0.00697	-0.00746	0.00103	0.00117	0.00217	0.00342	0.00836	0.00147
ABE	0.00406	-0.00287	-0.00063	0.00334	-0.00651	0.00451	0.00093	0.00177	0.00173	-0.00226
ACD	0.01660	0.00839	0.00733	0.00727	0.00131	0.01033	0.00688	0.00961	0.00504	0.00474
ACE	0.00189	-0.00502	-0.00618	-0.00177	0.00317	-0.01026	-0.01046	-0.00889	-0.02128	-0.01780
ADE	0.00510	-0.00136	0.00212	0.00270	0.00254	0.00151	0.00583	0.00258	0.00649	0.00899
BCD	-0.01860	-0.00051	-0.00248	-0.00071	-0.00463	-0.00734	-0.00549	-0.00208	-0.00161	0.00832
BCE	-0.00966	0.00366	-0.00302	-0.00199	0.00423	-0.00501	-0.00856	-0.00316	0.00032	0.00891
BDE	-0.01420	-0.00524	-0.00512	-0.00144	0.00376	0.00046	0.00063	0.00084	-0.00931	-0.00958
CDE	-0.02732	-0.00213	-0.01227	0.00130	0.00206	-0.00086	-0.00311	-0.00047	0.01146	0.00516
ABCD	-0.00443	-0.00041	0.00562	-0.00147	0.00202	0.01017	0.00414	0.00736	0.01262	0.01165
ABCE	-0.01131	-0.00187	-0.00007	0.00115	-0.00322	-0.00084	0.00276	-0.00149	0.00299	0.00024
ABDE	-0.00238	0.00019	0.00403	0.00242	-0.00592	-0.00556	-0.00773	-0.00299	-0.00418	-0.00243
ACDE	-0.03035	-0.01788	-0.00554	-0.01336	-0.00842	-0.01097	-0.00284	-0.00298	-0.00142	0.00419
BCDE	0.01567	0.00027	-0.00661	-0.00405	0.00012	-0.00434	-0.00604	-0.00449	-0.01954	-0.01602
ABCDE	0.00405	0.00241	0.00034	-0.00204	-0.00576	-0.01226	-0.01106	-0.01563	-0.01392	-0.01453

Table 4-5
SNAP-23A P-Leg Statistical Analysis Summary
(Seebeck Ratio)

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

Effect	Mean Effect and Test Hours									
	225	1000	2500	3500	5500	8000	8500	9000	9500	10,000
Average	0.96523	0.97758	0.98609	0.98672	0.98055	0.97250	0.97031	0.97008	0.96945	0.97031
A	0.10359	0.13234	0.14625	0.15219	0.15234	0.14531	0.14437	0.14203	0.14266	0.14344
B	0.00797	0.00797	0.00625	0.00781	0.00859	0.00719	0.00438	0.00641	0.00891	0.00781
C	0.01078	0.01328	0.01281	0.01156	-0.00141	-0.01781	-0.01906	-0.02141	-0.02641	-0.02719
D	-0.00109	0.00203	0.00469	0.00500	-0.00234	0.00094	0.00000	0.00422	0.00078	0.00125
E	0.00797	0.03547	0.04219	0.03437	0.04641	0.03250	0.02969	0.02859	0.02891	0.02594
F	0.00234	0.00109	0.00375	0.00156	0.00547	0.00469	0.00563	0.00578	0.00703	0.00531
AB	-0.00391	0.00047	-0.00031	-0.00094	0.00109	0.00313	0.00313	0.00203	0.00516	0.00375
AC	0.00078	0.00391	-0.01063	-0.01344	-0.01891	-0.02125	-0.02031	-0.02141	-0.02391	-0.02312
AD	0.00141	-0.00016	0.00187	-0.00125	-0.00047	0.00125	-0.00187	0.00109	-0.00172	0.00031
AE	-0.01141	-0.00359	-0.00563	-0.00938	-0.00609	-0.01344	-0.01406	-0.01328	-0.01297	-0.01250
AF	0.01547	0.00766	0.00469	0.00656	0.00547	0.00437	0.00437	0.00641	0.00453	0.00625
BC	-0.00109	0.00047	0.00063	0.00344	-0.00141	0.00063	0.00094	0.00047	0.00109	0.00125
BD	-0.00172	-0.00203	-0.00687	-0.00438	-0.00547	-0.00813	-0.00813	-0.01078	-0.00797	-0.01031
BE	-0.00328	-0.00422	0.00062	-0.00250	-0.00234	-0.00531	-0.00406	-0.00516	-0.00547	-0.00438
BF	0.00109	0.00078	0.00344	0.00219	-0.00078	0.00125	0.00187	0.00203	0.00203	0.00188
CD	-0.00016	-0.00109	-0.00344	-0.00750	-0.00484	-0.00312	-0.00281	0.00141	-0.00078	-0.00094
CE	0.00078	0.00109	0.00469	-0.00313	-0.00797	-0.02031	-0.01625	-0.02297	-0.01891	-0.02312
CF	-0.00172	-0.00766	-0.00563	-0.00531	-0.00578	-0.00313	-0.00406	-0.00266	-0.00578	-0.00125
DE	0.00203	0.00484	-0.00156	-0.00844	-0.00641	-0.00531	-0.00656	-0.00797	-0.00547	-0.00906
DF	0.00266	0.00609	0.00562	0.00688	0.00641	0.00562	0.00937	0.00984	0.00641	0.00594
EF	0.00484	0.01016	0.00937	0.01000	0.01203	0.01469	0.01594	0.01422	0.01391	0.01438
ABC	0.00016	0.00141	0.00156	0.00594	0.00484	0.00531	0.00719	0.00797	0.00609	0.00844
ABD	0.00453	0.00391	0.00594	0.00437	0.00391	0.00031	0.00375	0.00484	0.00453	0.00438
ABE	0.00234	-0.00141	-0.00156	-0.00375	-0.00359	-0.00313	-0.00281	-0.00078	-0.00109	0.00031
ABF	0.00422	0.00047	-0.00250	-0.00031	-0.00453	-0.00469	-0.00438	-0.00609	-0.00797	-0.00531
ACD	0.00047	-0.00016	0.00125	0.00125	-0.00172	0.00219	0.00031	0.00266	0.00297	0.00437
ACE	-0.00047	0.00016	-0.00062	-0.00063	-0.00297	-0.00625	-0.00500	-0.00422	-0.00203	-0.00281
ACF	0.00203	0.00078	0.00031	-0.00156	-0.00203	-0.00219	-0.00281	-0.00266	-0.00203	-0.00406
ADE	-0.00297	-0.00359	-0.00500	-0.00094	-0.00578	-0.00250	-0.00344	-0.00359	-0.00359	-0.00500

Effect	Mean Effect and Test Hours									
	225	1000	2500	3500	5500	8000	8500	9000	9500	10,000
ADF	0.00641	0.00203	0.00094	-0.00062	0.00078	0.00281	0.00375	0.00047	0.00016	0.00062
AEF	-0.00703	-0.00953	-0.00781	-0.01000	-0.00922	-0.00938	-0.00781	-0.01141	-0.01297	-0.01094
BCD	0.00109	-0.00078	-0.00125	-0.00312	-0.00047	0.00031	0.00031	-0.00047	-0.00203	-0.00125
BCE	0.00141	0.00078	0.00188	0.00250	0.00703	0.00687	0.00625	0.00641	0.00672	0.00531
BCF	-0.00609	-0.00234	-0.00219	-0.00219	-0.00203	-0.00031	0.00094	-0.00203	-0.00078	0.00156
BDE	-0.00234	0.00328	0.00500	0.00469	0.00672	0.00687	0.00781	0.00578	0.00391	0.00562
BDF	-0.00797	-0.00484	-0.00656	-0.00625	-0.00672	-0.00656	-0.00750	-0.00766	-0.00734	-0.00875
BEF	0.00234	-0.00266	-0.00281	-0.00063	-0.00047	0.00125	0.00031	0.00547	0.00578	0.00344
CDE	0.00547	0.00422	0.00094	0.00219	-0.00328	-0.00062	0.00188	-0.00078	0.00047	0.00000
CDF	0.00297	0.00109	-0.00250	-0.00437	-0.00484	-0.00469	-0.00344	-0.00484	-0.00266	-0.00500
CEF	0.00203	0.00141	0.00188	0.00500	0.00266	0.00563	0.00250	0.00328	0.00359	0.00406
DEF	0.00078	0.00266	0.00125	-0.00031	-0.00141	-0.00187	-0.00094	0.00141	-0.00047	0.00312
ABCD	-0.00078	-0.00297	-0.00094	-0.00187	-0.00234	-0.00625	-0.00531	-0.00797	-0.00828	-0.00531
ABCE	-0.00109	-0.00453	-0.00281	-0.00250	-0.00172	-0.00094	0.00000	0.00016	-0.00016	-0.00125
ABCF	0.00641	0.00547	0.00187	0.00406	0.00547	0.00750	0.00469	0.00547	0.00547	0.00562
ABDE	-0.00359	-0.00453	-0.00406	-0.00531	-0.00516	-0.00719	-0.00531	-0.00609	-0.00547	-0.00719
ABDF	0.01203	0.01047	0.01062	0.00625	0.01266	0.01250	0.01313	0.01422	0.01641	0.01531
ABEF	0.00047	0.00328	0.00188	0.00187	0.00453	0.00406	0.00594	0.00859	0.00766	0.00500
ACDE	0.00234	0.00141	0.00250	0.00219	-0.00016	0.00094	0.00000	-0.00078	-0.00141	-0.00219
ACDF	-0.00391	0.00141	-0.00219	-0.00187	-0.00172	0.00000	-0.00156	0.00016	-0.00016	0.00094
ACEF	-0.00047	0.00109	-0.00031	0.00375	0.00391	0.00406	0.00125	0.00453	0.00297	0.00250
ADEF	-0.00547	-0.00266	-0.00281	0.00094	-0.00078	0.00281	0.00344	0.00453	0.00391	0.00531
BCDE	0.00172	0.00203	-0.00125	0.00156	-0.00141	-0.00219	-0.00250	-0.00141	-0.00016	-0.00156
BCDF	-0.00203	0.00078	-0.00094	-0.00125	-0.00297	-0.00188	-0.00156	-0.00047	-0.00641	-0.00344
BCEF	-0.00016	-0.00078	-0.00156	-0.00313	-0.00109	-0.00031	-0.00000	0.00141	0.00297	0.00188
BDEF	-0.00109	0.00422	0.00344	0.00156	0.00172	-0.00031	-0.00031	-0.00484	-0.00484	-0.00281
CDEF	-0.00016	0.00266	0.00625	0.00656	0.00672	0.01031	0.01000	0.00922	0.00797	0.01094
ABCDE	-0.00141	-0.00141	-0.00031	0.00156	-0.00078	-0.00000	0.00188	0.00109	0.00172	0.00437
ABCDF	-0.00141	0.00172	0.00125	-0.00125	-0.00234	-0.00031	-0.00094	0.00203	0.00109	0.00187
ABCEF	-0.00109	0.00078	-0.00687	-0.00688	-0.00859	-0.01000	-0.00875	-0.00734	-0.00891	-0.00781
ABDEF	-0.00109	-0.00422	-0.00250	-0.00469	-0.00266	-0.00375	-0.00469	-0.00547	-0.00422	-0.00375
ACDEF	-0.00078	-0.00078	-0.00031	0.00031	-0.00016	0.00375	0.00188	0.00422	0.00109	0.00187
BCDEF	-0.00016	-0.00016	-0.00531	-0.00281	-0.00641	-0.00688	-0.00563	-0.00766	-0.00891	-0.01125
ABCDEF	0.00422	0.00453	0.00125	0.00094	0.00172	0.00594	0.00500	0.00484	0.00547	0.00656

Table 4-6
SNAP-23A P-Leg Statistical Analysis Summary
(Resistance Ratio)

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

Effect	Mean Effect and Test Hours									
	225	1000	2500	3500	5500	8000	8500	9000	9500	10,000
Average	1.17515	1.24789	1.28750	1.28586	1.33226	1.41758	1.43617	1.45515	1.45648	1.44414
A	0.42344	0.63766	0.70375	0.70484	0.68172	0.74141	0.75984	0.77562	0.75766	0.73109
B	-0.07219	-0.06984	-0.06938	-0.07766	-0.09078	-0.21172	-0.24641	-0.27937	-0.26359	-0.24266
C	0.01344	-0.05047	-0.08750	-0.06922	-0.10359	-0.22234	-0.24672	-0.28281	-0.29297	-0.28266
D	-0.11219	-0.11078	-0.09750	-0.07203	-0.10328	-0.07078	-0.11734	-0.12000	-0.15953	-0.14797
E	-0.18000	-0.23109	-0.29219	-0.30703	-0.38609	-0.63484	-0.68609	-0.72875	-0.73359	-0.71203
F	0.13156	0.11953	0.09813	0.08547	0.08859	0.19578	0.23359	0.26750	0.26516	0.26047
AB	-0.01531	-0.02422	-0.03688	-0.04203	-0.05297	-0.16922	-0.20141	-0.22844	-0.20453	-0.19922
AC	0.04031	0.00328	-0.03813	-0.03984	-0.05391	-0.14297	-0.15547	-0.18187	-0.17141	-0.15297
AD	-0.00844	-0.04766	-0.05563	-0.06328	-0.06797	-0.01016	-0.06359	-0.05844	-0.08547	-0.06266
AE	-0.04875	-0.12422	-0.19031	-0.21203	-0.21641	-0.35359	-0.37859	-0.41406	-0.39016	-0.38172
AF	-0.00656	-0.00109	-0.00937	-0.01266	-0.01484	0.06453	0.09484	0.11094	0.08547	0.08141
BC	0.02344	0.04703	0.05750	0.06641	0.07234	0.19391	0.21328	0.24313	0.24109	0.22078
BD	0.01844	0.02109	0.00625	0.00547	-0.01172	-0.07578	-0.02234	-0.02219	-0.00547	-0.02641
BE	0.01437	0.02703	0.03781	0.03797	0.04859	0.16328	0.19141	0.22594	0.20359	0.19578
BF	-0.07219	-0.06734	-0.04375	-0.04141	-0.06234	-0.16734	-0.19016	-0.22156	-0.20703	-0.19234
CD	0.01344	0.00609	-0.00687	-0.02547	-0.03453	-0.08516	-0.03203	-0.06938	0.00891	0.00047
CE	-0.02063	-0.00359	0.01906	0.00578	0.03578	0.15016	0.17734	0.22062	0.23422	0.21391
CF	-0.01906	-0.06234	-0.08375	-0.08422	-0.11828	-0.25734	-0.29297	-0.31875	-0.31141	-0.28859
DE	-0.00312	-0.00391	-0.00594	-0.03641	-0.01641	-0.04203	0.01484	0.01406	0.04578	0.02734
DF	-0.02906	-0.00453	0.01500	0.03734	0.04641	0.09422	0.05266	0.03719	0.00203	0.01297
EF	-0.06812	-0.09109	-0.09594	-0.07391	-0.07828	-0.19172	-0.22484	-0.25344	-0.26016	-0.25484
ABC	0.00156	-0.00672	-0.00062	0.00328	-0.01484	0.07078	0.09953	0.12844	0.11578	0.11234
ABD	0.01719	0.04047	0.05812	0.055547	0.06047	0.03984	0.08891	0.10500	0.12922	0.10703
ABE	-0.00188	0.00516	0.01719	0.02172	0.02141	0.13328	0.17141	0.19750	0.17641	0.16672
ABF	0.01844	0.01078	0.00500	0.01047	0.00609	-0.07984	-0.10641	-0.13375	-0.12359	-0.11703
ACD	-0.01031	0.00859	0.01437	0.01078	0.00453	-0.03516	0.01297	0.02906	0.04359	0.02516
ACE	-0.01438	-0.03734	-0.05219	-0.05797	-0.07328	0.03078	0.04609	0.07469	0.05953	0.04609
ACF	0.05156	0.03766	0.04063	0.04391	0.05078	-0.00422	-0.02547	-0.03594	-0.01797	-0.01203
ADE	-0.04875	-0.02578	-0.01094	-0.00203	-0.00234	-0.04141	0.00484	0.00750	0.02359	0.00141
ADF	0.06469	0.04609	0.01687	0.01109	-0.00016	0.04609	0.01016	-0.0083	-0.02953	-0.00609
AEF	0.01312	0.00328	-0.00406	0.00109	0.00828	-0.07797	-0.10609	-0.11937	-0.10359	-0.08891

Effect	Mean Effect and Test Hours									
	225	1000	2500	3500	5500	8000	8500	9000	9500	10,000
BCD	0.01031	0.01609	0.01750	0.01828	0.05453	0.12672	0.08172	0.07281	0.04734	0.06391
BCE	0.01750	-0.01984	-0.04531	-0.05672	-0.07453	-0.19734	-0.22641	-0.25281	-0.25047	-0.23641
BCF	-0.00281	0.02266	0.03500	0.02641	0.03953	0.14141	0.16203	0.18406	0.17578	0.16422
BDE	0.00187	0.00172	0.00219	0.00922	0.02641	0.07797	0.03234	0.02625	0.01359	0.03141
BDF	-0.00094	-0.01391	-0.03250	0.03391	0.05641	-0.13078	-0.08234	-0.07688	-0.05078	-0.07484
BEF	0.03625	0.03828	0.03531	0.03484	0.05578	0.17016	0.19016	0.22312	0.21141	0.19109
CDE	0.02125	0.01297	0.00844	0.02141	-0.00891	0.04734	0.01016	-0.01281	-0.03953	-0.02359
CDF	0.01906	0.02922	0.02500	0.01391	0.01016	-0.01953	0.03297	0.03844	0.06859	0.05828
CEF	-0.00125	0.02828	0.06719	0.06766	0.10859	0.25141	0.28109	0.30406	0.30203	0.29297
DEF	0.01313	0.01109	-0.00031	0.01641	0.03422	-0.07703	-0.03141	-0.01812	0.01109	0.00203
ABCD	-0.01844	-0.01641	-0.02500	0.02672	0.02453	-0.00453	-0.04828	-0.06688	-0.10109	-0.08203
ABCE	-0.02375	0.01859	-0.01281	-0.02172	0.00047	-0.10422	-0.12766	-0.15062	-0.14703	-0.14234
ABCF	0.01906	0.02266	0.01687	0.00953	0.02297	0.12203	0.14953	0.16250	0.14359	0.13391
ABDE	-0.02500	-0.04141	-0.04906	-0.05141	0.05266	-0.03391	-0.07766	-0.09344	-0.12297	-0.09891
ABDF	0.01031	0.02297	0.03937	0.03109	0.05766	0.02609	0.07766	0.09469	0.12953	0.11297
ABEF	-0.01750	-0.00609	0.00469	0.00359	0.00328	0.08516	0.10641	0.13531	0.12609	0.12141
ACDE	0.01187	-0.00953	-0.01844	0.02172	-0.03234	0.02109	-0.02609	-0.03375	-0.05609	-0.03516
ACDF	-0.01219	0.02797	0.04500	0.04266	0.05484	0.02047	0.05922	0.06875	0.08641	0.06234
ACEF	-0.03250	-0.03922	-0.04531	-0.04609	-0.06109	0.00828	0.02359	0.03875	0.02172	0.01453
ADEF	-0.01125	0.01172	0.03094	0.03672	0.03297	0.01016	0.03234	0.04719	0.06078	0.04172
BCDE	-0.05375	-0.04828	-0.03906	-0.04422	-0.06484	-0.13203	-0.08359	-0.08500	-0.05484	-0.06516
BCDF	0.00844	0.01672	-0.00312	0.00891	0.01984	0.07359	0.02672	0.02750	0.00141	0.02359
BCEF	0.01188	-0.01297	-0.03719	-0.03859	-0.04734	-0.14109	-0.17016	-0.18875	0.17953	-0.16797
BDEF	0.01187	0.01297	0.02531	0.02922	0.05172	0.12297	0.07609	0.06344	0.04703	0.05922
CDEF	-0.01125	-0.02016	-0.02281	-0.00609	0.00297	0.03422	-0.02109	-0.03312	0.06109	-0.04703
ABCD	0.05312	0.04672	0.03656	0.04016	0.04109	0.02047	0.06766	0.07969	0.12047	0.10016
ABCDF	-0.02531	-0.03703	0.03937	-0.04859	0.06484	-0.03516	-0.08703	0.09406	-0.11516	-0.09672
ABCEF	-0.07437	-0.05297	0.04844	0.02859	0.03766	-0.13672	0.16266	-0.17719	-0.16047	-0.14328
ABDEF	-0.01375	-0.03266	-0.04219	-0.05016	-0.05547	-0.03266	-0.09016	-0.10312	-0.13641	0.12172
ACDEF	-0.01438	-0.04641	-0.05219	0.05297	0.06328	-0.01953	-0.06609	0.06844	-0.09203	-0.06422
BCDEF	0.00500	0.01359	0.00844	0.00172	0.01328	-0.06641	-0.00984	-0.01469	0.00297	-0.01422
ABCDEF	0.07312	0.07234	0.05156	0.04641	0.06453	0.03609	0.08266	0.08938	0.12266	0.09672

Table 4-7
SNAP-23A P-Leg Statistical Analysis Summary
(Power Ratio)

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

Effect	Mean Effect and Test Hours									
	225	1000	2500	3500	5500	8000	8500	9000	9500	10,000
Average	0.82432	0.81605	0.81180	0.81315	0.78050	0.75514	0.74954	0.74732	0.74529	0.74746
A	-0.13442	-0.20447	-0.20263	-0.19327	-0.15606	-0.14005	-0.13622	-0.13413	-0.13101	-0.12065
B	0.05440	0.04431	0.03673	0.04268	0.04126	0.05344	0.05477	0.06057	0.06376	0.05618
C	0.01008	0.05134	0.06325	0.04898	0.03736	0.02171	0.02269	0.01742	0.01470	0.01687
D	0.06880	0.07183	0.06876	0.05641	0.06514	0.07332	0.06876	0.07561	0.07932	0.08043
E	0.12697	0.17946	0.20863	0.20385	0.25062	0.29963	0.30801	0.31041	0.31696	0.30915
F	-0.07978	-0.06593	-0.04428	-0.04373	-0.02691	-0.03390	-0.03691	-0.04142	-0.03760	-0.04278
AB	-0.00247	0.00151	0.00753	0.00943	0.02026	0.03792	0.04028	0.04017	0.03904	0.04221
AC	-0.02022	-0.01263	0.00118	0.00556	0.01192	0.02082	0.01849	0.02023	0.01986	0.01552
AD	0.00098	0.00715	0.00837	0.01391	0.00916	-0.00511	-0.00124	-0.00371	-0.00290	-0.00108
AE	-0.00844	0.02277	0.04550	0.05453	0.05162	0.06389	0.06164	0.07164	0.06590	0.07352
AF	0.04397	0.03418	0.03180	0.03305	0.02293	0.01471	0.01204	0.01460	0.01646	0.01640
BC	-0.02240	-0.02957	-0.02662	-0.02559	-0.02944	-0.04217	-0.03817	-0.04062	-0.04246	-0.03902
BD	-0.00822	-0.01024	-0.00685	-0.00613	-0.00340	0.00696	-0.00144	-0.00277	0.00024	-0.00015
BE	-0.00827	-0.01062	-0.00280	-0.00352	-0.00054	-0.01390	-0.01177	-0.01732	-0.01058	-0.01494
BF	0.05025	0.04285	0.02817	0.02336	0.02333	0.03433	0.03556	0.03970	0.03636	0.03632
CD	-0.00860	-0.00045	0.00458	0.00378	0.01220	0.01918	0.01419	0.01337	0.01292	0.01036
CE	0.01555	0.01000	0.00729	0.00117	-0.01576	-0.04019	-0.03919	-0.05545	-0.05762	-0.05872
CF	0.01689	0.02862	0.04146	0.04498	0.04928	0.07463	0.07762	0.08203	0.07302	0.07205
DE	0.01266	0.01797	0.00944	0.01504	0.00796	0.00654	-0.00261	-0.00024	-0.00073	-0.00053
DF	0.02260	0.01850	0.00307	-0.00590	-0.00933	-0.01526	-0.00850	-0.00460	-0.00360	-0.00394
EF	0.04377	0.06518	0.06386	0.05228	0.04902	0.06244	0.06606	0.06433	0.06937	0.07249
ABC	0.00775	0.02154	0.01786	0.02243	0.02686	0.02669	0.02458	0.02260	0.02482	0.02521
ABD	-0.00289	-0.00677	-0.01028	-0.01020	-0.00886	-0.01576	-0.01201	-0.01289	-0.01322	-0.01228
ABE	0.00742	0.00203	-0.00343	-0.01013	-0.00813	-0.01619	-0.02302	-0.02029	-0.01801	-0.01443
ABF	-0.01415	-0.01853	-0.01576	-0.01144	-0.01317	-0.00598	-0.00198	-0.00180	-0.00484	-0.00247
ACD	0.00646	-0.00000	0.00237	0.00470	0.00715	0.01371	0.00546	0.00438	0.00959	0.01182
ACE	-0.00127	0.01795	0.03425	0.03683	0.04572	0.02174	0.02569	0.02382	0.03020	0.02874
ACF	-0.03022	-0.02766	-0.03583	-0.04002	-0.04033	-0.04812	-0.04761	-0.04994	-0.04768	-0.04878
ADE	0.02636	0.01766	0.01540	0.01348	0.01637	0.02792	0.02443	0.02574	0.02834	0.02717
ADF	-0.03454	-0.03364	-0.01652	-0.01300	-0.00428	-0.00752	-0.00881	-0.01076	-0.00849	-0.01054
AEF	-0.02971	-0.03930	-0.03158	-0.03143	-0.02670	-0.01626	-0.01121	-0.01780	-0.01962	-0.02201

Effect	Mean Effect and Test Hours									
	225	1000	2500	3500	5500	8000	8500	9000	9500	10,000
BCD	-0.00331	-0.00755	-0.01172	-0.01081	-0.01998	-0.01626	-0.02761	-0.02510	-0.02468	-0.02736
BCE	-0.00980	0.00688	0.02067	0.02558	0.03929	-0.03091	0.05707	0.05738	0.05921	0.05920
BCF	-0.00932	-0.00663	-0.00863	-0.00463	-0.00497	0.05341	-0.00623	-0.01194	-0.01177	-0.01003
BDE	-0.00923	-0.00224	-0.00127	-0.00123	-0.00216	-0.00549	-0.00271	-0.00516	-0.00959	-0.00701
BDF	-0.01092	0.00321	0.01148	0.00880	0.01508	0.02548	0.02097	0.02128	0.01538	0.02320
BEF	-0.02065	-0.02240	-0.01513	-0.01032	-0.01786	-0.02908	-0.03099	-0.02573	-0.02403	-0.02290
CDE	-0.00438	-0.00253	-0.00538	-0.00690	0.00936	0.00604	0.00346	0.00793	0.01245	0.00758
CDF	-0.00806	-0.00993	-0.00688	-0.00895	-0.00752	-0.00780	-0.01106	-0.01061	-0.01256	-0.01844
CEF	-0.00128	-0.01537	-0.03558	-0.03393	-0.05037	-0.06615	-0.07065	-0.06841	-0.06882	-0.07083
DEF	0.00203	0.00316	0.01024	0.01137	0.01573	0.01415	0.01317	0.01572	0.00890	0.01372
ABCD	0.00685	-0.00056	0.00813	0.00752	0.00501	0.00333	0.00380	0.00354	0.00572	0.01005
ABCE	0.01172	0.00124	-0.00406	0.00297	-0.00694	0.01003	0.01181	0.01113	0.01264	0.01228
ABCF	0.00407	0.00028	0.00027	0.00277	-0.00139	-0.00896	-0.01564	-0.01131	-0.00771	-0.00757
ABDE	0.01352	0.01083	0.01002	0.01065	0.00677	0.00379	0.00536	0.00715	0.01388	0.00687
ABDF	0.01289	0.00558	-0.00314	-0.00292	-0.00571	-0.00166	-0.00410	-0.00523	-0.00439	-0.00795
ABEF	0.01897	0.01785	0.00565	0.00252	0.01047	0.00160	0.00675	0.00578	0.00336	-0.00113
ACDE	-0.00547	0.00599	0.01398	0.01603	0.01169	-0.00262	0.00606	0.00070	0.00307	0.00228
ACDF	0.00622	-0.00336	-0.01720	-0.01410	-0.01592	-0.00955	-0.00917	-0.00840	-0.00804	-0.00322
ACEF	0.02181	0.03000	0.03918	0.04431	0.05250	0.04811	0.04646	0.04992	0.04744	0.04577
ADEF	-0.00757	-0.01443	-0.02402	-0.02249	-0.02086	-0.00965	-0.01150	-0.01368	-0.00870	-0.00789
BCDE	0.04486	0.04175	0.02686	0.03255	0.03043	-0.03741	0.03076	0.03685	0.03441	0.02847
BCDF	-0.00757	-0.01560	-0.00341	-0.01130	-0.01607	-0.01759	-0.01668	-0.01629	-0.01768	-0.01908
BCEF	-0.01641	-0.01411	-0.00236	0.00285	0.00392	0.00836	0.01408	0.01321	0.01672	0.01763
BDEF	-0.00963	-0.00409	-0.01358	-0.01722	-0.02174	-0.03424	-0.03341	-0.03421	-0.03746	-0.03328
CDEF	0.00782	0.00600	0.00955	0.00295	0.00123	0.00368	0.00942	0.01173	0.01334	0.01676
ABCDE	-0.04303	-0.03781	-0.02369	-0.02349	-0.02379	0.02401	-0.02309	-0.02538	-0.03123	-0.02238
ABCDF	0.00741	0.01872	0.01184	0.01815	0.01717	0.01348	0.01780	0.02109	0.01553	0.01887
ABCEF	0.04563	0.03483	0.01662	0.00561	0.00699	0.01764	0.01850	0.02067	0.01494	0.01128
ABDEF	0.00783	0.00861	0.01649	0.01917	0.01969	0.02013	0.02760	0.02551	0.03161	0.03315
ACDEF	0.00252	0.01823	0.01653	0.02002	0.02129	0.01722	0.01685	0.01703	0.01482	0.01105
BCDEF	-0.00413	-0.00380	-0.00987	-0.00256	-0.00547	-0.00536	-0.01155	-0.01069	-0.01287	-0.01603
ABCDEF	-0.02998	-0.02451	-0.01224	-0.01212	-0.01432	-0.00135	-0.00263	-0.00078	-0.00659	0.00038

Table 4-8
Summary of Statistical Analysis Findings
(After 10,000 Hours of Operation)

Variable		Differences Between Variable Levels (+) and (-)	
Code	Description	N-Leg	P-Leg
A	Leg Segmenting Technique	I	Note 1
B	Hot Contact Material	I	I
C	Hot Junction Temperature	I	I
D	Hot Contact Pressure	Note 3	I
E	Thermal Insulation	Note 4	Note 2
F	Contact Type	I	I

Key:

I indicates insignificant effect.

Note 1: On the average, a simultaneously pressed P-leg exhibits a 14.3% higher Seebeck ratio, a 73% higher resistance ratio, and a 12.0% lower power ratio than a corresponding bonded type of P-leg.

Note 2: On the average, P-legs operating in a Min-K 1301 environment exhibit a 2.5% higher Seebeck ratio, a 71% lower resistance ratio, and a 30.9% higher power ratio than those operating in a microquartz environment.

Note 3: On the average, N-legs with 250 psi contact pressure exhibit an 11.8% lower resistance ratio and a 10.6% higher power ratio than those with 150 psi contact pressure.

Note 4: On the average, N-legs operating in a Min-K 1301 environment exhibit a 14.8% lower resistance ratio and a 10.3% higher power ratio than those operating in a microquartz environment.

Figure 4-7
N-Leg Statistical Analysis Summary Data, 10-Couple Modules 5 thru 12
Average and Main Effects for Seebeck Ratio

Figure 4-8
N-Leg Statistical Analysis Summary Data, 10-Couple Modules 5 thru 12
Average and Main Effects for Resistance Ratio

Figure 4-9
N-Leg Statistical Analysis Summary Data, 10-Couple Modules 5 thru 12
Average and Main Effects for Power Ratio

Figure 4-10
P-Leg Statistical Analysis Summary Data, 10-Couple Modules 5 thru 12
Average and Main Effects for Seebeck Ratio

Figure 4-12
P-Leg Statistical Analysis Summary Data, 10-Couple Modules 5 thru 12
Average and Main Effects for Power Ratio

Figure 4-13
N-Leg Statistical Analysis, Comparison of Average Resistance
Ratio for Different Contact Pressure

Figure 4-14
N-Leg Statistical Analysis, Comparison of Average Resistance
Ratio for Different Thermal Insulations

Figure 4-15
P-Leg Statistical Analysis, Comparison of Average Power
Ratio for Different Thermal Insulations and Leg Segmenting Techniques

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 4-9 and shown graphically in Figure 4-16.

Analysis of recent data indicates that the Seebeck degradation mode which had overshadowed the expected resistance degradation mode (due to sublimation) during the 15,000- to 30,000-hour period now appears to be the less significant of the two degradation modes.

4.3.2 Converter 23P-2

Long-term test of converter 23P-2 continued during the quarter. Performance data for over two years of converter operation is summarized in Table 4-10. Normalized performance curves are shown in Figure 4-17; data is normalized to $T_h = 1071^\circ \text{F}$, $T_c = 200^\circ \text{F}$. Initial and current 23P-2 experimental-to-theoretical performance ratios are presented in Table 4-11. Analysis of recent data indicates that the slight improvement in performance noted over the last 5,000 hours is primarily due to a decrease in P-leg resistance. This behavior is typical of the simultaneously pressed P-leg.

Table 4-9
 Six-Couple Module 23A3 N-Leg Performance Data
 (Start of Test: 3/4/65: Current Reading: 3/31/69)

Hours	$T_h, ^\circ\text{F}$	$T_c, ^\circ\text{F}$	E, mv	R, m Ω	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
33,531	1096	189	112.5	29.6	2.31
35,694	1096	193	111.0	30.3	2.26

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 4-16
 SNAP-23 Six-couple Module A3 N-Leg Performance History
 ($T_H \cong 1100^\circ\text{F}$, $T_C \cong 200^\circ\text{F}$)

Table 4-10
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

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 4-17
 SNAP -23 Prototype P-2 Converter BOL Performance History
 (Normalized Data, $T_h = 1070^\circ\text{F}$, $T_c = 200^\circ\text{F}$)

Table 4-11
 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
	17,069	0.99	1.06
	19,232	0.99	1.06
Typical N-Leg	48	1.03	1.00
	14,884	1.01	0.95
	17,069	1.01	0.93
	19,232	1.01	0.95
Typical P-Leg	48	0.95	1.10
	14,884	0.98	1.25
	17,069	0.98	1.20
	19,232	0.98	1.21

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

APPENDIX A
COLD FRAME STRESS ANALYSIS

APPENDIX A
COLD FRAME STRESS ANALYSIS

Fin Base Hoop Force

For the cold frame-fin base loading depicted in Figure 3-5, the solution for the hoop force (F_b) is determined from the following calculation.

Equating the hoop force to the total pressure force

$$pA_p = 2F_b \quad (1)$$

where

F_b = hoop force in pounds

p = radial pressure in psi

A_p = projected area in square inches

Since the projected area, A_p , equals diameter, d , times the fin base length, l , equation (1) becomes

$$pld = 2F_b$$

Solving for F_b

$$F_b = \frac{pld}{2}$$

Substituting

$$p = 150 \text{ psi (Westinghouse interface drawing)}$$

$$l = 3.75 \text{ inches}$$

$$d = 9.25 \text{ inches}$$

$$F_b = \frac{150 \times 3.75 \times 9.25}{2} = 2600 \text{ lbs}$$

Outer Case Hoop Force

For the cold frame-outer case loading depicted in Figure 3-5, the solution for the hoop force (F_a) is determined from the following calculations.

$$F_a = S_h t l$$

where

$$S_h = \text{hoop stress in thin section in psi}$$

$$t = \text{wall thickness in inches}$$

$$l = \text{length of outer case in inches}$$

Substituting

$$S_h = 60,000 \text{ psi (Inconel 625, solution anneal)}$$

$$t = 0.040 \text{ inch}$$

$$l = 3.75 \text{ inches}$$

$$F_a = 60,000 \times 0.040 \times 3.75 = 9000 \text{ lbs}$$

Cold Frame Web Force

For the cold frame force loading depicted in Figure 3-5, the solution for the web force (F_w) is determined from the following calculations.

$$15 F_w = F_a + F_b$$

Substituting

$$F_a = 9000 \text{ lbs}$$

$$F_b = 2600 \text{ lbs}$$

$$15 F_w = 9000 + 2600$$

$$F_w = \frac{9000 + 2600}{15} = 775 \text{ lbs}$$

Cold Frame Hold Distortion

The solution for hold diametrical shrinkage is established by the following calculations.

Equating the web force to the web stress

$$F_w = A_w S_w \tag{2}$$

where

$$A_w = \text{total web area in square inches}$$

$$S_w = \text{web stress in psi}$$

Since the web area (A_w) equals the web thickness (t_w) times the web length (l_w) equation (2) becomes

$$F_w = t_w l_w S_w$$

Solving for S_w

$$S_w = \frac{F_w}{t_w l_w}$$

Substituting

$$F_w = 775 \text{ lbs}$$

$$t_w = 0.0488 \text{ inches}$$

$$l_w = 1.875 \text{ inch}$$

$$S_w = \frac{775}{0.0488 \times 1.875} = 8450 \text{ psi}$$

The web stress of 8450 psi occurs only at the thinnest portion of the web. As the web thickness increases, web stress decreases. Therefore, to calculate hole distortion, the effects of the varying stress must be integrated over the radial height of the web. Figure A-1 shows the limits of integration and the geometrical relationship of a web to the hole.

The total force acting on the thin section (shown as width a) of a single web is equal to the web stress, S_w , times the single web area, $A = a \cdot l$, where l is the length of the web in the direction perpendicular to the paper. Expressed mathematically,

$$F_w = S_w a \cdot l \quad (3)$$

Figure A-1
Web-to-Hole Relationships

This same force also acts on the element of area located at a distance X from the thinnest portion of the web. Since stress is equal to force divided by area, the stress on this element of area, noticing the width of the area in Figure A-1, is

$$S_x = \frac{S_w a \cdot l}{A_x}$$

or

$$S_x = \frac{S_w a \cdot l}{(a + 2r - 2 \sqrt{r^2 - x^2}) l} \quad (4)$$

The shortening of the element thickness, dx , caused by the compressive stress, S_w , is

$$d\delta = E dx$$

Since the unit strain, δ , is equal to the stress, S_x , divided by the modulus of elasticity, E ,

$$d\delta = \frac{S_x dx}{E} \quad (5)$$

Substituting equation (4) in equation (5)

$$d\delta = \frac{S_w a}{(a + 2r - 2 \sqrt{r^2 - x^2}) E} dx \quad (6)$$

Integrating,

$$\delta_r = \frac{S_w a}{E} \int_r^0 \frac{1}{(a + 2r - 2 \sqrt{r^2 - x^2})} dx$$

The expression is integrated by making the substitutions

$$M = \frac{a + 2r}{2r}$$

$$X = r \sin \theta$$

$$dx = r \cos \theta d\theta$$

Subsequently,

$$\delta_r = \frac{S_w a}{E} \left[\frac{\pi}{4} - \frac{M}{\sqrt{M^2 - 1}} \tanh^{-1} \frac{\sqrt{M^2 - 1}}{M - 1} \right]$$

where

δ_r represents the radial deformation of the hole.

$$\text{With } M = \frac{a + 2r}{2r} = \frac{0.0488 + 2 \left(\frac{0.219}{2} \right)}{2 \left(\frac{0.219}{2} \right)} = 1.2228$$

$$\delta_r = 0.06885 \frac{S_w}{E}$$

Substituting $S_w = 8450$ psi and $E = 10,000,000$ psi for aluminum,

$$\delta_r = 0.06885 \frac{(8450)}{10,000,000}$$

$$\delta_r = 0.000057 \text{ inch}$$

Hole diametral shrinkage, δ_d , is twice this value.

$$\delta_d = 2 (0.000057)$$

$$\delta_d = 0.000114 \text{ inch}$$

APPENDIX B
DISSIMILAR METAL WELD FLANGE ANALYSIS

APPENDIX B

DISSIMILAR METAL WELD FLANGE ANALYSIS

1.0 Location Analysis

During the quarter the outer case material was changed from 304 stainless steel to Inconel alloy 625. The hot frame material remained 304 stainless steel.

The objective of this analysis was to determine where the Inconel 625 to stainless 304 interface should occur. Figure B-1 shows the various interface possibilities with dimensions of flanges as used for PMC-1. Table B-1 shows the difference in thermal expansion at the pertinent temperatures. Note that the outer flange will always be the Inconel 625 which has the lower thermal expansion, thus placing the flange interface under pressure as the temperature rises.

For this analysis, the interface between the flanges (weld and flange lip; see Figure B-2) is rigid; thus the overall flange must strain to the extent of the difference in thermal expansion. The weld joint and the flange weld lips are analyzed in the second section of this appendix.

1.1 Outer Case - Support Cone (Figure B-1a)

The support cone flange (0.28 x 0.31 in. cross section) is much weaker than the outer case flange and is assumed to do all the straining caused by difference in thermal expansion. The resulting stress in the 304 stainless support cone, if there is a dissimilar metal joint, is calculated from:

$$\begin{aligned}\text{Stress} &= \text{Modulus} \times \text{strain} = 28.2 \times 10^6 \times 0.3125 \times 10^{-3} = 8.8 \times 10^3 \\ &= 8,800 \text{ psi}\end{aligned}$$

This is an acceptable value since it is considerably lower than the limit specified in Table B-1.

1.2 Hot Frame - Support Cone (Figure B-1b)

The hot frame thin wall is a weak flange and considered to do all the straining. The resulting stress in the hot frame thin wall, if there is a dissimilar metal joint, is then

$$\begin{aligned}\text{Stress} &= \text{modulus} \times \text{strain} \\ &= 26.4 \times 10^6 \times 1.06 \times 10^{-3} \\ &= 28 \times 10^3 \text{ or } 28,000 \text{ psi}\end{aligned}$$

This value is approaching the typical value of 35,000 psi in Table B-1 and therefore is considered marginal.

1.3 Outer Case - Lower Cover (Figure B-1c)

Same as for preceding calculation of outer case - support cone (lower cover is weak flange)

$$\text{lower cover stress} = 8,800 \text{ psi}$$

This is an acceptable stress (see 1.1).

1.4 Hot Frame - Lower Cover (Figure B-1d)

Again the hot frame is a weak flange and here stress = modulus x strain

$$\begin{aligned}&= 22.5 \times 10^6 \times 2.48 \times 10^{-3} \\ &= 55.8 \times 10^3 = 55,800 \text{ psi}\end{aligned}$$

This value exceeds the typical yield stress of 35,000 psi and therefore, is considered unacceptable.

1.5 Conclusion

Locate dissimilar metal joint at outer case interfaces.

2.0 Weld and Weld Lip Analysis

In Section 1, the flange interface assumed for the dissimilar metal joints is shown in (Figure B-2, theoretical). Because the normal flange interface has a gap (Figure B-2, normal) the stress/strain loads caused by differential thermal expansion must be transferred across the flange interface through the offset flange "weld lips" and "weld bead". The analysis of the stress/strain in the weld lips and weld bead for the acceptable dissimilar metal joints (outer case - support cone and outer case - lower cover) is the objective of Section 2.

2.1 Outer Case - Support Cone (Figure B-1a and B-2b)

2.1.1 Interface Pressure

The interface pressure results from restraining the differential thermal expansion of the support cone (weakest flange). The pressure is calculated using the formula -

$$P = \frac{2F}{D}$$

Where

P is the interface pressure - (lbs per inch) of circumference

D is the interface diameter

F is the circumferential force (lbs) which equals support cone stress (lbs/in²) times area (in²)

Substituting

$$D = 9.23 \text{ inches}$$

$$F = SA$$

Where

$$S = 8,800 \text{ lbs/in}^2 \text{ (see Table B-1)}$$

$$A = (0.28 \times 0.31) + (2.0 \times 0.025) = 0.137 \text{ in}^2$$

$$F = 8,800 \times 0.137 = 1205 \text{ lbs}$$

$$P = \frac{2 \times 1205}{9.23} = 262 \text{ lbs per inch}$$

2.1.2 Weld Bead Bearing Stress

The weld bead will directly counteract the interface pressure for a possible loading condition, whereas the support cone flange and weld lip are rigid (no strain) members. For this load condition, the weld bead stress is the interface pressure (262 lbs per inch) divided by the matching weld bead area. The weld bead depth (Figure B-2) is $3/4 \times 0.045 = 0.0337$ inch. The bead stress then equals

$$\frac{262 \text{ lbs}}{0.0337 \times 1.0} = 7,780 \text{ lbs/in}^2$$

2.1.3 Weld Bead and Weld Lip Bending Stress

As the weld bead is offset from the action line of the interface pressure, moment (pressure times offset distance) must also be counteracted. The weld lip then becomes a cantilever beam fixed at the flange and guided at the weld bead for a possible second condition of loading. Here it will be assumed that the interface radius is large and the beam is then the lip thickness (0.045 in) by 1" in cross-section and 0.120 in. in length.

2.1.3.1 Weld Lip Stresses

The maximum stress occurs at both ends and is calculated from equation

$$s_b = \frac{Wl}{2Z}$$

Where

s_b is maximum bending stress extreme fiber (lbs/in²)

W is load (lbs) = 262 lbs

l is length (inches) = 0.120 inches

Z is section modulus = $\frac{bd^2}{6}$

Where

b = 1 inch and d = 0.045 inch

Giving

$$Z = \frac{1 \times 0.045 \times 0.045}{6} = 0.000338 \text{ in}^3$$

Solving for s_b

$$s_b = \frac{262 \times 0.120}{2 \times 0.000338} = 46,500 \text{ lbs/in}^2$$

This exceeds the value of 42,000 psi in Table B-1.

As the stress level is shown to be marginal in the weld lip, another possibility exists that the lip deflection (Y) is sufficient to reduce the thermal restraint pressure load (W).

The lip deflection is calculated by equation $Y = \frac{Wl^3}{12EI}$ where

Y = deflection of web (inch)

W = Pressure load (lbs) = 262

$$\begin{aligned}
l &= \text{web length (inch)} &= 0.120 \\
E &= \text{Material modulus of elasticity (lbs/in}^2\text{)} &= 28 \times 10^6 \\
I &= \text{Cross section moment of inertia (in}^4\text{)} \\
I &= \frac{bd^3}{12}
\end{aligned}$$

Where

$$\begin{aligned}
b &= 1.0 \text{ inch} \\
d &= 0.045 \text{ inch} \\
I &= \frac{1.0 \times (0.045)^3}{12} = \frac{0.000091}{12} = \frac{7.5}{10^6}
\end{aligned}$$

Solving for Y

$$Y = \frac{262 \times (0.12)^3}{12 \times \frac{7.5}{10^6}} = \frac{1.8}{104} = 0.00018''$$

This deflection is insignificant.

The deflection, under load (262 lbs) giving stresses of 46,500 psi, is only 10% of that required to relieve the interface restraint (0.00289 inch on dia.)

2.1.3.2 Weld Bead Stresses

The weld bead stress for this load condition is the direct bearing load (W) stress (7,780 lbs/in²) plus an additional moment ($\frac{Wl}{2}$) stress.

The moment of stress (S_m) is maximum at the outer fibers and is calculated from formula

Action = Reaction

$$\frac{Wl}{2} = \frac{2}{3} wF$$

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

Where

$$W = 262 \text{ lbs}$$

$$l = 0.120 \text{ inch}$$

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

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

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

Solving

$$\frac{262 \times 0.12}{2} = 2/3 \times 0.034 (1/2 S_m \times 1/2 \times 0.034 \times 1.0)$$

$$15.7 = 0.0226 (0.0085 S_m)$$

$$S_m = \frac{15.7}{0.0226 \times 0.0085} = 81,500 \text{ lbs/in}^2$$

This stress exceeds the typical value of 42,000 psi specified in Table B-1 and therefore is unacceptable.

Note: Total maximum - stress one edge fiber = 81,500 + 7,780 = 89,280 psi.

2.1.3.3 Comments

- a) The depicted outer case - support cone flange configuration having a normal interface gap would give stress beyond yield point, thus giving deformation of the weld lip and weld bead.
- b) One corrective flange configuration is the No-gap interface. This is covered in Section 3 of this appendix - i.e., force-fit interface for outer case - header ring (preliminary PMC-2 dissimilar metal weld flange).
- c) A second corrective flange configuration is to lengthen the weld lip to give deflection sufficient to relieve the restrained flange pressure. See next portion of this section (Section 2.2). Note: deflection varies as the cube of length!

2.2 Outer Case - Lower Cover (Figure B-1c and B-3)

A review of the referenced figures and Table B-1 data shows that the lower cover flange has the much smaller cross-section; therefore, it will be stressed/strained to compensate for the dissimilar metal thermal expansion difference.

From section 1.0 calculations, the straining is 0.3125×10^{-3} inch/inch or 2.89×10^{-3} inch for 9.25 dia. The strain per interface is $2.89 \times 10^{-3} \div 2 \cong 1.5 \times 10^{-3}$ inch.

By further reviewing the preceding section 2.0 analysis of flange stress/strains, it is noted that the lower cover flange can function only as a stressed beam of 0.045 inch depth, 1.0 inch width, and 0.36 length. The loading will be a distributed (restraining stress in flange) load and an end load (restraining stress in cover). The two loads are additive both as to deflection and max stress in flange and as to max stress in weld bead.

2.2.1 Interface Pressure

The interface pressure for both of the distinct cross-sections will be calculated and analyzed separately.

For the flange, the cross section according to Figure B-1c is 0.045" by 0.366" and is stressed to 8,800 psi (Table B-1). The resulting interface pressure is obtained by the formula

$$P = \frac{2F}{D}$$

Where

P is interface pressure (lbs) per inch of interface circumference

F = circumferential force for the flange (lbs) and equals flange stress x flange cross-section (8,800 psi) x (0.045 x 0.366)

= 145 lbs.

$$P = \frac{2 \times 145}{9.25} = 31.3 \text{ lbs per inch of circumference}$$

For the cover (flat) the cross-section is 0.020" by 2.0" and the stress is 8,800 psi. The resulting interface pressure is then

$$P = \frac{2F}{D}$$

Where

$$F = 8,800 \times \frac{(0.02 \times 2.0)}{0.04}$$

$$= 352 \text{ lbs}$$

$$P = \frac{2 \times 352}{9.25} = 76.0 \text{ lbs per inch of circumference}$$

2.2.2 Flange Bending Stress and Deflection (Gap Interface)

The flange is assumed to be a rectangular beam (0.045 depth, 1.0 width) with support conditions fixed at one end and guided at the other end having a distributive additive load of 31.3 lbs and a load of 76.0 lbs at the guided end.

Where

$$W_1 = \text{distributive load}$$

$$W_2 = \text{load at guided end}$$

2.2.2.1 Distributed Load

The bending stress due to the distributed load is given by the formula (maximum at either end):

$$\begin{aligned}
 S_{b1} &= \frac{WL}{3Z} \\
 &= \frac{31.3 \times 0.366}{3 \times 0.000337} \\
 &= 11,350 \text{ psi}
 \end{aligned}$$

Where

$$WL = \text{total load} = 31.3 \text{ lbs}$$

$$L = 0.366 \text{ in}$$

$$Z = \frac{bd^2}{6} = 1.0 \times \frac{0.045^2}{6} = 0.000337 \text{ in}^3$$

The deflection due to the distributed load is given by formula

$$Y_1 = \frac{W_1 L^3}{24 EI}$$

Where

$$W_1 = 31.3 \text{ lbs}$$

$$L = 0.366 \text{ in}$$

$$E = 28 \times 10^6 \text{ psi}$$

$$I = \frac{bd^3}{12} = \frac{1.0 \times (0.045)^3}{12} = \frac{7.5}{10^6} \text{ in}^4$$

$$Y_1 = \frac{31.3 \times (0.366)^3}{24 \times 28 \times 10^6} \times \frac{7.5}{10^6} = \frac{0.304}{10^3} \text{ inch}$$

2.2.2.2 Concentrated load at Guided End

The bending stress due to the concentrated load is given by the formula:

$$S_{b2} = \frac{W_2 L}{2Z}$$

Where

$$W_2 = 76.0 \text{ lbs}$$

$$L = 0.366 \text{ inch}$$

$$Z = 0.000337 \text{ in}^3$$

$$S_{b2} = \frac{76.0 \times 0.366}{2 \times 0.000337} = 41,300 \text{ psi}$$

This value approaches the value of 42,000 psi in Table B-1. Therefore, the design using this configuration would be marginal.

The deflection is given by the formula:

$$Y_2 = \frac{W_2 L^3}{12EI}$$

Where

$$W_2 = 76.0 \text{ lbs}$$

$$L = 0.366 \text{ inch}$$

$$E = 28 \times 10^6 \text{ psi}$$

$$I = \frac{7.5}{10^6} \text{ in}^4$$

$$Y_2 = \frac{76.0 \times (0.366)^3}{12 \times 28 \times 10^6} \times \frac{7.5}{10^6} = \frac{1.48}{10^3} \text{ inch}$$

2.2.2.3 Combined stress/deflection and comments:

The combined stress $S_b + S_{b2}$ gives $11,350 + 41,300 = 52,650$ psi which is noted to be unsatisfactory since it will yield or deform the flange. However, the combined deflection $Y_1 + Y_2$ gives $\frac{0.3 + 1.48}{10^3} = 0.00178$ inch which is noted to be sufficient to relieve the restrained flange stress due to thermal expansion differences.

The exact solution to the actual stress and deflection can be approximated by assuming only partly restrained and by checking to assure that deflection and stresses (bending) are satisfactory.

2.2.2.4 Partly Restrained (0.5)

The interface pressure loads are then reduced 0.5 for the concentrated load and 0.25 for the distributed load:

Giving

$$W_1 = 31.3 \times 0.75 = 23.4 \text{ lbs}$$

$$W_2 = 76.0 \times 0.5 = 38.0 \text{ lbs}$$

as the new loads for the flange in bending.

The stresses and deflections are reduced by similar ratios also.

Giving

$$S_{b1} = 11,350 \times 0.75 = 8,500 \text{ psi}$$

$$S_{b2} = 41,300 \times 0.5 = \underline{20,600 \text{ psi}}$$

$$\text{Total } S_b = 29,100 \text{ psi}$$

This is considerably below the typical yield stress of 42,000 psi in Table B-1; and therefore, is acceptable for the converter design

and

$$Y_1 = 0.000304 \times 0.75 = 0.000228$$

$$Y_2 = 0.00148 \times 0.5 = \underline{0.000740}$$

$$\text{Total } Y = 0.000968 \text{ in.}$$

This is considerably over 1/2 of the restrained dimension of 0.0015" (1-0.5) or 0.00075" and therefore, a subsequent iteration was conducted at a restraint of 0.44.

2.2.2.5 Partly Restrained (0.44)

A closer analysis of the flange is possible by noting that the relationships are linear functions.

Selecting a 44% restraint gives

$$W_1 = 31.3 \text{ lbs} \times 0.72 = 22.5 \text{ lbs}$$

$$W_2 = 76.0 \text{ lbs} \times 0.44 = 33.4 \text{ lbs}$$

as the new loads for the flange (in bending).

A check on the deflection (Y) of the beam to the movement to obtain reduced restraint gives

$$Y_1 = 0.0003 \times 0.72 = 0.000216 \text{ in}$$

$$Y_2 = 0.00148 \times 0.44 = \underline{0.000651 \text{ in}}$$

$$\text{Total Y} = 0.000867 \text{ in}$$

versus restraint

$$0.0015 (1-0.44) = 0.0015 \times 0.56 = 0.00084 \text{ in}$$

In this calculation, the deflection and the restraint are nearly equal; therefore this set of values is satisfactory for the converter design.

$$S_{b1} = 11,350 \text{ lbs/in}^2 \times 0.72 = 8,170 \text{ lb/in}^2$$

$$S_{b2} = 41,300 \text{ lbs/in}^2 \times 0.44 = \underline{18,200 \text{ lb/in}^2}$$

$$\text{Total Sb} = 26,370 \text{ lbs/in}^2$$

This value is less than the 29,100 psi value; therefore, it too is acceptable for the converter design.

2.2.3 Weld Bead Stress (Gap Interface)

The weld bead stress consists of four parts which are additive for obtaining a maximum fiber stress. The four parts are (ref. 2.2.2.5 for values)

- (1) Direct bearing caused by W_1

$$W_1 = 22.5 \text{ lbs}$$

- (2) Direct bearing caused by W_2

$$W_2 = 33.4 \text{ lbs}$$

- (3) Moment load caused by W_1

$$M_1 = \frac{W_1 L}{3}$$

- (4) Moment load caused by W_2

$$M_2 = \frac{W_2 L}{2}$$

Note: $L = 0.366 \text{ inch}$

The weld bead penetration is again $0.75 \times 0.045 \text{ flange thickness} = 0.034 \text{ inch}$, and the weld bead length (by assumption) is 1.0 inch.

2.2.3.1 Direct Bearing Stress

The direct bearing loads W_1 and W_2 are transmitted across the interface by the weld bead having cross section area of $0.034 \times 1.0 = 0.034 \text{ in}^2$. The bearing stress is $S_w = (W_1 + W_2) \div 0.034 = \frac{22.5 + 33.4}{0.034}$

$$S_w = \frac{55.9}{0.034} = 1,640 \text{ lbs/in}^2$$

Compressive

2.2.3.2 Moment Stress

The moment (M₁ and M₂) are

$$M_1 = \frac{W_1 L}{3} = \frac{22.5 \times 0.366}{3} = 2.75 \text{ in-lbs}$$

$$M_2 = \frac{W_2 L}{2} = \frac{33.4 \times 0.366}{2} = 6.1 \text{ in-lbs}$$

The total moment equals M₁ + M₂ giving

$$M = 2.75 + 6.1 = 8.85 \text{ in-lbs}$$

Assuming triangular loading, then the reaction forces (F) have a moment arm of 2/3 weld bead penetration giving

$$M = F \times 2/3 (0.034) = 0.02265 F$$

and

$$F = \frac{M}{0.02265} = \frac{8.85 \text{ in-lbs}}{0.02265 \text{ in}} = 391 \text{ lbs}$$

The stress triangle to develop force (F) is given by

$$\begin{aligned} F &= S_{avg} \times A \\ &= (1/2 S_m \frac{0.034}{2}) \times (\frac{0.034}{2} \times 1.10) \\ 391 &= \frac{0.034 \times 0.034}{8} S_m \end{aligned}$$

and

$$S_m = \frac{391 \times 8}{0.034 \times 0.034} = \frac{3,130}{0.001155} = 3,130,000/\text{lbs}/\text{in}^2$$

This shows a definite need for increasing weld bead penetration to prevent weld deformation during thermal cycling.

2.2.3.3 Weld Bead Penetration

For a gap interface, the weld bead was shown to be over-stressed by the flange bending moment. (Ref 2.2.3.2)

An acceptable weld penetration for counteracting the flange moment is given by iterations on

$$\begin{aligned} M &= F \times 2/3 p \\ F &= (1/2 S_m \times p/2) \times (P/2 \times 1.0) \end{aligned}$$

Where S_m assumed to be 25,000 lbs/in² and $M = 8.85$ in lbs.

Combining

$$M = 0.67p \frac{(S_m \times p)}{4} (\frac{p}{2})$$

Substituting

$$8.85 = 0.67p (\frac{25,000}{4} p) (P/2)$$

Transferring

$$\frac{8 \times 8.85}{67 \times 25,000} = P^3 = \frac{4.23}{1000} = \frac{4.23}{10^3}$$
$$P = \frac{1.63}{10} = 0.163 \text{ inch}$$

3.0 Preliminary PMC-2 Dissimilar Metal Joints

Figure B-3 shows sketches of the preliminary weld joints which are detailed for use in the present development program (fabrication outer case and mating components).

3.1 Outer Case - Header Ring

The outer case header ring is a new interface configuration to be developed for PMC-2. Here the outer case flange is of the smaller cross section; and also the interface is proposed to be a press fit of 0.001 to 0.003 on the 9.25 diameter. This assembly restraint adds to the dissimilar thermal expansion of roughly 0.003 giving a 0.006" restraint at 200°F operating temperature.

The outer case flange strain (in/in) is then 0.006 restraint ÷ 9.25 diameter which is 0.00065 in/in.

The stress in the flange is then the strain times the modulus giving

$$0.00065 \text{ in/in times } 29.2 \times 10^6 \text{ lbs/in}^2$$
$$0.65 \times 10^{-3} \times 29.2 \times 10^6 = 18.95 \times 10^3$$
$$\text{stress} = 18,900 \text{ psi}$$

The interface restraint load is directly bearing on the flanges and does not produce large magnitude weld bead stress.

3.2 Outer Case - Lower Cover

The outer case - lower cover interface is essentially identical to that of prior units (PMC-1). The interface loads, stresses, strains, etc., were analyzed in the 2.2 sections of this appendix. As shown, the weld bead is overstressed. The most likely change will be to use a press-fit interface.

Figure B-1
Flange Configuration

(a) Top - Outer

(b) Top - Inner

(c) (Bottom - Outer)

(d) (Bottom - Inner)

Table B-1
Materials Properties

Temperature (°F)			
Operating -	200	500	1200
Ambient -	75	75	75
Δ T -	125	425	1125
Reference Figure B-1	Figure B-1a and B-1c	Figure B-1b	Figure B-1d
Mean Coef. of Expan. over Δ T (in/in - °F)			
304 Stainless	9.6×10^{-6}	9.9×10^{-6}	10.4×10^{-6}
625 Alloy	7.1×10^{-6}	7.4×10^{-6}	8.2×10^{-6}
Δ Coef.	2.5×10^{-6}	2.5×10^{-6}	2.2×10^{-6}
Diff. in Expansion(in/in)	0.3125×10^{-3}	1.06×10^{-3}	2.48×10^{-3}
Interface Dia. (in.)	9.23	3.79	3.79
Diff. in Dia. Change at Operating Temp.	2.89×10^{-3} in.	4.02×10^{-3} in.	9.4×10^{-3} in.
Modulus of Elast. (E) (Tensile) PSI			
304 Stainless	28.2×10^6	26.4×10^6	22.5×10^6
625 Alloy	29.2×10^6	28.0×10^6	24.4×10^6
Yield Stress (Type) (0.2% Tension) PSI			
304 Stainless	42,000	35,000	20,000
625 Alloy	56,000	50,000	37,000
Weak Flange Stress (PSI)	Support Cone 8,800	Lower Cover 8,800	Hot Frame 55,800
Comment	OK	OK	Very marginal Unacceptable

Figure B-2
 Typical Weld and Weld-Lip Configuration
 (Approximate Scale 10X) - Ref: Section 1.0 and Fig. B-1a

Figure B-3
 PMC-2 Preliminary Weld Joint Configuration
 (Approximate Scale 4X)

APPENDIX C
STRESS ANALYSIS OF SUPPORT CONE FOR PMC-2

APPENDIX C

STRESS ANALYSIS OF SUPPORT CONE FOR PMC-2

Reduction in outer diameter and change in cone angle from 30° to 45° was used in the revised analysis and is found on succeeding pages.

Conclusion:

Since all margins of safety were found to be greater than before, it is concluded that the new design will be satisfactory. Those values marked with an * are the margin of safety for the previous cone design (EMC-1, EMC-2, EMC-3, and PMC-1).

SNAP-23A REDESIGN

Stress Analysis of Cone

Design factor = 2.0 based on 1.5 basic safety factor with 0.85 reduction factor is allowable for fatigue and 1.062 magnification factor for vibration.

$\frac{1.5 \times 1.062}{0.85} = 1.875$ which has been arbitrarily increased to 2.0 for convenience. An increase in weight of the supported system to 120 lbs will be assumed.

For a 10 g load factor, the design yield load becomes $2 \times 10 \times 120 = 2400$ lbs.

For the vertical direction, this load is applied uniformly (w_o psi) around the circumference of the outer cylinder as shown in Figure C-1, resisted by uniform reaction around the inner cylinder.

The forces shown in Figure C-1 can be reversed if acceleration is in opposite direction.

Load in median direction of cone (along element at radius $r_o = 3.61$)

$$q_o = \frac{W_o}{\sin 45^\circ} = \frac{106}{0.707} = 150 \text{ lb/in (153.4')})$$

$$\text{stress } f_o = \frac{q_o}{t} = \frac{150}{0.025} = 6000 \text{ psi T (6140')})$$

at radius $r_i = 2.01$

$$q_i = \frac{W_i}{\sin 45^\circ} = \frac{190}{0.707} = 269 \text{ lb/in (382')})$$

$$f_i = \frac{269}{0.025} = 10,750 \text{ psi T (15,280')})$$

T indicates tension, C indicates compression.

The above values assume 0.025" thickness all the way to the ring center-lines. To be correct at the 0.025" thickness, use ratios

$$\frac{3.61}{3.61 - 0.37} \text{ for } f_o \quad \text{and} \quad \frac{2.01}{2.01 + 0.25} \text{ for } f_i$$

$$f_o = 1.114 \times 6000 = 6680 \text{ psi T (the 6140' was at center line of ring in original analysis)}$$

$$f_i = 0.89 \times 10750 = 9560 \text{ psi T (15,280')})$$

Internal pressurization due to change in altitude.

$$p = 30.2 \text{ psi}$$

$$\text{Cone hoop stresses will be } f_h = \frac{p_r}{t \sin 45^\circ}$$

Figure C-1
Load Diagram
of
SNAP-23 PMC-2 Converter Design

$$W_o = \frac{2400}{2 \times 3.1416 \times 3.61} = 106 \text{ lb/in} \quad W_i = \frac{2400}{2 \times 3.1416 \times 2.01} = 190 \text{ lb/in}$$

At radius $r_o = 3.61 - 0.37 = 3.24$

$$f_{H_o} = \frac{30.2 \times 3.24}{0.025 \times 0.707} = 5,530 \text{ psi T (11,220*)}$$

At radius $r_i = 2.01 + 0.25 = 2.26$

$$f_{H_i} = \frac{30.2 \times 2.26}{0.025 \times 0.707} = 3,880 \text{ psi T (4,520*)}$$

Cone meridional stresses are given by

$$f_M = \frac{p_r}{2t \sin 45^\circ}$$

at $r_o = 3.24$

$$f_{M_o} = \frac{30.2 \times 3.24}{2 \times 0.025 \times 0.707} = 2,765 \text{ psi T (5,610*)}$$

at $r_i = 2.26$

$$f_{M_i} = \frac{30.2 \times 2.26}{2 \times 0.025 \times 0.707} = 1,940 \text{ psi T (2,260*)}$$

Total meridional stress = $f_m + \frac{q}{t}$

at $r_o = 3.24$

$$f_{x_o} = 2765 + 6680 = 9,445 \text{ psi T (11,750*)}$$

at $r_i = 2.26$

$$f_{x_i} = 1940 + 9560 = 11,500 \text{ psi T (17,540*)}$$

Hoop stress $f_\phi = f_{II}$

$$f_{\phi_o} = 5,300 \text{ psi T (see } f_{II_o} \text{)}$$

$$f_{\phi_i} = 3,880 \text{ psi T (see } f_{II_i} \text{)}$$

Stresses are combined in accordance with "Maximum Distortion Energy Theory" (Hencky-VonMises)

$$f = (f_x^2 + f_\phi^2 - f_x f_\phi)^{1/2}$$

$$f_o = (9445^2 + 5530^2 - 9445 \times 5530)^{1/2} = 8,200 \text{ psi T (11,500*)}$$

$$f_i = (11500^2 + 3880^2 - 11500 \times 3880)^{1/2} = 10,130 \text{ psi T (15,750*)}$$

At r_o the temperature will be approximately 200°F. From the curves of Figure C-2, the allowable yield stress is $0.82 \times 30,000 = 24,600$ psi. Similarly, for an estimated 500°F temperature at r_i , allowable yield stress = $0.65 \times 30,000 = 19,500$ psi.

$$\text{at } r_o = 3.24, \text{ M.S.} = \frac{24,600}{8,200} - 1 = + 2.00 (1.10*)$$

$$\text{at } r_i = 2.26, \text{ M.S.} = \frac{19,500}{10,130} - 1 = + 0.925 (0.16*)$$

On the most conservative basis, neglecting pressurization internally and reduced atmospheric pressure externally,

$$\text{at } r_o = 3.24, \text{ M.S.} = \frac{24,600}{9,445} - 1 = + 1.61$$

$$\text{at } r_i = 2.26, \text{ M.S.} = \frac{19,500}{11,500} - 1 = + 0.70$$

For acceleration acting in opposite direction, pressure-induced stresses will be identical to those above. Acceleration-induced stresses will be compression in cone meridional direction.

$$\text{at } r_o = 3.24, \text{ net meridional stress} = -6680 + 2765 = 3915 \text{ psi C}$$

$$f_{H_o} = 5530 \text{ psi T (see page C-4)}$$

The yield allowable values for tension and compression are different; therefore, the more fundamental concept in the combined stress formula using "stress ratios" is considered:

Figure C-2
Effect of Temperature on Yield Strength of Annealed Series 300 Corrosion Res. Steel

$$M.S. = \frac{1}{(R_x^2 + R_y^2 - R_x R_y)^{1/2}} - 1 > = 0$$

$$R_x = \frac{f_x}{F'} \text{ and } R_y = \frac{f_y}{F''}$$

From curves of Figure C-2, the tension allowable (at 200°F) $F' = 24,600$ psi and the compression allowable (at 200°F) $F'' = 31,500$ psi.

$$R_x = \frac{5,530}{24,600} = 0.225 \quad R_y = \frac{-3,915}{31,500} = -0.124$$

$$M.S. = \frac{1}{[(0.225)^2 + (-0.124)^2 - (0.225)(-0.124)]^{1/2}} - 1 = +2.88 (1.20^*)$$

$$\text{At } r_i = 2.26, f_{H_i} = 3880 \text{ psi T (see page C-4)}$$

$$\text{Net meridional stress } f_{M_i} = -9560 + 1940 = 7620 \text{ psi C}$$

For the 500°F temperature, $F' = 19,500$ and $F'' = 25,200$

$$R_x = \frac{3,880}{19,500} = 0.199 \quad R_y = \frac{-7,620}{25,200} = -0.301$$

$$M.S. = \frac{1}{[(0.199)^2 + (-0.301)^2 - (0.199)(-0.301)]^{1/2}} - 1 = +1.29 (0.42^*)$$

With no pressure differential:

$$\text{at } r_o = 3.24; f_{M_o} = \frac{q_o}{t} = -6680 \text{ psi (compression)}$$

$$M.S. = \frac{31,500}{6,680} - 1 = +3.72 (4.23^*)$$

$$\text{at } r_i = 2.26; f_{M_i} = \frac{q_i}{t} = -9560 \text{ psi (compression)}$$

$$M.S. = \frac{25,200}{9,560} - 1 = +1.64 (0.56^*)$$

Cone Buckling Strength

Only the case with zero pressure differential will be checked since it is most critical: internal pressure stabilizes a shell against buckling; also for acceleration induced compression-loading the net meridional stress is reduced by pressurization (internal, that is).

Allowable axial compression load is given by $P_{cr} = 2\pi C E' t^2 \cos^2 \alpha$.

"C" is from curve of Figure C-3, for $\frac{r}{t \cos \alpha}$ where "r" is the radius at small end of cone (r_i), then

$$\frac{r_i}{t \cos \alpha} = \frac{2.26}{0.025 \times 0.707} = 127.8, \text{ and } C = 3.25$$

$E' = \sqrt{E_T E_S}$ where E_T = tangent modulus and E_S = secant modulus.

Both can be found from the curves of Figure C-5, after establishing the stress level. We will conservatively use the highest stress level (at inner radius) as a uniform value. Also the secant and tangent moduli must be reduced for temperature effects. Again we adopt a very conservative approach and use the 500°F temperature to be found at the inner radius. Correction curves for temperature are on Figure C-5.

$$\text{at } r_i = 2.26; f_{M_i} = 9560 \text{ psi } C$$

From Figure C-4, $E_T = 2.8 \times 10^7$ psi and $E_S = 2.8 \times 10^7$ psi.

Temperature correction is $\frac{25.6 \times 10^6}{2.8 \times 10^7} \times 2.8 \times 10^7 = 2.56 \times 10^7$ psi

$$\sqrt{E_S E_T} = 2.56 \times 10^7 \text{ psi} = E' \text{ for our case.}$$

$$P_{cr} = 2 \times 3.1416 \times 0.325 \times 2.56 \times 10^7 \times (0.025)^2 (0.707)^2$$

$$= 16,320 \text{ lbs (7,580*)}$$

Design axial load = 2400 lbs (page C-2)

$$\text{M.S. against cone buckling} = \frac{16,320}{2,400} - 1 = +5.8 \text{ (2.38*)}$$

Figure C-3
Critical Buckling Loads for Cones in Compression

Figure C-4
 Stress vs Tangent and Secant Modulii Typical for Types
 304 and 347 Cres. at Room Temperature for Plate or
 Bar Stock in Compression in Transverse Direction

Figure C-5
Modulus of Elasticity vs Temperature Types 304 and 347
Corrosion Res. Steel

Strength of cone-rings in resisting radial loading:

Note: Hoop stresses in the cone do not require an external reaction as do the meridional stresses.

For the lower ring (outer) we use $r_o = 3.61$ which is the radius to the centroid of the ring cross section. For the tension loading case, total equivalent meridional stress = $9445 \times \frac{3.24}{3.61} = 8500$ psi.

Load per inch at r_o circumference = $tr = 0.025 \times 8500$ (since $t = 0.025$ was used for determining stresses originally) = 213 lb/in at 45° to the horizontal direction. In the plane of the ring, inward acting radial loading = $213 \cos 45^\circ = 213 \times 0.707 = 150$ lb/in.

$$\text{Stress in ring} = \frac{P r_o}{A} = \frac{150 \times 3.61}{0.0871} = 6220 \text{ psi (12,800*) } C$$

Allowable compression yield at $200^\circ F = 31,500$ psi

$$M.S. = \frac{31,500}{6,220} - 1 = + 4.06 \text{ (1.51*)}$$

Stability of ring against compression buckling

$$P_{cr} = \frac{3 E' I}{r_o^3} = \frac{3 \times 2.74 \times 10^7 \times 5.73 \times 10^{-4}}{(3.61)^3} = 1025 \text{ lb/in (532*)}$$

Stress is low; so $E' = E_T = E_S$ and the correction for $200^\circ F$ temperature are used to give the above value.

Actual loading 150 lb/in

$$M.S. = \frac{1025}{150} - 1 = + 5.83 \text{ (1.09*)}$$

For the upper ring $r = r_i = 2.01$ at ring cross section centroid.

$$A = 0.0484 \text{ in}^2; I = 1.95 \times 10^{-4} \text{ in}^4$$

The loading condition to produce compression of the ring is the reverse of the one above, i.e., acceleration-induced load must be compression; hence we use 269 lb/in (from page C-2, neglecting pressurization which would reduce the value.

Ring stability against buckling

Radial load in plane of ring = $0.707 \times 269 = 190$ lb/in

$$\text{Ring stress} = \frac{P r_i}{A} = \frac{190 \times 2.01}{0.0484} = 7900 \text{ psi (14,900*)}$$

and the allowable elastic yield stress at $500^\circ\text{F} = 25,200$ psi, therefore, the M.S. against elastic yield = $\frac{25,200}{7,900} - 1 = 2.2$ (0.60*)

This ring stress is low enough so that $E' = E_T = E_S$ and, at 500°F the value of $E' = 2.56 \times 10^7$ psi and $I = 1.95 \times 10^{-4}$

$$\text{then } P_{cr} = \frac{3 \times 2.56 \times 10^6 \times 1.95 \times 10^{-4}}{(2.01)^3} = 1840 \text{ lb/in (1480*)}$$

Actual design loading = 190 lb/in

$$\text{M.S.} = \frac{1840}{190} - 1 = + 8.3 \text{ (3.47*)}$$

The tension condition on the upper ring with combined meridional stress = 11,500 psi (from page C-4), the equivalent stress level at $r_i = 2.01$ will be $\frac{2.24}{2.01} \times 11,500 = 12,800$ psi.

In the plane of the ring, $P = \frac{0.707 \times 12,800 \times 0.025}{1} = 226$ lb/in

$$f = \frac{2.26 \times 2.01}{0.0484} = 9,400 \text{ psi (17050*)}$$

At 500°F , allowable tension = 19,500 psi

$$\text{M.S.} = \frac{19,500}{9,400} - 1 = + 1.08 \text{ (0.07*)}$$

APPENDIX D
PRELIMINARY STRUCTURE HEAT LOSS

APPENDIX D

PRELIMINARY STRUCTURE HEAT LOSS

Upper and Lower Surface Temperature Analysis

The SNAP-23A Converter is designed so that all shunt heat losses are confined to a radial or horizontal direction with respect to the vertical axis of the converter. With the converter mounted on the heat spud, converter performance characteristics are based on an adiabatic (perfectly insulated) boundary for all exposed support cone, lower cover, hot frame, assembly bolt, and assembly washer surfaces. Surface temperatures at intermediate points along the exposed surfaces can be calculated after the heat flow rates along the paths are determined. The intermediate temperatures must be known for estimating yield stresses and are also of value when estimating external converter heat flow in the vertical direction. Therefore, this analysis is concerned with the intermediate temperature calculations. Figure D-1 shows the system interface temperature and the calculated intermediate temperatures. Also shown is the direction of heat flow in the upper and lower converter surfaces; the upper surface consists of the upper hot frame cylinder and support cone.

Upper Surface

As noted in Figure D-1, the hot frame temperature at the thick threaded section is 1110° F at BOL. Starting at this point, the heat travels upward through the thin walled cylindrical portion of the hot frame (referred to as upper hot frame

Figure D-1
Converter Surface Temperatures

cylinder in Figure D-2) after which the heat moves radially outward through the thin walled support cone. The final temperature at the outer ring of the support cone is 161°F at BOL*. The thermal resistance of each portion of this series circuit must be calculated before the heat flow rate and the intermediate temperature at the hot frame/support cone junction can be determined. The thermal resistance of the upper hot frame cylinder is calculated with reference to Figure D-2, which shows the dimensions.

Figure D-2
Sketch Showing the Upper Hot Frame Cylinder Dimensions

*Because of the large thick sections on the outer case, it is assumed that the temperature along the outer case is the same as the fin base temperature.

Letting R_f be the thermal resistance of the upper hot frame cylinder,

$$R_f = \frac{l}{t\pi D_M k}$$

where

t = wall thickness in feet

D_M = mean cylinder diameter in feet

l = cylinder length in feet

k = thermal conductivity for stainless steel and is equal to
11.2 Btu-ft/ft²hr-°F

R_f = 10.86 hr-°F/Btu

A textbook formula is not available for calculating the thermal resistance of the support cone and is therefore derived as follows. The formula is derived with reference to Figure D-3.

Figure D-3
Support Cone Thermal Resistance Calculation Parameters

Considering the heat flowing through a small ring section having length, $d\ell$, and a radius, r , the heat flow rate is given by the relation:

$$q = \frac{t \, 2\pi r \, k \, dT}{d\ell}$$

where k is the thermal conductivity of the material and dT is the temperature drop across the ring element.

To put r in terms of ℓ and the known dimensions r , ℓ_o and r_2 , it is noted from similar triangles that:

$$\frac{\ell}{r - r_1} = \frac{\ell_o}{r_2 - r_1}$$

Substituting and separating variables,

$$\int_{\ell_o}^o \frac{d\ell}{\frac{r_2 - r_1}{\ell_o} \ell + r_1} = \int_{T_2}^{T_1} \frac{-t \, 2\pi k \, dT}{q}$$

Integrating,

$$\frac{\ell_o}{r_2 - r_1} \ell_n \frac{r_2}{r_1} = \frac{t \, 2\pi k (T_1 - T_2)}{q}$$

Solving for q ,

$$q = \frac{t \, 2\pi k (T_1 - T_2)}{\ell_n \frac{r_2}{r_1}} \cdot \frac{r_2 - r_1}{\ell_o}$$

Resistance can now be isolated from the derived equation for q since q is defined by the relation:

$$q = \frac{T_1 - T_2}{R}$$

Equating and letting support cone resistance be designated as R_s ,

$$\frac{T_2 - T_1}{R_s} = \frac{t \cdot 2\pi k (T_1 - T_2)}{\ln \frac{r_2}{r_1}}$$

From which

$$R_s = \frac{\ln \frac{r_2}{r_1}}{2\pi k t} \cdot \frac{1}{\ln \frac{r_2}{r_1}}$$

The numerical values for the above resistance equation terms are shown in Figure D-4.

Figure D-4
Sketch Showing Support Cone Thermal Resistance Numerical Values

Letting k equal 11.2 and substituting the numerical values from Figure D-4,

$$R_s = 4.59 \frac{\text{hr} \cdot ^\circ \text{F}}{\text{Btu}} \text{ for the PMC-2 design.}$$

The heat flow rate in the upper surface series circuit can now be calculated. For this circuit, heat flow rate is found by the relation:

$$q = \frac{T_1 - T_3}{R_f + R_s}$$

where T_1 is the temperature at base of the upper hot frame cylinder and is equal to 1110°F at BOL. T_3 is the temperature at the outer edge of the support cone and is equal to 161°F at BOL. This temperature has been designated as T_3 since T_2 is being reserved for the intermediate temperature designation.

$$q = 61.5 \frac{\text{Btu}}{\text{hr}} \text{ or } 18.0 \text{ watts}$$

This heat loss of 18.0 watts compares with a loss of 15.4 watts with the previous cone configuration.

The intermediate temperature, T_2 , is found from the relation:

$$q = \frac{T_1 - T_2}{R_f}$$

$$\text{or } T_2 = 442^\circ\text{F at BOL}$$

When EOL temperatures (925° and 144° F) are substituted for T_1 and T_3 in the above equations, the heat flow rate is 50.5 Btu per hour (14.8 watts) and T_2 is equal to 374° F. This heat loss of 14.8 watts compares with a loss of 12.7 watts with previous cone configuration.

APPENDIX E
INSULATION STRIP PINNING

APPENDIX E

INSULATION STRIP PINNING

Couple Alignment Analysis (Figures E-1 and E-2)

Couple alignment was a major design consideration because proper operation of the thermoelectric legs and couples depends on the leg being positioned such that good contact is maintained at all times between the leg hot end and hot junction button. The couple hot junction is a flat, butt-type joint; any loss of edge contact due to cocking would tend to decrease the thermal heat transfer area and increase electrical contact resistance.

Proper contact, in turn, is dependent on minimum misalignment in both the hot and cold conditions and minimum relative motion between the cold frame and the electrical insulation (boron nitride strips) during the initial heating period.

Thermal expansion of the boron nitride strips in the vertical (axial direction) is negligible compared to the hot frame expansion. Since the hot junction end of the legs must follow the boron nitride strips during expansion, it is desirable that the strips be anchored to the hot frame at a point that has no relative motion with respect to the cold frame (which guides the cold junction end of the legs). The cold frame expands a small amount in the vertical direction with respect to the boron nitride strips. To distribute the misalignment evenly between the upper and lower couples, the vertical midpoint of the cold frame (Figure E-1) is the point selected as having zero relative motion with respect to the boron nitride anchoring point on the hot frame.

Figure E-1
Sketch Showing Thermoelectric Couple Alignment Parameters

The boron nitride anchor point was found by iterative type calculations. The final calculations which located the anchor point shown in Figure E-1 are presented in this analysis.

The welded joint between the support cone and hot frame is selected as the fixed reference point. All parts move downward with respect to this fixed reference point. The distance of the cold frame midpoint from the fixed reference point is the summation of dimensions a, b, and c. It is desirable that the combined thermal expansion of dimensions a, b, and c equals the thermal expansion of dimension f. The expansion of the support cone in the downward direction (change in dimension a) is complicated by the two thickened rings which act as stiffeners for the thin (0.025 inches thick) section of the cone. The outer ring, being cooler, does not expand at the same rate as the inner ring and the thin portion; therefore, the cone angle changes during thermal expansion. This change in cone angle causes a considerable increase in dimension, a, compared to a simple linear expansion. The expanded dimension, a, is found by first calculating the expansion of the rings and thin section separately and then reassembling the three pieces to form a cone with a steeper angle. The support cone will be analyzed with reference to Figure E-2 which shows the dimensions involved in the calculation of an expanded a-dimension.

Figure E-2
Support Cone Sketch Showing Dimension Parameters

The expanded length for each dimension must be calculated before dimension a can be determined for the hot condition. Table E-1 lists the dimensions in the cold condition.

Table E-1
Couple Alignment Cold Condition Dimensions

Dimension	Length - Cold (inch)	Average Temp Hot (°F)	Thermal Coefficient of Expansion
a	1.574	---	---
g	0.3444	445	0.99×10^{-5}
h	2.116	445	0.99×10^{-5}
i	3.47	160	0.96×10^{-5}
j	0.12	160	0.96×10^{-5}
k	1.915	305	0.99×10^{-5}

A typical calculation is shown below:

For the g dimension,

$$\Delta g = (\Delta T) g \sigma$$

where

Δg = thermal expansion of dimension g in inches

ΔT = temperature differential between hot conditions and room temperature in °F

σ = thermal coefficient of expansion for the stainless steel support cone in inches per inch - °F

Substituting the appropriate values from Table E-1 and assuming a 75°F room temperature,

$$\Delta g = 0.00126 \text{ in.}$$

Letting g_h be the hot length designation for g ,

$$g_h = g + \Delta g = 0.34526 \text{ in.}$$

The hot lengths for the various dimensions, with the exception of dimension a which is to be determined, are tabulated in Table E-2.

Table E-2
Couple Alignment Hot Condition Dimensions

Dimension	Length, Hot (inch)
g_h	0.34526
h_h	2.12375
i_h	3.47283
j_h	0.12010
k_h	1.91936

Letting a_h be the hot length designation for (a) and noting the right triangle dimensional relationship in Figure E-2,

$$a_h = g_h + \sqrt{k_h^2 - (i_h - h_h)^2} - j_h$$

Substituting the corresponding values from Table E-2,

$$a_h = 1.59042 \text{ in.}$$

The change in the a dimension is

$$\Delta a = a_h - a = 0.01242 \text{ in.}$$

The hot lengths for dimensions b, c, d, and e in Figure E-1 are found by the same equation used for calculating g_h . Results are in Table E-3.

Table E-3
Couple Alignment Hot and Cold Condition Dimensions

Dimension	Cold Length (inch)	Hot Length (inch)	Change in Length (inch)	Average Hot Temp. (°F)	Thermal Coefficient of Expansion
b	1.812	1.81344	0.00114	160	0.74×10^{-5}
c	1.876	1.87830	0.00230	170	1.29×10^{-5}
d	2.40	2.417	0.017	777	1.04×10^{-5}
e	0.381	0.3851	0.0041	1110	1.04×10^{-5}

It is noticed in Figure E-1 that the boron nitride anchor point, f, is directly in line with a point on the hot frame equal to a distance $d + e$ from the fixed reference point.

$$\text{or } f = d + e$$

It should also be noted that the location of the anchor point, f, is as close to the upper end of the converter as possible.

Therefore, the downward movement of the anchor point during heating with respect to the reference point is

$$\Delta f = \Delta d + \Delta e$$

Substituting the values for Δd and Δe from Table E-3,

$$\Delta f = 0.021 \text{ in.}$$

To prevent an appreciable relative motion between the anchor point and the cold frame midpoint, the combined expansion of dimensions a, b, c must be approximately equal to Δf or

$$\Delta f \sim \Delta a + \Delta b + \Delta c$$

From Table E-3 and the calculation for Δa ,

$$\Delta a + \Delta b + \Delta c = 0.016 \text{ in.}$$

Since the difference between 0.021 and 0.016 represents the relative motion between the boron nitride anchor point and the cold frame midpoint (this relative motion being 0.005 inch), it is seen that for negligible relative motion the anchor point should be established at approximately 2.312 inches (this is $d + e$ as shown in Figure E-1 for the cold condition) from the fixed reference point.