1298

MASTER

THIS DOCUMENT CONFIRMED AS
UNCLASSIFIED
DIVISION OF CLASSIFICATION
BY 4c
DATE 4/8/70

**SNAP-23A PROGRAM, PHASE 1
THERMOELECTRIC CONVERTER
DEVELOPMENT PROGRAM
QUARTERLY REPORT NO. 12**

P4766

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in United States of America

Available from:

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

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

Report No. MMM-3824-0043

Issue Date: January 31, 1970

AEC RESEARCH AND DEVELOPMENT REPORT

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

SNAP-23A PROGRAM, PHASE I

THERMOELECTRIC CONVERTER

DEVELOPMENT PROGRAM

QUARTERLY REPORT NO. 12

October 1, 1969 through December 31, 1969

Prepared by:

SNAP-23A
Technical Staff

Approved by:

J. F. Weinig
J. F. Weinig
Manager
SNAP-23A Program

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission
A. Makes any warranty or representation, expressed or implied with respect to the accuracy, completeness, or usefulness of the information contained in this report or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights, or
B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method or process disclosed in this report
As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor

Issued by

Space and Defense Products

MINNESOTA MINING AND MANUFACTURING COMPANY

St. Paul, Minnesota 55101

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Dep

Report No. MMM-3824-0043

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

BLANK

DISTRIBUTION LIST

<u>Addressee</u>	<u>No. of Copies</u>
U. S. Atomic Energy Commission Division of Reactor Development and Technology Washington, D. C. 20545 Attn: S. J. Seiken	5
U. S. Atomic Energy Commission New York Operations Office 376 Hudson Street New York, New York 10014 Attn: L. Wasser	2
U. S. Atomic Energy Commission NY Patents Group Upton, New York 11973	1
Westinghouse Electric Corporation Astronuclear Laboratory Post Office Box 10864 Pittsburgh, Pennsylvania 15236 Attn: Mr. W. Wilgus	4
Director, Nuclear Engineering Division Naval Facilities Engineering Command Washington, D. C.	1
U. S. Atomic Energy Commission RDT Site Office, 3M Company 2501 Hudson Road Space Center, Building 551 St. Paul, Minnesota 55119 Attn: John J. Stefano	1
Isotopes Development Center ORNL Post Office Box X Oak Ridge, Tennessee 37830 Attn: R. A. Robinson	2
Hittman Associates, Inc. Technical Information Department 9190 Red Branch Road Columbia Maryland 21043 Attn: J. Leiken	1
U. S. Atomic Energy Commission Division of Reactor Development and Technology Washington, D. C. 20545 Attn: Mr. J. M. Simmons	1
TID-4500 Category UC-33	

BLANK

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 October 1969 through 31 December 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

BLANK

TABLE OF CONTENTS

Section		Page
1.0	SUMMARY	1-1
2.0	PROGRAM MANAGEMENT	2-1
2.1	Liaison	2-1
2.2	Documentation and Reports	2-2
2.3	Work Forecast For Next Quarter	2-2
3.0	CONVERTER DEVELOPMENT - 60-WATT	3-1
3.1	Long-Term Test Converters	3-1
3.1.1	Experimental Mockup Converters (EMC)	3-1
3.1.1.1	Experimental Mockup Converter No. 2 (EMC-2)	3-1
3.1.1.2	Experimental Mockup Converter No. 3 (EMC-3)	3-2
3.1.2	Prototype Mockup Converters (PMC)	3-2
3.1.2.1	Prototype Mockup Converter No. 1A (PMC-1A)	3-2
3.1.2.2	Prototype Mockup Converter No. 1B (PMC-1B)	3-3
3.2	Prototype Mockup Converter No. 2 (PMC-2)	3-15
3.2.1	Design and Assembly of PMC-2 Hardware	3-15
3.2.2	Initial Processing of PMC-2	3-16
3.2.3	Disassembly and Repair of PMC-2	3-17
3.3	Failure Analysis of Prototype Mockup Converters (PMC)	3-33
3.3.1	Failure Analysis of PMC-2	3-33
3.3.1.1	Performance Analysis of PMC-2	3-33
3.3.1.2	Radiographic Analysis of PMC-2	3-34

TABLE OF CONTENTS (Continued)

Section		Page
3.3.1.3	Disassembly of PMC-2	3-34
3.3.1.4	Evaluation of Components Removed from PMC-2	3-35
3.3.2	Failure Analysis of PMC-1B	3-42
3.3.2.1	Performance Analysis of PMC-1B	3-42
3.3.2.2	Radiographic Analysis of PMC-1B	3-44
3.3.2.3	Disassembly of PMC-1B	3-44
3.3.2.4	Evaluation of Thermopile from PMC-1B	3-44
3.3.3	Failure Mechanism	3-45
3.4	Prototype Mockup Converter No. 3 (PMC-3)	3-53
3.4.1	Component Design Changes	3-53
3.4.2	Selection of Thermoelectric Material	3-53
3.5	Interface With Westinghouse	3-56
3.6	Fire Safety Test	3-56
3.6.1	Test Module Design	3-56
3.6.2	Test Fixture Modifications	3-57
3.6.3	Test Procedures	3-60
3.6.3.1	Dummy Module Test	3-60
3.6.3.2	Instrumented Couple Module Test	3-60
3.6.3.3	Fixture Calibration Test	3-61
3.6.3.4	Module Test (1475 ^o F Fire Transient)	3-61
3.6.3.5	Module Test (1850 ^o F Fire Transient)	3-62
3.6.4	Test Results	3-62
3.6.4.1	Raw Data	

TABLE OF CONTENTS (Continued)

Section		Page
3.6.4.2	Dummy Module Test	3-62
3.6.4.3	Instrumented Couple Module Tests	3-63
3.6.4.4	Fixture Calibration Test Results	3-63
3.6.4.5	1475°F and 1850°F Fire Module Test Results	3-64
3.6.5	Post-Test Fire Module Disassembly	3-67
4.0	THERMOELECTRIC COUPLE DEVELOPMENT	4-1
4.1	Introduction	4-1
4.2	Bell Jar Tests	4-2
4.3	Ten-Couple Modules	4-2
4.3.1	Modules 1 and 3	4-2
4.3.2	Module 5 through 12	4-10
4.4	Continuation Testing on Related Devices	4-41
4.4.1	Module 23A3	4-41
4.4.2	Converter 23P-2	4-41
	APPENDIX A - TEST PLAN AND PROCEDURE: FIRE SAFETY EVALUATION	
	APPENDIX B - SNAP-23A FIRE TEST RAW DATA	

LIST OF FIGURES

Figure		Page
3-1	SNAP-23A Performance History (BOL) Conditions)	3-6
3-2	SNAP-23A Converter EMC-3 Performance History (BOL Conditions)	3-10
3-3	SNAP-23A Converter PMC-1B Performance History (BOL Conditions)	3-14
3-4	PMC-2 Removed from Test and Process Station	3-20
3-5	Mounted on Rotary Table on Bridgeport Vertical Mill	3-21
3-6	Copper Pinch-off Tube Cut Open and Filled with Microquartz to Prevent Chips from Falling into Converter	3-22
3-7	Pinch-off Tube Adaptor Cut Off	3-23
3-8	Pinch-off Tube Standoff Milled Even and Counter-bored	3-24
3-9	Support Cone Machined Off of Hot Frame	3-25
3-10	Support Cone Machined Off at Connector Ring	3-26
3-11	Support Cone Cut in Half to Facilitate Removal	3-27
3-12	Inner Half of Support Cone Removed	3-28
3-13	Outer Half of Support Cone and Microquartz Pads Removed	3-29
3-14	Insulation Cone Removed	3-30
3-15	Removing Powdered Min-K 1301 Using Suction Hose	3-31
3-16	Removing Powdered Min-K 1301 Using Suction Hose	3-31
3-17	Melted Fiberglass Insulation Sleeving (Light Colored Sleeving Normal	3-32

LIST OF FIGURES (Continued)

Figure		Page
3-18	Comparison of P-Legs	3-40
3-19	Erosion of Hot Junction Electrode	3-41
3-20	Converter PMC-1B Thermoelectric Couples (Row 5)	3-46
3-21	Converter PMC-1B Thermoelectric Couples (Row 16)	3-47
3-22	Converter PMC-1B Thermoelectric Legs from Row 16	3-48
3-23	Converter PMC-1B Thermoelectric Legs from Row 16 (Legs A8 through A10 from right to left)	3-49
3-24	Thermoelectric N-Leg from Row 16 of Converter PMC-1B (Leg A7)	3-50
3-25	Thermoelectric P-Leg from Row 16 of Converter PMC-1B (Leg A6)	3-51
3-26	Converter PMC-1B Thermoelectric Couples (Row 4)	3-52
3-27	Fire Module Test Stand	3-59
3-28	Cut-Away View of Fire Module After 1475°F Test	3-70
3-29	Cut-Away View of Fire Module After 1850°F Test	3-70
4-1	Seebeck Voltage Ratio versus Elapsed Time (Module 1)	4-4
4-2	Resistance Ratio versus Elapsed Time	4-5
4-3	Power Ratio versus Elapsed Time (Module 1)	4-6
4-4	Seebeck Voltage Ratio versus Elapsed Time (Module 3)	4-7

LIST OF FIGURES (Continued)

Figure		Page
4-5	Resistance Ratio versus Elapsed Time (Module 3)	4-8
4-6	Power Ratio versus Elapsed Time (Module 3)	4-9
4-7	N-Leg Statistical Analysis (Microquartz Modules) Average and Main Effects for Seebeck Ratio	4-27
4-8	N-Leg Statistical Analysis (Microquartz Modules) Average and Main Effects for Resistance Ratio	4-28
4-9	N-Leg Statistical Analysis (Microquartz Modules) Average and Main Effects for Power Ratio	4-29
4-10	N-Leg Statistical Analysis (Min-K-1301 Modules) Average and Main Effects for Seebeck Ratio	4-30
4-11	N-Leg Statistical Analysis (Min-K-1301 Modules) Average and Main Effects for Resistance Ratio	4-31
4-12	N-Leg Statistical Analysis (Min-K-1301 Modules) Average and Main Effects for Power Ratio	4-32
4-13	P-Leg Statistical Analysis (Microquartz Modules) Average and Main Effects for Seebeck Ratio	4-33
4-14	P-Leg Statistical Analysis (Microquartz Modules) Average and Main Effects for Resistance Ratio	4-34
4-15	P-Leg Statistical Analysis (Microquartz Modules) Average and Main Effects for Power Ratio	4-35
4-16	P-Leg Statistical Analysis (Min-K-1301 Modules) Average and Main Effects for Seebeck Ratio	4-36
4-17	P-Leg Statistical Analysis (Min-K-1301 Modules) Average and Main Effects for Resistance Ratio	4-37
4-18	P-Leg Statistical Analysis (Min-K-1301 Modules) Average and Main Effects for Power Ratio	4-38

LIST OF FIGURES (Continued)

Figure		Page
4-19	Comparison of Power Ratio for Various Combinations of P-Legs and Hot Junction Temperature (Min-K-1301 Modules)	4-39
4-20	Comparison of Average Power Ratio for Various Combinations of P-Legs and Thermal Insulations	4-40

LIST OF TABLES

Table		Page
1-1	Operating Time of SNAP-23A Devices	1-2
1-2	History of Converter Performance for End-of-Life Conditions	1-3
3-1	SNAP-23A EMC-2 Performance Data (End-of-Life Conditions)	3-4
3-2	SNAP-23A Converter EMC-2 Performance History (Beginning-of-Life Conditions)	3-5
3-3	SNAP-23A Converter EMC-2 Performance Data (Ratio of Experimental-to-Theoretical Values)	3-7
3-4	SNAP-23A Converter EMC-3 Performance Data (End-of-Life Conditions)	3-8
3-5	SNAP-23A Converter EMC-3 Performance History (Beginning-of-Life Conditions)	3-9
3-6	SNAP-23A Converter EMC-3 Performance Data (Ratio of Experimental-to-Theoretical Values)	3-11
3-7	SNAP-23A Converter PMC-1A Performance Data (Ratio of Experimental-to-Theoretical Values)	3-12
3-8	SNAP-23A Converter PMC-1B Performance History (Beginning-of-Life Conditions)	3-13
3-9	SNAP-23A Converter PMC-2 Performance versus Design Criteria	3-37
3-10	Q. C. Data Summary	3-38
3-11	Emission Spectrographic Analysis of Foreign Material	3-39
3-12	Microprobe Analysis of Foreign Material	3-39

LIST OF TABLES (Continued)

Table		Page
3-13	Hot Segment Material for P-Leg	3-55
3-14	Instrumented Couple Test Module Comparison with PMC-2 Converter	3-63
3-15	25 November 1969 Calibration Test Results	3-64
3-16	Conductance Values (K) - Watts/oF	3-66
3-17	Fire Test Reduced Data	3-68
3-18	Fire Test Reduced Data	3-69
4-1	PMC-2 Bell Jar Test Performance Ratios	4-2
4-2	SNAP-23A Ten-Couple Module Performance Analysis (Modules 1 and 3)	4-3
4-3	SNAP-23A N-Leg Statistical Analysis Summary (Microquartz Modules) (Seebeck Ratio)	4-15
4-4	SNAP-23A N-Leg Statistical Analysis Summary (Microquartz Modules) (Resistance Ratio)	4-16
4-5	SNAP-23A N-Leg Statistical Analysis Summary (Microquartz Modules) (Power Ratio)	4-17
4-6	SNAP-23A N-Leg Statistical Analysis Summary (Min-K 1301 Modules) (Seebeck Ratio)	4-18
4-7	SNAP-23A N-Leg Statistical Analysis Summary (Min-K 1301 Modules) (Resistance Ratio)	4-19
4-8	SNAP-23A N-Leg Statistical Analysis Summary (Min-K 1301 Modules) (Power Ratio)	4-20
4-9	SNAP-23A P-Leg Statistical Analysis Summary (Microquartz Modules) (Seebeck Ratio)	4-21
4-10	SNAP-23A P-Leg Statistical Analysis Summary (Microquartz Modules) (Resistance Ratio)	4-22
4-11	SNAP-23A P-Leg Statistical Analysis Summary (Microquartz Modules) (Power Ratio)	4-23

LIST OF TABLES (Continued)

Table		Page
4-12	SNAP-23A P-Leg Statistical Analysis Summary (Min-K 1301 Modules) (Seebeck Ratio)	4-24
4-13	SNAP-23A P-Leg Statistical Analysis Summary (Min-K 1301 Modules) (Resistance Ratio)	4-25
4-14	SNAP-23A P-Leg Statistical Analysis Summary (Min-K 1301 Modules) (Power Ratio)	4-26
4-15	Six-Couple Module 23A3 N-Leg Performance Data (Start of Test: 3/4/65; Current Reading 12/31/69)	4-42
4-16	Converter 23P-2 Performance Data	4-43
4-17	SNAP-23 Converter P-2 BOL Performance Data (Ratio of Experimental-to-Theoretical Values)	4-44

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

1.0 SUMMARY

During this quarter the design for all components and their associated drawings were completed for the top cover assembly of PMC-2. The PMC-2 converter proper which was assembled in the previous quarter was processed. During initial processing opens and shorts occurred which precipitated a failure analysis consisting of X-rays, partial disassembly, replacement of eleven couples and Min K-1301, rewelding and reprocessing. This effort was completed and PMC-2 is now ready for initial performance and stability testing.

In addition to the failure of PMC-2, converter PMC-1B experienced an open after approximately one year of operation. A detailed analysis of these two failures which appear to be related is in progress. The cause for the failures appears to be copper contamination of the thermoelectric materials, but what initiated the reaction is unknown at the present time.

Other activities performed this quarter were:

- Completed fire module testing and data analysis
- Prepared design for PMC-3
- Initiated planning for Phase II activities
- Continuation of long term operation and testing of the following devices:
 - 10-couple modules 1, 3 and 5-12
 - Converter 23 P2

- Six couple module 23A-3
- Converters EMC-2 and EMC-3

Table 1-1 summarizes the operating time of the long term devices while Table 1-2 shows the new EOL data for EMC-2 and EMC-3 along with the previous reported data for EMC-1 and PMC-1A.

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

Device	Operating Time	
	Hours	Years
EMC-2	13,133	1.50
EMC-3	16,446	1.88
PMC-1A	11,152	1.27
PMC-1B	8,842*	1.01
10-Couple Modules 1 & 3	19,184	2.19
10-Couple Modules 5 - 12	16,500	1.88
23P2	25,831	2.95
23A3	42,292	4.83

*Time Data Acquisition System indicated on open circuit in this converter. Converter was subsequently removed for analysis on 3 November 1969.

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

Parameter	Symbol	Unit	EMC-1	EMC-2	EMC-3	PMC-1A
Net Power Input	P_{in}	Watts (t)	834	860	879	849
Power Output	P_o	Watts (e)	50.9	57.1	60.3	69.4
Efficiency		Percent	6.08	6.64	6.86	8.16
Open Circuit Voltage	E_o	Volts	40.9	40.9	40.9	41.8
Load Voltage	V_l	Volts	23.0	24.0	24.0	24.0
Load Current	I_l	Amps	2.21	2.38	2.51	2.89
Internal Resistance	R_g	Ohms	8.10	7.12	6.71	6.16
Temperatures						
Hot Junction	T_h	°F	900	898	900	919
Cold Junction	T_c	°F	173	171	172	177
Heat Loss	P_l	Watts (t)	27	28	28	28
Gross Power	P_t	Watts (t)	864	888	907	880
Internal Gas Pressure	P_g	PSIG	9.4		8.6	10.0
Test Time	Hrs	Hours	43	12,959	16,272	507

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

2.0 PROGRAM MANAGEMENT

2.1 LIAISON

Liaison activities during this quarter were primarily concerned with 1) completion of the Fire Safety Test and 2) providing Westinghouse with a converter that could be used in the Fueled Prototype Mockup System (FPMS).

After completing assembly of the Fire Module Test Stand in October 1969 test effort on dummy modules began. During the interface meeting on 5 November 1969 Westinghouse requested that the cold end heater power be recorded during the fire incidents tests. This change was made and subsequent dummy module, instrumented module and fire module tests were conducted with Westinghouse and Hittman Associates Inc. personnel present for observation.

Early in October during processing, converter PMC-2 indicated abnormal performance. Since this converter was to be used in the FPMS, meetings were conducted with Westinghouse and the AEC to explain the abnormal performance, and to determine alternate courses of action. The results of these meetings indicated that PMC-2 was not suitable for the FPMS and that PMC-1B was a likely candidate based on the analysis of the hot frame interface. The course of action became very complex when on 31 October 1969, converter PMC-1B indicated an open circuit. This open circuit in PMC-1B was verified to be internal to the converter; thus negating this converter as a candidate for the FPMS.

Subsequent meetings with Westinghouse and the AEC indicated that PMC-2 should be disassembled, repaired, reprocessed, and tested. After a 500 hour seasoning test the converter will be shipped to Westinghouse for use in the FPMS. It was

pointed out that this converter would satisfy the thermal but not necessarily the electrical performance. It was further agreed to by Westinghouse and AEC to build converter PMC-3 using the followers and cold frame from PMC-1B. This converter, at a later date, will be used in the FPMS and is intended to meet the converter electrical and thermal performance requirements.

2.2 DOCUMENTATION AND REPORTS

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

- Quarterly Report No. 11 (MMM 3824-0040)
- October Monthly Report (MMM 3824-0041)
- 10-Couple Module Data for period reported in Quarterly No. 11 (MMM 3824-1272)
- SNAP-23A Program Plan, Volume II, Revision 4 dated 15 September 1969

2.3 WORK FORECAST FOR NEXT QUARTER

Major effort scheduled for next quarter is as follows:

- Complete initial performance and stability listing of PMC-2
- Complete failure analysis of PMC-1B and PMC-2 failures
- Initiate fabrication and assembly of Converter PMC-3
- Prepare documentation for SNAP-23A Phase II effort
- Initiate procurement for Phase II converter long-lead items
- Continue long term testing of the following devices:

- Experimental Mockup Converter No. 2 (EMC-2)
- Experimental Mockup Converter No. 3 (EMC-3)
- 10-Couples Modules
- Module A -3

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 was interrupted during the quarter to rebuild the heat source following failure of one of the heaters. After resumption of testing, converter performance was re-evaluated 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 Seebeck voltage of the simultaneously-pressed N-legs decreased slightly while the resistance remained basically unchanged. This trend is the same as that observed on comparable N-legs in the ten-couple modules and in converter EMC-3.
- Simultaneously-pressed P-leg resistance was significantly higher following the resumption of testing. This increase is most likely the result of a change in hot contact resistance and should subside with time (resulting in an increase in output power and efficiency).

- Changes in heat input were necessitated primarily by load current differences rather than thermal performance changes.

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

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

- The resistance of the bonded-type P-legs appears to have stabilized at a minimum value while the Seebeck voltage remains relatively stable. This trend agrees with that observed on comparable P-legs in PMC-1A and PMC-1B.
- The Seebeck voltage of the simultaneously-pressed N-legs decreased slightly while the resistance increase observed previously leveled off. This trend is similar to that observed on comparable N-legs in the ten-couple modules and in converter EMC-2.
- Thermal performance remained relatively stable.
- EOL efficiency decreased slightly as a result of the N-leg voltage decline.

3.1.2 Prototype Mockup Converters (PMC)

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

PMC-1A long-term test continued during the quarter. This converter is on test at WANL as a component in the Experimental Mockup System life-test. PMC-1A performance history is presented in Table 3-7 in the form of experimental-to-theoretical performance ratios. Analysis of recent data indicates a slight increase

in the thermopile resistance. This trend is similar to that observed on comparable converters (EMC-3 and PMC-1B).

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

PMC-1B long-term testing was terminated at 8,842 hours, (just six hours after the last recorded data point) when an open developed in the thermopile circuit. Subsequent to this open a post-test analysis was conducted (see paragraph 3.3.2). PMC-1B BOL performance history is presented in Table 3-8 and shown graphically in Figure 3-3.

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

Parameter	Symbol	Units	Measured Values at Specified Hours							
			3.5	508 (Pre- dynamic Test)	628 (Post- dynamic Test)	3683	7142	9488	11,810	12,959**
Net Power Input	P_{in}	Watts (t)	832	852	860	896	891	881	873	860
Power Output	P_o	Watts (e)	57.6	57.6	57.1	63.2	63.6	61.2	60.2	57.1
Efficiency	η	Percent	6.92	6.16	6.64	7.05	7.14	6.95	6.90	6.64
Open Circuit Voltage	E	Volts	41.1	42.4	42.9	43.2	42.8	41.9	41.1	40.9
Load Voltage	V_l	Volts	23.0	23.0	24.0	24.0	24.0	24.0	24.0	24.0
Load Current	I_l	Amps	2.50	2.50	2.38	2.63	2.65	2.55	2.51	2.38
Internal Resistance	R_g	Ohms	7.23	7.76	7.94	7.28	7.08	7.00	6.80	7.12
Temperatures										
Hot Frame	T_{hf}	°F	931	926	934	933	935	932	930	928
Hot Junction	T_h	°F	901	898	904	903	905	902	900	898
Cold Junction	T_c	°F	173	172	176	171	175	174	172	171
Outer Case	T_{oc}	°F	128	129	125	119	119	116	114	117
Gross Power Input*	P_t	Watts (t)	860	880	888	924	919	909	901	888

* Watts-transducer was recalibrated at 3511, 6440 and 12,936 hours.

** Reading recorded on 24 December 1969.

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

Parameter	Symbol	Units	Measured Values at Specified Hours													
			75.5	170.0	483	820	1612	3009	4469	6010	7349	8167	10,370	11,840	12,585	13,133**
Power Output	P _O	Watts (e)	79.5	79.0	79.7	78.3	78.8	84.0	85.2	86.2	86.2	84.0	83.6	82.9	77.9	77.3
Normalized Power Output	P _N	Watts (e)	79.6	79.1	79.9	78.9	80.7	83.8	84.1	84.6	84.6	84.2	82.9	81.7	83.2	76.6
Open Circuit Voltage	E	Volts	53.7	54.2	54.5	54.1	54.2	55.2	55.6	55.3	55.3	54.3	54.0	53.4	49.8	52.8
Normalized O. C. Voltage	E _N	Volts	53.8	54.3	54.8	54.8	54.7	55.0	55.5	55.2	55.0	55.0	53.8	53.0	53.9	52.8
Internal Resistance	R _g	Ohms	9.03	9.24	9.26	9.30	9.27	8.99	8.99	8.79	8.77	8.73	8.67	8.59	7.95	8.99
Norm. Int. Resistance	R _N	Ohms	9.04	9.25	9.31	9.42	9.33	9.12	8.98	8.83	8.81	8.77	8.67	8.59	8.72	9.07
Load Voltage	V _l	Volts	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
Load Current	I _l	Amps	3.18	3.16	3.19	3.13	3.15	3.36	3.41	3.45	3.45	3.36	3.34	3.31	3.12	3.09
Temperature																
Hot Junction	T _h	°F	1084	1084	1081	1076	1076	1078	1089	1086	1086	1082	1087	1088	1024	1083
Cold Junction	T _c	°F	191	191	190	189	195	186	188	185	185	190	189	187	180	186
Gross Power Input**	P _t	Watts (t)	1104	1112	1120	1132	1128	1156	1179	1175	1153	1145	1150	1144	1059	1119

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

Watts-transducer was recalibrated at 3511, and 12,936 hours

Reading recorded on 31 December 1969

Figure 3-1
SNAP-23A 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
	9559		1.01		1.08		0.95
	11840		1.00		1.06		0.94
	13133		0.99		1.12		0.88
Typical N-leg ⁽³⁾	Initial EOL - 3.5	1.00		0.97		1.03	
	Initial BOL - 47.5		0.99		0.93		1.05
	5288		1.00		0.94		1.06
	7349		1.00		0.96		1.04
	9559		0.98		0.96		1.00
	11840		0.98		0.97		0.99
	13133		0.97		0.97		0.97
Typical P-Leg ⁽³⁾	Initial EOL - 3.5	1.04		1.34		0.80	
	Initial BOL - 47.5		1.03		1.28		0.83
	5288		1.06		1.24		0.91
	7349		1.05		1.21		0.92
	9559		1.03		1.19		0.90
	11840		1.01		1.16		0.88
	13133		1.01		1.29		0.79

(1) Theoretical resistance includes no extraneous resistance allowance.

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

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

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

Parameter	Symbol	Units	Measured Values at Specified Hours								
			11 5	1203	2783	3750	6078	9539	11 906	14,211	16,272
Net Power Input	P_{in}	Watts (t)	824	860	864	848	866	851	882	882	87 9
Power Output	P_o	Watts (e)	61 2	65 3	66 5	66 2	67 2	64 1	61 2	61.3	60 3
Efficiency	η	Percent	7 43	7 59	7 79	7 81	7 76	7 53	6 94	6.95	6.86
Open Circuit Voltage	F	Volts	40 7	41 5	41 3	41 5	41 6	41 5	41 2	40.9	40 9
Load Voltage	V_l	Volts	23 0	24 0	24 0	24 0	24 0	24 0	24 0	24.0	24 0
Load Current	I_l	Amps	2 66	2 72	2 77	2 77	2 80	2 67	2 55	2 56	2.51
Internal Resistance	R_g	Ohms	6 65	6 43	6 25	6 34	6 30	6 56	6 72	6.63	6.71
Temperatures											
Hot Frame	T_{hf}	F	928	931	925	930	928	930	931	930	930
Hot Junction	T_h	°F	900	903	899	900	898	901	901	900	900
Cold Junction	T_c	°F	172	172	174	175	171	176	174	172	172
Outer Case	T_{oc}	°F	151	150	151	151	146	151	149	149	148
Gross Power Input	P_t	Watts (t)	852	888 0	892	876	894	879	910	910	907
Internal Gas Pressure	P_g	PSIG	8 4	9 4	9 6	9 4	9 1	8 8	8 9	8.7	8 6

* Watts-transducer was recalibrated at 3507, 5907, 8837 and 13,943 hours
Reading recorded 24 December 1969

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

Parameter	Symbol	Units	Measured Values at Specified Hours												
			123	681	1107	1800	4014	6223	8407	10,563	12,765	14,237	14,981	15,605	16,446***
Power Output	P_o	Watts (e)	88.0	89.3	91.0	91.5	92.3	92.9	90.8	90.2	87.8	87.5	87.7	87.1	86.2
Normalized Power Output	P_N^*	Watts (e)	88.2	91.2	92.6	92.9	93.3	91.7	91.0	88.9	88.1	87.4	87.4	87.2	86.4
Open Circuit Voltage	E	Volts	54.1	53.7	54.1	53.9	54.3	54.8	54.5	54.4	53.7	53.9	53.7	53.7	53.5
Normalized O.C. Voltage	E_N^*	Volts	54.4	54.6	54.6	54.7	54.9	54.5	54.7	54.2	54.0	53.8	53.8	53.8	53.7
Internal Resistance	R_g	Ohms	8.27	8.04	7.99	7.90	7.94	8.02	8.11	8.15	8.17	8.26	8.17	8.25	8.28
Norm. Int. Resistance	R_N^*	Ohms	8.34	8.14	8.01	8.02	8.03	8.03	8.14	8.20	8.22	8.25	8.25	8.26	8.30
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	3.57	3.64	3.66	3.69	3.71	3.63	3.61	3.51	3.49	3.51	3.48	3.45
Temperature															
Hot Junction	T_h	°F	1080	1074	1080	1074	1077	1087	1083	1085	1081	1086	1081	1084	1083
Cold Junction	T_c	°F	189	193	195	191	191	187	191	185	190	191	187	191	191
Gross Power Input**	P_t	Watts(t)	1096	1108	1120	1124	1112	1140	1122	1123	1161	1161	1158	1160	1154
Internal Gas Pressure	P_g	PSIG	10.4	11.2	11.1	11.0	11.0	10.9	10.3	10.2	10.2	10.3	10.2	10.0	10.1

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

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

*** Reading recorded on 31 December 1969

Figure 3-2.
SNAP-23A Converter EMC-3 Performance History
(BOL 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
	10563		0.98		1.00		0.96
	14237		0.98		1.02		0.94
	16446		0.97		1.02		0.93
Typical N-Leg ⁽³⁾	Initial EOL - 11.5	1.01		1.05		0.97	
	Initial BOL - 41		1.00		1.01		0.99
	5500		1.00		0.96		1.04
	10563		0.99		1.00		0.98
	14237		0.99		1.06		0.92
	16446		0.98		1.06		0.90
Typical P-Leg ⁽³⁾	Initial EOL - 11.5	0.96		1.13		0.82	
	Initial BOL - 41		0.96		1.09		0.84
	5500		0.97		1.02		0.92
	10563		0.97		1.00		0.94
	14237		0.96		0.96		0.96
	16446		0.96		0.96		0.96

(1) Theoretical resistance includes no extraneous resistance allowance.

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

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

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

Thermoelectric Designation	Time Evaluated in Hours	Seebeck Ratio	Resistance Ratio ^(*)
Thermopile ⁽²⁾	47.5	0.98 ⁽³⁾	0.98 ⁽³⁾
	508	0.99 ⁽³⁾	0.96 ⁽³⁾
	704	(0.98)	(0.98)
	1782.5	(0.98)	(0.96)
	3798	(0.98)	(0.94)
	7758	(0.99)	(0.95)
	10,326	(0.99)	(0.98)

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

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

(3) EOL ratios obtained during performance verification tests.

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

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

Parameter	Symbol	Units	Measured Values at Specified Hours														
			126	267	528	1070	1540	2285	2906	3722	4426	5169	5810	6626	7270	8091	8836**
Power Output	P _o	Watts (c)	86.2	86.0	80.2	81.0	81.5	81.2	81.2	81.2	80.0	79.5	79.6	79.6	79.2	78.3	77.3
Normalized Power Output	P _n	Watts (c)	86.1	88.7	80.3	80.2	81.1	80.7	81.1	80.0	87.3	87.7	86.6	86.7	86.7	85.7	83.5
Open Circuit Voltage	E	Volts	52.4	52.6	52.6	52.3	52.7	52.6	52.5	48.2	47.9	47.5	47.4	47.5	47.4	47.3	47.3
Normalized O.C. Voltage	E _n	Volts	52.4	52.4	52.7	52.2	52.8	52.3	52.7	52.6	52.4	52.4	52.0	52.0	52.0	51.8	51.7
Internal Resistance	R _g	Ohms	7.94	7.76	7.66	7.58	7.64	7.55	7.54	6.96	7.15	7.07	7.04	7.06	7.08	7.12	7.22
Norm. Int. Resistance	R _n	Ohms	7.93	7.70	7.67	7.63	7.53	7.51	7.53	7.66	7.86	7.81	7.78	7.75	7.75	7.79	7.98
Load Voltage	V _l	Volts	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
Load Current	I _l	Amps	3.45	3.56	3.61	3.60	3.62	3.65	3.65	3.33	3.20	3.18	3.18	3.18	3.17	3.13	3.09
Temperatures																	
Hot Junction	T _h	°F	1081	1079	1079	1079	1079	1084	1075	1014	1014	1009	1012	1015	1015	1015	1013
Cold Junction	T _c	°F	192	190	192	188	194	192	189	184	187	188	185	187	189	189	183
Gross Power Input	P _t	Watts (r)	1076	1103	1116	1118	1124	1139	1138	1038	1034	1028	1022	1022	1022	1014	1011
Internal Gas Pressure	P _g	PSIG	11.1	11.9	12.7	13.0	12.7	13.0	12.5	11.8	11.6	11.7	11.7	11.4	11.4	11.3	11.2

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

* Reading recorded on 31 October 1969

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

* Watts-transducer was recalibrated at 5543 hours

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

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

The following major PMC-2 events occurred during the quarter.

1. Completion of converter design and assembly
2. Completion of initial converter processing
3. Partial disassembly and repair of thermopile problems encountered during processing.

Details surrounding these events are presented in the following subsections of this report.

PMC-2 was subsequently reprocessed near the end of the quarter. Since the test plan and procedure and other preparations necessary for short-term testing of PMC-2 have been completed, it is anticipated that testing will begin very early next quarter.

3.2.1 Design and Assembly of PMC-2 Hardware

The design of the few remaining components was completed. These few components had short procurement lead times and were required for the final steps of assembly. All assembly drawings were also completed and released. Follow-up was provided during the assembly and processing of the converter. The assembly was completed through to the processing configuration (converter less top cover components).

3.2.2 Initial Processing of PMC-2

The following paragraphs detail events surrounding the initial processing of PMC-2.

During a routine in-process check of the test panel electronic load, an open was detected in the thermopile circuit. The thermopile was under vacuum at this point with the hot junction at 600°F and cold junction at 225°F. The converter was cooled to room temperature and a resistance check indicated a thermopile resistance of 2 megohms. The high resistance was determined to be in rows 36-40. As the unit was again heated up, the high resistance disappeared and a short to ground was detected in the region between rows 36 and 40.

After completion of processing the converter was held in an argon atmosphere to run further checks. The ground was found to be the equivalent of 6-couples shorted out in rows 36-40. Thermoelectric checks indicated that the average P-leg Seebeck ratio was below the design value. To aid in determining the cause of the short, the converter was cooled to room temperature and the resistance to ground was checked with a volt-ohmmeter. This check indicated an intermittent or momentary ground. Subsequent checks with a 100-volt "megger" indicated no ground. The converter was again heated and at 92°F on the hot junction, the ground reappeared. The unit was cooled to room temperature and no ground was indicated. Power was again applied to the converter and between 750 and 850°F on the hot junction, the ground reappeared. The unit was cooled to room temperature and no ground was indicated. The unit was again heated and the ground reappeared at a hot junction temperature of 800°F. After approximately four hours at 800°F, the ground disappeared. The unit was then thermally cycled five times between room temperature and BOL conditions without a return of the ground.

The performance of rows 36-40 was still below that of the remainder of the thermopile. In the 28-couple string which can be monitored in this converter region, the Seebeck voltage observed was equivalent to that of 26 couples (as opposed to the 22 couple equivalent observed while the short to ground existed). This 2-couple voltage loss is comparable to that expected if one couple in the string was reversed.

Previous investigation done in the SNAP-21 program had indicated that an X-ray technique could prove useful in detecting a reversed couple. PMC-2 was then removed from its processing station and prepared for radiographic examination. This examination indicated that:

1. No couples were reversed
2. There was evidence of foreign material laying between rows 37 and 38, and extending for a length of approximately two thermoelectric couples.

3.2.3 Disassembly and Repair of PMC-2

At this point it was determined that partial disassembly and repair of the affected thermopile region was necessary to provide a converter which could be thermally stabilized and calibrated prior to system integration. The following paragraphs detail the disassembly and repair procedure.

To gain access to the thermopile area the upper support cone was removed by machining. The sequence for performing this operation is shown in Figures 3-4 through 3-16. During removal of the powdered MIN-K 1301 thermal insulation, a loose section of foreign material was found between rows 37 and 38 (refer to section 3.3 for analysis). Another section of it was firmly attached to the hot frame between the boron nitride strips of rows 37 and 38 (this material was later removed). Other observations made during the disassembly:

- 1) The following instrumentation wires had some portion of their fibreglass insulations melted (Figure 3-17)
 - a) T/C No. 65, iron voltage probe, row 1
 - b) T/C No. 20, both iron and constantan, row 36
 - c) T/C No. 17, iron, row 4
- 2) Six boron nitride insulation strips were broken off across the thick section through the pinned area.

- 3) Visual inspection of the couples in row 37 and 38 indicated a massive chemical reaction had affected five and one-half couples in each row (see section 3.3 for analysis).

Because of the potential electrical and thermal instability problems involved if only the foreign material and not the affected couples were removed, it was deemed necessary to remove those couples and their associative hot buttons and hot electrodes. This repair would correct the effect of two couples being shorted in rows 37 and 38, however, it would not correct for the low average P-leg Seebeck ratio and hence the converter would not be expected to produce design power output. However, by adjusting the electrical current in the thermopile, the converter could be forced to operate to match the thermal impedance of a converter that met design objectives. With this current loading, PMC-2 could be mated with Westinghouse FPMS for system thermal evaluation. It was on this basis that the repair of PMC-2 was undertaken.

To repair PMC-2 by replacing the parts removed from the upper eleven positions of Rows 37 and 38 it was necessary to cut away a portion of the boron nitride hot sink insulation strip (see sketch below). The pins which hold this strip in place at the upper end were removed and the strips cut as shown. Special tools were

made to lift and hold the followers. T-shaped channels were used to hold the followers up in each row during leg removal and a U-shaped channel was used to hold the followers up during couple replacement.

Replacement of components using the special tooling described in the preceding paragraph was difficult because of 1) the limited volume and 2) the followers could not be removed prior to insertion of the new thermoelectric couples. Because of these difficulties, several of the followers were chipped in the spherical socket area; therefore, PMC-2 is not suitable for shock and vibration testing.

Temperature instrumentation wires were attached to the cold caps of the legs at the ends of Rows 37 and 38 to provide a means of measuring the cold junction temperature at these two points and monitoring the thermoelectric performance of the couples in Rows 37 and 38.

With the replacement parts installed in Rows 37 and 38, the rebuild proceeded up through converter processing configuration. The converter was processed again with just one change from the standard procedure. The maximum hot junction temperature for the seat-in operation was restricted to 1100°F maximum rather than 1200°F to reduce the possibility of initiating a failure mechanism. After processing was completed the top cover components were assembled on the unit and the converter was placed on the test station. Data taken during processing confirmed that there was circuit continuity and no shorts to ground.

Figure 3-4. PMC-2 Removed from Test and Process Station

Figure 3-5. Mounted on Rotary Table on Bridgeport Vertical Mill

Figure 3-6. Copper Pinch-off Tube Cut Open and Filled with Microquartz to Prevent Chips from Falling into Converter

Figure 3-7. Pinch-off Tube Adaptor Cut Off

Figure 3-8. Pinch-off Tube Standoff Milled Even and Counterbored

Figure 3-9. Support Cone Machined Off of Hot Frame

Figure 3-10. Support Cone Machined Off at Connector Ring

Figure 3-11. Support Cone Cut in Half to Facilitate Removal

Figure 3-12. Inner Half of Support Cone Removed

Figure 3-13. Outer Half of Support Cone and Microquartz Pads Removed

Figure 3-14. Insulation Cone Removed

Figure 3-15 Removing Powdered Min-K 1301
Using Suction Hose

Figure 3-16

Figure 3-17. Melted Fiberglass Insulation Sleeving
(Light Colored Sleeving Normal)

3.3 FAILURE ANALYSIS OF PROTOTYPE MOCKUP CONVERTERS (PMC)

An analysis was started to determine the cause of failure and what initiated the failure of PMC-2 and PMC-1B. As the chemical reaction which occurred in PMC-2 and PMC-1B appeared to be the same type the failure analyses of PMC-2 and PMC-1B were conducted simultaneously.

3.3.1 Failure Analysis of PMC-2

3.3.1.1 Performance Analysis of PMC-2

Several anomalies were observed during the initial processing of PMC-2 and are detailed in Section 3.2.2. The performance of PMC-2 as measured on the test station is compared in Table 3-9 to design values, bell jar tests with couples from the same lot and batch as PMC-2 was built, and computer predictions. By examining the values in Table 3-9, it can be concluded that the low power output of PMC-2 is due to low Seebeck voltage and high circuit resistance. The low Seebeck of the P legs is the greatest contributing factor to the low power output. Table 3-10 is a summary of the thermoelectric QC data used to determine the acceptability of the P legs. This table compares the QC data of PMC-2 with that of PMC-1a and PMC-1b. Converter PMC-1a and PMC-1b had acceptable thermoelectric performance. From examination of the Seebeck data presented in

Table 3-10, it can be concluded that the present QC measurements do not give a good indication of how thermoelectric legs will perform in a thermopile. There is a correlation between the thermoelectric QC data and thermopile performance, but the range of correlation is greater than the design Seebeck and resistance ratios range of values. Either the range of values for design Seebeck and resistance ratios will need to be increased or a better method of taking thermoelectric leg QC measurements will need to be devised.

3.3.1.2 Radiographic Analysis of PMC-2

Radiographic analysis was conducted to determine if any reversed couples (position of P and N leg reversed) existed in the Row 36 and 40 section of the thermopile. The radiographs showed there were no reversed couples. In addition, the radiographs did show a foreign object between Row 37 and 38 extending from position A4 through A7. The hot junction electrodes in Row 38, position A9-10 and at Row 37, position A7-8, had a phantom appearance in the radiographs. These radiographs did show some unusual conditions in the Row 37-38 region. While it was not possible to come to an absolute conclusion from the radiographs, it was concluded that the foreign object between Rows 37 and 38 was shorting out two couples. This would explain the reduction in power output of this section of the thermopile.

3.3.1.3 Disassembly of PMC-2

PMC-2 was disassembled to remove what appeared on the radiographs as a foreign object between Rows 37 and 38 (refer to Section 3.2.3 for details). This foreign object was of irregular shape 1/4" to 3/16" long and 0.025" to 0.030" in diameter. It has the appearance and texture of slag. A chemical analysis of this foreign object was conducted to determine its composition. The results of the emission spectrographic analysis is shown in Table 3-11.

The results of these analyses indicated that the foreign object between Rows 37 and 38 was the product of a chemical reaction between copper and the thermoelectric leg material.

A boroscope was used to visually examine the condition of the legs, hot junction buttons, and hot junction electrodes in Rows 37 and 38. It was apparent that the hot junction buttons at Positions A7 and A8 of Row 37 and Positions A5, A6, A7, A8, A9 and A10 of Row 38 had been involved in a chemical reaction. The surface of these hot junction buttons was rough with a slag-like appearance while the other hot junction electrodes had a shiny surface. The "P" type legs also had a reddish brown ring on the surface part way up the leg. One "P" type leg was also shortened about 1/8" to 1/4". None of the components in adjacent Rows 36 and 39 appeared to be involved in any chemical reaction.

The initial conclusion from the visual examination was that the low power output observed in the Row 36 to 40 section was caused by a chemical reaction between the thermoelectric leg and the copper of the hot junction electrode. The reaction product had caused a short circuit path shorting out several couples and could easily have provided a short to ground. At this point in time this reaction had only caused a reduction in power output, but as this reaction would continue it could cause an open circuit by consuming the copper from the hot junction electrode. It was decided to remove from PMC-2 those legs, hot junction electrodes, and hot junction buttons which had been involved in the reaction and replace with new components (refer to Section 3.2.3 for details).

3.3.1.4 Evaluation of Components Removed from PMC-2

The legs, hot junction buttons, and hot junction electrodes removed from the thermopile were examined visually. This was the first step in the analysis to determine the cause of failure and what initiated the failure reaction. The "N" legs at Positions R38A5, R37A7, R37A8 and R38A9, showed evidence of chemical reaction by a copper colored band around the leg part way up from the hot end. The "P" legs at Positions R38A6, R37A7, R38A8 and R38A10, showed signs of being involved in a chemical reaction because of the dark grey layer of material on the surface of the leg. The "P" leg at Position R38A10 was also only about one-half normal length. This can be seen in the photograph of this "P" leg and

a normal "P" leg at Position R38A4 (see Figure 3-18). Hot junction buttons at Positions R38A5, A6, A7, A8, A9 and A10, R37A7 and A8, had the exposed surfaces covered with a dark grey material with the appearance of slag. The hot junction electrodes at Positions R37A7-8, R38A9-10 and R38A7-8, had part of the copper material eroded away by the chemical reaction.

Figure 3-19 shows the extent that one hot junction electrode was eroded. After the visual examination, these parts were identified and stored for further analysis. The preliminary conclusion from this visual examination was that a reaction had taken place between the copper of the hot junction electrodes and the thermoelectric leg material. What initiated this failure was not apparent from the visual examination.

Table 3-9
SNAP-23A
Converter PMC-2 Performance
versus Design Criteria

	PMC-2 Data		Design	Actual Bell Jar ⁽²⁾		Computed EOL
	EOL Actual	BOL Actual		EOL	BOL	
E_x E_t	0.945 (0.95)	0.945	0.98			
R_x R_t	1.02 (1.05)	1.035	1.02			
En_x En_t	0.985 (0.985)	0.99	1.00	0.99	1.00	0.985
Ep_x Ep_t	0.93 (0.925)	0.95	0.96	0.945	0.955	0.93
Rn_x Rn_t	0.97 (0.965)	0.96	1.0	0.95	0.96	0.97
Rp_x Rp_t	1.05 (1.06)	1.14	1.03	1.05	1.035	0.93
P_{in} watts	55.7	74.6	61.2 EOL 80.4 BOL			61.7
Efficiency	7.05	7.7 ⁽¹⁾	7.52			7.55

() - Data in brackets recorded 17 October 1969.
Other data was recorded 20 October 1969.

(1) - Design value 7.7 percent

(2) - Data from 2 couples from same lot and batch as couples used for PMC-2.

Table 3-10
Q.C. Data Summary

Material	Converter	Resistivity				Seebeck (Millivolts)			
		Spec.	Max.	Min.	Avg.	Spec.	Max.	Min.	Avg.
3P Powder	PMC-1a & 1b	450 max	395	373	382	58.0 min	64.7	63.6	64.4
3P Powder	PMC-2	450 max	355	333	342	58.0 min	62.3	61.3	61.7
3P-4P Segment	PMC-1a	450 max	384	346	362	56.0 min	62.0	58.9	60.7
3P-4P Segment	PMC-1b	450 max	369	352	358	56.0 min	60.6	58.0	59.6
3P-4P Segment	PMC-2	450 max	342	315	331	56.0 min	62.0	60.4	61.2
10P Powder	PMC-1a & 1b	350 max	260	232	248	62.0 min	69.5	68.7	69.0
10P Powder	PMC-2	350 max	261	240	247	62.0 min	68.7	67.8	68.0

Table 3-11
Emission Spectrographic Analysis
of
Foreign Material

Element	Percent Weight
FE	1
CU	30
NI	0.1
CR	0.1
SN	2
TE	10
PB	5
MN	0.3
BI	1
SB	5

NOTE: The emission spectrographic data are semi-quantitative since corrections for quantitative analysis were not made. Consequently; the results are accurate to within a factor of 1/2 to 2 times the amount present.

A microprobe analysis was also conducted. Tabulation of this analysis is shown in Table 3-12.

Table 3-12
Microprobe Analysis of Foreign Material

Element	Grey	Rose	White	Ridge-Like
CU	53	58	3	34-58
SB	45	30	--	12-16
TE	2	7	30	---
BI	--	--	2	---
PB	--	--	65	---
FE	--	2	--	14-48
SN	--	3	--	6-12

NOTE: Three phases were detected and arbitrarily designated as grey, rose and white. In addition, several areas with ridge-like structures were observed in the rose phase. Photomicrographs of the slag indicated eutectic alloys present in the slag.

Data are expressed in weight percent.
Data are within $\pm$ 15% of the amount present.

Figure 3-18. Comparison of P-Legs

Figure 3-19. Erosion of Hot Junction Electrode

3.3.2 Failure Analysis of PMC-1B

3.3.2.1 Performance Analysis of PMC-1B

PMC-1B was built as a companion to PMC-1A. Both were built to the same design prints, but the better hardware components were used for PMC-1A. The thermoelectric legs and couples were identical within the limits of manufacturing variability. The units should and did have similar thermoelectric performance (refer to previous Quarterly Reports).

PMC-1B was placed on test October 28, 1968. It ceased producing electrical power after 8,842 test hours (on October 31, 1969) as a result of an internal open in the thermopile. The end came suddenly and without warning. A BOL (beginning-of-life) data point taken six hours prior to failure indicated that the recent trend of increasing internal resistance was continuing, but had certainly not reached catastrophic proportions (refer to Section 3.1.2.2 for data).

During its lifetime, PMC-1B in addition to being thermally cycled occasionally to obtain EOL (end-of-life) data had suffered two relatively short over-temperature incidents.

- 1) On December 26, 1968 (1400 test hours), a cooling water blockage caused the cold electrode temperature to exceed 225°F for a period of approximately forty minutes during which the cold electrode temperature reached a peak of 350°F.
- 2) On January 27, 1969 (2200 test hours), a line voltage regulator malfunction caused a 25 percent increase in input power. As a result of this, the hot electrode temperature exceeded 1100°F for a period of 14 hours during which a maximum of approximately 1300°F was achieved.

Since a similar converter (EMC-3) has been exposed to comparable over-temperature conditions without suffering any significant effect, the above incidents probably did not cause the PMC-1B failure.

The first indication of the failure came at 9:52 p.m. on October 31, 1969, via a data acquisition system alarm which indicated that load current had dropped from about 3 amps to zero and, as a result, hot frame temperatures had risen from about 1050°F to 1113°F. Shortly thereafter, input power was reduced to bring the temperature back within limits.

Since substitution of an electronic load panel known to be in good working condition failed to correct the problem, it was assumed that the problem was excessive thermopile resistance. Subsequent resistance checks, using a 100 volt "megger", indicated no shorts to ground and an internal open circuit condition between Rows 4 and 8 of the thermopile. After cooling the converter to room temperature, measurement of the capacitance to ground of the two continuous portions of the thermopile indicated that the segment which terminates at Row 1 is approximately 38 couples in length which tentatively places the open between Rows 6 and 7. PMC-1B was then heated to a hot electrode temperature of 1080°F at which the internal resistance measured 100,000 ohms (the lowest value observed since failure). Upon cooling to room temperature, once again the resistance increased to greater than 20 meg-ohms.

3.3.2.2 Radiographic Analysis of PMC-1B

Radiographic analysis was conducted to gain additional information about where the open existed and what would have caused the failure. Radiographs were taken of Rows 3, 4, 5, 6, 7, 8 and 9, which were in the vicinity of where the measurements showed the open circuit existed. Radiographs were also taken of Rows 20, 30 and 39 as control samples. These radiographs showed that the top six legs in Row 5 had a "halo" around the legs. The hot junction electrodes for these same six legs had phantom appearance. All the other rows which were X-rayed appeared normal. It could not be determined from the radiographs the exact location of the open in the circuit.

3.3.2.3 Disassembly of PMC-1B

As the radiographs did not show the cause or point of failure the converter was disassembled for further analysis. The support cone, outer case and lower cover were completely cut away from the thermopile. Then the thermal insulation from the ends of the thermopile and between the rows was removed. The power output and instrumentation wires were cut and removed. All these operations were conducted in a manner designed to preserve any evidence related to the failure or cause of failure. Row 5 was resistance probed to locate the exact position of the open circuit. The open was found to exist in the hot junction electrode which connects legs at Position A7 and A8 in Row 5. All couples were removed from the thermopile in the following manner. The leg compression springs and followers were removed. Then each row of legs could be removed by extracting the boron nitride hot side insulation strips with the couples in position on their hot junction buttons and hot junction electrodes.

3.3.2.4 Evaluation of Thermopile from PMC-1B

From visual observation it was obvious that some of the legs in both Rows 5 and 16 had been involved in a massive chemical reaction. This can be seen from the photographs of Rows 5 and 16 and selected legs from Row 16 (see Figure 3-20 through 3-25). A photograph of Row 4 (Figure 3-26) is included to display the appearance of a normal row. The "N" legs involved in the chemical reaction had greatly increased in diameter at the middle of the leg. The hot ends were

discolored white and the mid-point was surrounded with a thick layer of fuzz with both white and orange coloration. The "P" legs involved in the chemical reaction had an orange band near the cold end and some increase in overall diameter. The hot junction electrodes in these areas of massive chemical reaction had much of the copper consumed in the reaction with the thermoelectric legs. All that remained of some hot junction electrodes in the affected rows was the iron plating. In fact, the open in Row 5 resulted from a loss of electrical continuity through one of the iron plate shells that comprised the hot electrode.

3.3.3 Failure Mechanism

The approach taken to determine the mechanism which initiated the failure was to thoroughly examine all the components removed from the two thermopiles. The purpose of this examination was to detect an abnormal material phase which would provide clues to the mechanism that initiated the failure reaction. These clues would in most cases require additional analysis, such as microprobe, emission spectrograph, or sectioning and polishing to obtain data for determining the primary failure mechanism.

By analysis it was verified that the chemical reaction was between the copper of the hot junction electrode and the thermoelectric leg materials. The next step was the determination of the mechanism by which this reaction was initiated. The reaction which had taken place in Rows 5 and 16 of PMC-1B was so far advanced that they did not contain any clues of how the reaction started. A check was conducted to verify that none of the "P" legs were mounted upside down, i. e. , BAT material at the hot end and the 3P at the cold end.

The rest of the thermopile components were carefully examined visually for evidence of the start of a reaction. Metallic nodules were found on some legs and hot junction buttons. To determine if these nodules were the start of the observed chemical reaction a chemical analysis will be conducted. The best method to do this analysis is by microprobe. This analysis has been delayed because of microprobe equipment breakdown; therefore chemical analysis of the nodules will be completed next quarter. The results of this analysis plus any determination of failure mechanism will also be included in the next quarterly report.

Figure 3-20. Converter PMC-1B Thermoelectric Couples
(Row 5)

Figure 3-21. Converter PMC-1B Thermoelectric Couples
(Row 16)

Figure 3-22. Converter PMC-1B Thermoelectric Legs from Row 16

Figure 3-23. Converter PMC-1B Thermoelectric Legs from Row 16
(Legs A8 through A10 from right to left)

Figure 3-24. Thermoelectric N-Leg from Row 16
of Converter PMC-1B (Leg A7)

Figure 3-25. Thermoelectric P-Leg from Row 16
of Converter PMC-1B (Leg A6)

Figure 3-26. Converter PMC-1B Thermoelectric Couples (Row 4)

3.4 PROTOTYPE MOCKUP CONVERTER NO. 3 (PMC-3)

PMC-3 will be built to replace PMC-2 on the FPMS. It will be the same basic design as PMC-2 but does require some modification of design. These modifications were related to the use of PMC-1B cold frame and the requirement to mate with FPMS. The leg material powder batches with the best QC data were selected for leg manufacture.

3.4.1 Component Design Changes

The design of the outer case, cold frame and hot frame required some design modifications. The outer case design for PMC-2 was modified by changes of inside and outside diameter so that the cold frame from PMC-1B could be used. This change in outside diameter of outer case will result in PMC-3 not meeting the dimensional requirements of Westinghouse Interface Drawing No. 914E462. A print for the cold frame was prepared so that the cold frame from PMC-1B could be modified for PMC-3. The print for PMC-2 hot frame was modified to show the taper which would correspond to the heat spud taper of FPMS. The rest of the components were not changed from those of PMC-2.

3.4.2 Selection of Thermoelectric Material

Selection of thermoelectric material for PMC-3 was given special consideration in an attempt to improve PMC-3 electrical performance over that exhibited by PMC-2. In making this selection, the quality control measurements of electrical resistivity at room temperature and Seebeck voltage of various batches were examined and evaluated. This examination revealed the major variation indicated for the other thermoelectric materials. Thermoelectric material batch selection for PMC-3 was therefore confined to the hot P segment material. Quality control measurements from all P hot segment batches available at the time of selection are listed in Table 3-13. The data shows a variation of 2 mv in Seebeck voltage and 20 micro-ohm-inches in room temperature resistivity among the batches. In addition, the relative power number, E^2/p , indicates a variation of 10 percent. Based on the Seebeck voltage and the relative power number, batch B-90 was selected for PMC-3.

The above selection technique will not guarantee that converter performance will fall in the design range set down for SNAP-23A. Only an ingradient test performed at or near the SNAP-23A cold and hot junction temperatures can provide expected couple performance in a converter. As such, couples made for PMC-3 will be tested ingradient prior to converter assembly.

Table 3-13
Hot Segment Material for P Leg

<u>Batch No.</u>	<u>$\bar{E}$ mv*</u>	<u>$\bar{\rho} \mu\Omega$ in.**</u>	<u>E^2/ρ</u>
77	62.4	370.5	10.5
78	62.0	376.0	10.2
79	62.2	362.8	10.7
80	63.3	365.0	11.0
81	63.2	360.3	11.1
82	63.5	368.8	10.9
83	63.4	369.5	10.9
84	63.1	357.3	11.2
85	63.6	375.0	10.8
86	63.9	372.5	11.0
87	63.6	373.5	10.8
89	64.1	375.8	10.9
90	63.6	364.3	11.1 PMC-3
91	63.6	364.8	11.1
92	62.4	353.8	11.0
93	62.0	352.5	10.9
94	62.5	354	11.0

*Th = 875°F, Tc = 75°F; Average of four segments.

**Temperature = 75°F; Average of four segments.

3.5 INTERFACE WITH WESTINGHOUSE

After PMC-2 displayed its anomalies the possibility was considered of mounting PMC-1B on FPMS. Specific interface dimensions were transmitted to WANL for determination of acceptability of mating PMC-1B on the system. This effort was aborted when PMC-1B failed due to an open in the electrical circuit.

The details of controlling the cold side heat input for fire module testing was described to WANL and Hittman at the November interface meeting. This resulted in a request for cold side heater input to be recorded during the testing. During the fire module testing Westinghouse and Hittman were kept advised of progress and were transmitted data. Westinghouse and Hittman personnel were also present at 3M to observe certain testing sequences.

3.6 FIRE SAFETY TEST

SNAP-23A thermoelectric converter simulation modules were constructed and tested to cold frame temperature profiles, as defined by Hittman Association, which could be expected from a 1475°F and 1850°F fire of approximately 1/2 hour duration. The Test Plan and Procedures Document (see Appendix A) was used for conducting the fire safety tests.

In this report deviations from the Test Plan Procedure are noted and all data obtained from the various test phases are presented.

3.6.1 Test Module Design

Four different test module designs were used for this test program. One test module was made of a cylinder of Min-K 2000 the same size as the six-couple module. It was used for test fixture tare heat loss determination. One dummy module was made to fit in the test fixture to simulate the thermal conductance

of the six-couple module. It was constructed of material (molybdenum cold frame) that would not be damaged by the temperatures of the fire test. It was used to check out the ability of the test fixture and control equipment to simulate the time-temperature conditions of the Hittman supplied curves. One six-couple module was made with thermocouples installed on hot buttons and cold caps of several couples, in addition to the external thermocouple on the hot and cold frames. This module was used to establish the temperature differential between the externally measured temperatures and the leg junction temperatures. Four six-couple modules were made as shown by Figure A-1 of the test plan with the following exceptions:

- In one unit, indium foil was omitted from between the cold cap and followers.
- Powdered Min-K 1301 was packed with the Microquartz insulation between the outer case and the cold frame.

Three units with indium foil were used for the fire tests. Two for 1475°F fire tests and one for 1850°F fire tests. These three units were disassembled after the fire test sequence and visually examined for effects of exposure to the elevated temperatures.

3.6.2 Test Fixture Modifications

Several modifications to the test fixture were made to improve test accuracy. The following is a description of those changes which are also shown by Figure 3-27.

- 1) Copper foil was placed between the Armco iron standard and module hot frame. Larger studs were used to attach module to standard.
- 2) A copper plug was made to smooth the angular temperature gradient in the Armco iron standard.

- 3) Guard heater differential thermocouples were installed at inner and outer radial locations instead of being embedded in the Min-K-2000 ring insulators.
- 4) Only one differential thermocouple was used for the Armco iron standard guard heater (two are shown on the drawing included in the test plan).

Figure 3-27.

Fire Module Test Stand

Modifications To Test Stand⁽¹⁾

3.6.3 Test Procedures

3.6.3.1 Dummy Module Test

The dummy module was installed in the Fire Module Test Stand (see Figure 3-27) and the 1475°F and 1850°F cold end temperature versus time programs were used to check out fixture heating rate and cooling rate capabilities. These tests were rerun with additional instrumentation to display a plot of cold end heater power, at the request of Westinghouse and Hittman personnel.

Several changes to the dummy module test plan were made.

- 1) Bell jar containing fixture was evacuated to 40-50 μ pressure range before backfilling.
- 2) Fill gas used was nitrogen at a pressure of approximately 1.0 atmosphere.
- 3) Radial temperature gradients at guard heater locations were controlled but differences were not recorded.
- 4) Coolant mass flow rate, inlet and outlet temperatures were not recorded.
- 5) Heater power at cold end was controlled by an electronic programmer which followed Hittman supplied temperature versus time plots of cold frame temperature for the 1475°F and 1850°F fire transients.

3.6.3.2 Instrumented Couple Module Test

The instrumented six-couple module was not mounted in the fire module test stand for measurement of internal temperature drops. This test was satisfactorily completed by raising the module hot and cold frame temperatures to 1047°F and 148°F respectively, in the processing station. The module was insulated with a layer of microquartz during this test.

3.6.3.3 Fixture Calibration Test

This test was added to the planned sequence of testing. The purpose was to determine what quantity of heat would flow through the Armco iron standard under conditions where ideally no heat flow should occur. A cylinder of Min-K-2000 was installed in the fire module test stand. Test stand tare heat loss correction was measured with and without mid-guard heater energized, with cold side temperature the same as hot side temperatures, and with cold and hot side temperature at BOL test temperatures (THEX = 1050°F, TCEX = 155°F).

3.6.3.4 Module Test (1475°F Fire Transient)

All six-couple module tests were run in "open circuit" condition. The test was conducted according to the test plan with the following exceptions.

- 1) The bell jar was backfilled with nitrogen gas at approximately 1.0 atmosphere pressure.
- 2) Additional post-fire conductance data was taken at a cold junction temperature below 400°F.
- 3) Radial temperature gradients at guard heaters were not recorded.
- 4) Coolant flow rate and temperature data was not recorded.
- 5) Heater power at cold end was programmed rather than controlled manually to follow Hittman curves. Heater input power was recorded.

The 1475°F fire transient was rerun with a second module, following the test procedures with deviations described above. Also, during this 1475°F rerun and subsequent tests, the actual temperatures rather than temperature differentials were recorded at the instrumented points of the Armco iron standard.

3.6.3.5 Module Test (1850°F Fire Transient)

The six-couple module was operated under "open circuit" conditions, and the test conducted according to the test plan with the following exceptions.

- 1) Bell jar was backfilled with nitrogen gas at 1.0 atmosphere.
- 2) Radial temperature gradients were not recorded.
- 3) Coolant flow rate and temperature data was not recorded.
- 4) Heater power at cold end was programmed rather than controlled manually to follow Hittman curves. Heater input power was recorded.
- 5) Additional post-fire conductance data was taken at 400°F and a lower cold junction temperature.

3.6.4 Test Results

3.6.4.1 Raw Data

The raw data from all the tests conducted are included in Appendix B.

3.6.4.2 Dummy Module Test

The results of the initial dummy module test for an 1850°F fire indicated a poor mechanical contact between the hot frame and the Armco iron standard as indicated by Figure B-1 and raw data A-6 in Appendix B. To eliminate the poor mechanical contact, two design changes were incorporated in subsequent test hardware. Copper foil was added between the Armco iron standard and the module hot frame, and larger studs for attaching the Armco iron standard to the module were used, thus allowing a greater torque on the hold down nuts. Both of these changes greatly reduced the thermal impedance of the standard-module interface. Subsequent test results indicated that the test fixture was suitable for the program. The time trace of measured cold side temperatures showed that this temperature could be controlled within $\pm 50^\circ\text{F}$ of the values of the Hittman supplied time-temperature curve.

3.6.4.3 Instrumented Couple Module Tests

Table 3-14 is a summary of the data taken during the test with the instrumented couple module. This table shows an adequate similarity between the six-couple module temperature differential and the PMC-2 type converter.

Table 3-14
Instrumented Couple Test Module
Comparison with PMC-2 Converter

	Six-Couple Module	Average of Several PMC-2 Type Converters
Hot Frame External	1047	1050
External-Internal Temperature Difference	35	52
Hot Button (Average of 3T/C's)	1012	998
Cold Cap (Average of 2T/C's)	185	190
External-Internal Temperature Difference	37	35
Cold Frame External	148	155

3.6.4.4 Fixture Calibration Test Results

When the cold end heater block and Armco iron standard were controlled at the same temperature, heat flow through the standard ideally should be zero. Data was taken with and without the middle guard heater energized, since it was postulated that the heat flow error would be much greater with the middle guard de-energized. Data was reduced and the results tabulated in Table 3-15.

Based upon the test results and the temperatures for which conductance is to be determined, it was decided to subtract 1.4 watts from the heat flow indicated by the Armco iron standard for all module data reductions.

Table 3-15
25 November 1969 Calibration Test Results

		Temperature °F		
		Hot	Cold	Standard Heat Loss
Hot and Cold Ends Equal Temperature	Mid Guard De-Energized	1047	1056	+ 1.20 watts
	Mid Guard Energized	1059	1058	+ 0.86 watts
Hot End at High Temperature, Cold End at Low Temperature	Mid Guard De-Energized	1066	155	+ 1.18 watts
	Mid Guard Energized	1063	155	+ 1.45 watts

3.6.4.5 1475°F and 1850°F Fire Module Test Results

The raw data from these 1475°F and 1850°F fire tests were used to calculate equivalent conductance for a PMC-2 converter. First step was to calculate the conductance for the test six-couple modules.

The conductance of the fire module was determined from measured heat flow through an iron standard and measured temperature at the hot and cold ends of the module as shown in Equation A. The iron standard was in thermal series with the module and located adjacent to the hot side as illustrated in Figure 3-27. A pair of differential thermocouples were located on the iron standard to determine the temperature gradient ($\Delta T / l$) in the iron. This gradient is then converted to heat flow using the known thermal conductivity (K) of iron and the area (A) of the iron standard ($Q = KA \frac{\Delta T}{l}$). A correction for radial heat losses from the module was made by a calibration experiment.

$$K(6\text{-couple Module}) = \frac{Q \text{ flow through 6 couple module}}{T_{\text{(hot frame)}} - T_{\text{(cold frame)}}} \quad (A)$$

The effective conductance of a full sized SNAP-23A converter was determined based on measured fire module conductance with adjustments for number of couples and losses through the structures. The conductance of the couples and Min-K surrounding the legs was first determined by subtracting the conductance of the outer case from the measured module conductance. This quantity was then multiplied by the ratio of couples in the converter to couples in the module to obtain the respective conductance of the converter without structural losses. The effective conductance equation with the addition of structural losses is shown as Equation (B).

$$K_{\text{conv}} = \frac{280}{6} (K_{\text{mod}} - K_{\text{case}}) + K_{\text{sc}} + K_{\text{lc}} \quad (\text{B})$$

The conductance of the module case was calculated treating the structure as a cylindrical fire with axial heat transfer along the wall and radial heat transfer to the cold frame. The conductance of the converter case (support case and lower case) was also determined from calculation reported in Quarter No. 9 and earlier analysis.

A sample calculation is shown below for the 1475°F fire, second test (Test of 3 December 1969).

Pre-Fire BOL Conditions

$$\begin{aligned} K_m &= \frac{Q \text{ (flow through 6-couple module)}}{T_{\text{(hot frame external)}} - T_{\text{(cold frame external)}}} \\ &= \frac{25.57 \text{ watts}}{1043^\circ\text{F} - 156^\circ\text{F}} \\ &= 0.0288 \text{ watts}/^\circ\text{F} \\ K_c &= \frac{280}{6} \left[K_m - K_{\text{mo}} \right] + K_{\text{sc}} + K_{\text{lc}} \\ &= \frac{280}{6} \left[0.0288 \frac{\text{watts}}{^\circ\text{F}} - 0.0102 \frac{\text{watts}}{^\circ\text{F}} \right] + 0.072 \frac{\text{watts}}{^\circ\text{F}} \\ &= 0.94 \text{ watts}/^\circ\text{F} \end{aligned}$$

where

K_m = conductance of the 6-couple module

K_{mo} = conductance of the module outer case

K_c = conductance of the PMC-2 converter

K_{sc} = conductance of the PMC-2 converter support cone

K_{lc} = conductance of PMC-2 lower cover

Table 3-16 compares those calculated values with a value calculated values with a value calculated for PMC-2 with the design analysis computer code.

Table 3-16
Conductance Values (K) - Watts/°F

Temperatures °F			Method of K Determination
Hot External	Cold External	K	
1050	155	0.844	TEG 18A Calculations for a PMC-2 Converter
1053	160	0.83*	Calculated with the two Proceeding Formulas
1043	156	0.94*	Calculated with the two Proceeding Formulas
1038	161	1.04*	Calculated with the two Proceeding Formulas

*Data used to calculate these conductance values was that taken with six-couple modules before fire simulation temperature excursions.

Tables 3-17 and 3-18 are the reduced data from the fire module tests. The test module and converter conductance values in these two tables were calculated by using equations (A) and (B) previously described.

3.6.5 Post-Test Fire Module Disassembly

The modules were disassembled with Westinghouse and Hittman personnel in attendance. During disassembly the following major changes were noted:

- A) In the 1475°F fire module, the cold end segment of the "P" leg melted. This is normal since during this test the element temperature exceeded the melting temperature of the material. The followers were locked in the cold frame holes probably due to warping of the material but still in contact with the cold caps. The reduced length of the "P" legs would account for the increased conductivity observed after the test.
- B) In the 1850°F fire module, the elements (N and P) experienced some melting in addition to that noted for the 1475°F test. In addition, the top (upside in the fixture) of the aluminum cold frame melted down to the first couple with the molten material probably running into the follower holes. The followers and some elements were skewed, however, all followers were still in contact with their cold cap. The increased conductivity is probably due to the reduced heat path length resulting from the shortening of the legs due to melting and plastic flow.

In no case was the outer case of the module breached and the external appearance was that of a device which had been exposed to a high temperature environment. None of the components appear to have reacted with each other. The included photographs shows condition of the internal components after a 1475°F incident fire (Figure 3-28) and an 1850°F incident fire (Figure 3-29).

Table 3-17
Fire Test Reduced Data

Test Module Conductance and Predicted Converter Total Conductance

PRE-FIRE

	BOL Conditions (1050/155)			First Hold Point (400°F)			Second Hold Point (600°F)			Max. ext. Cold Frame Temperatures
	THEX/ TCEX °F	Test Module W/F	Conv. W/F	THEX/ TCEX °F	Test Module W/F	Converter W/F	THEX/ TCEX °F	Test Module W/F	Converter W/F	
First 1475° Test	1053/ 160	0.026	0.83	1057/ 395	0.029	0.93	1072/ 595	0.033	1.07	1152° F
Second 1475°F Test	1043/ 156	0.029	0.94	1098/ 402	0.030	0.98	1152/ 602	0.033	1.10	1152° F
1850°F Test	1038/ 161	0.031	1.04	1088/ 400	0.033	1.15	1130/ 601	0.036	1.23	1742° F

- NOTES:
- THEX is hot frame external temperature.
 - TCEX is cold frame external temperature.
 - W/F is watts conductance per external temperature differential °F.
 - 0.94 shown in sample calculations.

Table 3-18
Fire Test Reduced Data

Test Module Conductance and Predicted Converter Total Conductance

POST-FIRE

	Third Hold Point (600°F)			Fourth Hold Point (400°F)			Last Hold Point (Optional)		
	THEX/ TCEX °F	Test Module W/F	Converter W/F	THEX/ TCEX °F	Test Module W/F	Converter W/F	THEX/ TCEX °F	Test Module W/F	Converter W/F
First 1475°F Test	1070/ 595	0.036	1.23	1054/ 400	0.033	1.14	---	---	---
Second 1475°F Test	1172/ 604	0.036	1.22	1153/ 406	0.032	1.08	1126/ 190	0.029	0.96
1850°F Test	1104/ 600	0.052	1.99	1053/ 400	0.050	1.89	960/ 202	0.051	1.97

- NOTES: (A) THEX is hot frame external temperature.
(B) TCEX is cold frame external temperature.
(C) W/F is watts conductance per external temperature differential °F.

Figure 3-28. Cut-Away View of Fire Module
After 1475°F Test.

Figure 3-29. Cut-Away View of Fire Module
After 1850°F Test.

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 degradation analysis.

4.2 BELL JAR TESTS

A bell jar test evaluation of PMC-2 couples was completed during the first part of the quarter. Test results in the form of experimental-to-theoretical performance ratios are presented in Table 4-1. These bell jar values correlate well with the leg performance observed during PMC-2 (pre-build) processing.

Table 4-1
PMC-2 Bell Jar Test Performance Ratios

Leg Type	Seebeck Ratio		Resistance Ratio ⁽¹⁾		Power Ratio ⁽²⁾	
	EOL	BOL	EOL	BOL	EOL	BOL
N-leg	0.99	1.00	0.95	0.96	1.03	1.04
P-leg	0.945	0.955	1.05	1.035	0.85	0.88

(1) Theoretical resistance includes no extraneous resistance allowance.

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

4.3 TEN-COUPLE MODULES

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

4.3.1 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 (10,000 hours to present) for modules 1 and 3 is summarized in Table 4-2.

Table 4-2
SNAP-23A Ten-Couple Module Performance Analysis
(Modules 1 and 3)

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

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

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

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

Thermal Insulation = MIN-K 1301	○ 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 4-2
Resistance Ratio
versus
Elapsed Time
(Module 1)

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

Thermal Insulation = MIN-K 1301

Contact Pressure = 250 psi

Hot Electrode = 1100°F

Cold Electrode = 190°F

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

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

△ P-Leg, Even, Bonded, Hard Nose

× N-Leg, Even, Bonded, Hard Nose

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

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

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

○ P-Leg, Odd, Simul. Pressed, Hard Nose
◻ N-Leg, Odd, Simul. Pressed, Hard Nose
Δ P-Leg, Even, Bonded, Hard Nose
X N-Leg, Even, Bonded, Hard Nose

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

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

Thermal Insulation = Microquartz	○ P-Leg, Odd, Simul. Pressed, Soft Nose
Contact Pressure = 150 psi	□ N-Leg, Odd, Simul. Pressed, Hard Nose
Hot Electrode = 1100°F	Δ 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

X N-Leg, Even, Bonded, Hard Nose

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

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

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

4.3.2 Module 5 through 12

Statistical analyses of the data taken on 10-couple modules 5 through 12 at their respective 14,500-, 15,000- 15,500-, 15,000-, and 16,500-hour points were completed during the quarter. Tables 4-3 through 4-14 present summaries of the statistical analyses completed thus far. Figures 4-7 through 4-19 graphically present the N- and P-leg average Seebeck, resistance, and power ratios versus time for both the microquartz modules and the Min-K 1301 modules; significant effects are shown on a second scale. Analysis of these graphs indicate the following:

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

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

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

Those legs with iron hot buttons (factor B+) exhibit a resistance ratio 0.134 higher than those with molybdenum buttons (factor B-). As a result of the first and second order interactions of hot junction temperature and hot contact pressure (factors C, D, and DC), the various combinations result in the following resistance ratios after 16,500 hours of operation.

Hot Junction Temperature, °F	Contact Pressure, psi	Resistance Ratio
1000 (C-)	150 (D-)	1.23
1000 (C-)	250 (D+)	1.08
1100 (C+)	150 (D-)	1.62
1100 (C+)	250 (D+)	1.11

Differences between the lower (-) and upper (+) levels of each of the significant effects are increasing with time, thus increasing their significance. The resistance of the C+, D- combination increased significantly during the past quarter, while that of the other combinations did not change significantly.

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

Those legs with iron hot buttons (factor B+) exhibit a power ratio 0.062 lower than those with molybdenum buttons (factor B-). The various combinations of hot

junction temperature (factor C) and hot contact pressure (factor D) result in the following power ratios after 16,500 hours of operation:

Hot Junction Temperature, °F	Contact Pressure, psi	Power Ratio
1000 (C-)	150 (D-)	0.85
1000 (C-)	250 (D+)	0.96
1100 (C+)	150 (D-)	0.63
1100 (C+)	250 (D+)	0.92

Differences between the lower (-) and upper (+) levels of each of the significant effects are increasing with time, thus increasing their significance. The power ratio of the C+, D- combination decreased significantly during the past quarter, while that of the other combinations did not change significantly.

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

The Seebeck ratio of those legs with an 1100°F hot junction temperature continues to decrease and is now 0.03 lower than that of legs with a 1000°F hot junction temperature (whose voltage has remained relatively stable).

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

As a result of the first and second order interactions of hot junction temperature and hot contact pressure (factors C, D and CD) the various combinations result in the following resistance ratios after 16,500 hours of operation.

Hot Junction Temperature, °F	Contact Pressure, psi	Resistance Ratio
1000 (C-)	150 (D-)	1.01
1000 (C-)	250 (D+)	1.01
1100 (C+)	150 (D-)	1.13
1100 (C+)	250 (D+)	0.92

Resistance changes during the past quarter were relatively small.

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

The various combinations of hot junction temperature (factor C) and hot contact pressure (factor D) result in the following power ratios after 16,500 hours of operation:

Hot Junction Temperature, °F	Contact Pressure, psi	Power Ratio
1000 (C-)	150 (D-)	0.99
1000 (C-)	250 (D+)	1.04
1100 (C+)	150 (D-)	0.87
1100 (C+)	250 (D+)	1.04

Differences between the lower (-) and upper (+) level of each of the significant effects are increasing slightly with time. Power ratio changes during the past quarter were relatively small.

- P-leg Seebeck voltage – Microquartz Modules (Figure 4-13):

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

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

The resistance of the bonded type P-leg is increasing while that of the simultaneously-pressed type has stabilized. However, the resistance ratio of the bonded type is currently 0.38 lower than that of the simultaneously pressed variety.

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

The power ratio of the simultaneously-pressed P-legs has stabilized while that of the bonded type is decreasing. However, the power ratio of the bonded type is currently 0.06 higher than that of the simultaneously-pressed variety.

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

The simultaneously-pressed legs continue to exhibit a Seebeck ratio approximately 0.12 higher than their bonded counterparts. The Seebeck ratio of legs with an 1100°F hot junction temperature continues to decrease more rapidly than the ratio for 1000°F legs (the lower temperature legs now exhibit a 0.08 higher Seebeck ratio than the 1100°F legs).

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

The resistance of the simultaneously-pressed legs is decreasing while that of the bonded type is stable. However, the resistance ratio of the simultaneously-pressed type is still 0.27 higher than that of the bonded type legs. The 1000°F legs continue to exhibit a 0.07 higher resistance ratio than those with an 1100°F hot junction temperature. The resistance ratio of legs with a 250 psi contact pressure remains approximately 0.10 lower than that of the 150 psi legs. Those legs with iron hot buttons (factor B+) exhibit a resistance ratio 0.06 lower than those with molybdenum buttons (factor B-).

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

The various combinations of leg manufacturing technique (factor A) and hot junction temperature (factor C) result in the following power ratios after 16,500 hours of operation:

P-Leg Type	Hot Junction Temperature, °F	Power Ratio
Simultaneously Pressed (A+)	1000 (C-)	0.92
Simultaneously Pressed (A+)	1100 (C+)	0.83
Bonded (A -)	1000 (C-)	0.93
Bonded (A -)	1100 (C+)	0.84

The power ratios of bonded legs at 1000°F and simultaneously pressed legs at 1100°F tend to be fairly stable, while those associated with bonded legs at 1100°F and simultaneously pressed legs at 1000°F are decreasing and leveling-off respectively (see Figure 4-19). The power ratio of legs with a 250 psi contact pressure remains approximately 0.06 higher than that of the 150 psi legs. Those legs with iron hot buttons exhibit a power ratio 0.06 higher than those with molybdenum buttons.

Based on the foregoing analyses the following conclusions can be drawn from modules 5 through 12 after 16,500 test hours:

1. As concluded earlier based on modules 1 and 3, N-type and particularly P-type legs are more stable and produce more power when operated in a Min-K 1301 as opposed to a microquartz environment (see Figure 4-20).
2. Those legs (both P- and N-type) operating at the lower hot junction temperature (1000°F) are outperforming their 1100°F counterparts from a relative power standpoint (see Figure 4-19).
3. As concluded earlier based on modules 1 and 3, legs with 250 psi contact pressure produce more power than comparable legs with 150 psi contact pressure. In the case of the N-legs the higher pressure resulting in greater initial performance and more stability. The primary difference in P-leg performance with 250 psi is better seat-in and thus greater initial power output than the 150 psi P-legs.

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

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

Effect	Mean Effect and Test Hours										
	225	2500	5500	8500	11500	13500	14500	15000	15500	16000	16500
AVERAGE	1.01750	1.01468	1.01417	1.01948	1.02302	1.02198	1.02156	1.01626	1.01645	1.01884	1.01239
A	0.00375	0.00104	0.00251	0.00271	0.00480	0.00104	-0.00312	-0.00291	-0.00500	0.00229	0.00646
B	-0.00125	-0.00021	0.00001	-0.00104	-0.00020	-0.00646	-0.00813	-0.00166	-0.00125	-0.00146	0.01021
AB	0.00250	0.00811	0.00584	0.00771	0.00605	0.00646	0.00812	0.00876	0.01165	0.00644	0.00354
C	-0.00168	-0.00854	0.00041	-0.00894	-0.00727	-0.00604	-0.00270	-0.00834	-0.00958	-0.01021	-0.01729
AC	-0.00458	-0.00356	-0.00291	-0.00354	-0.00687	-0.00146	-0.00480	-0.00626	-0.00833	-0.00396	0.00189
BC	-0.00458	0.00269	0.00209	0.00521	0.00313	0.00104	0.00720	0.00499	0.00542	0.00479	0.01314
ABC	0.00082	0.00771	0.00041	0.00231	-0.00228	0.00146	0.00730	0.00291	0.00417	0.00104	-0.00604
D	0.00165	0.01271	0.00416	0.00436	0.00562	0.00311	0.00165	0.00541	0.00415	0.00561	-0.00021
AD	0.00125	0.01104	0.00334	0.00396	0.00352	0.00019	0.00730	0.00749	0.00375	0.00271	0.01146
BD	0.00125	-0.00521	0.00084	-0.00229	-0.00147	0.00019	0.00230	-0.00126	-0.00250	-0.00354	0.00521
ARD	-0.00085	-0.00354	0.00166	-0.00439	-0.00438	-0.00189	-0.00395	-0.00834	-0.00710	-0.00314	-0.01146
CD	0.01083	0.01646	0.01209	0.01146	0.01230	0.00646	0.00773	0.01041	0.01082	0.01271	0.00521
ACD	0.00207	0.00479	-0.00124	0.00271	-0.00145	0.00104	0.00312	0.00499	0.00457	0.00146	0.00939
BCD	0.00207	-0.00396	-0.00124	-0.00104	-0.00145	0.00104	0.00312	0.00124	0.00332	-0.00229	0.00564
ABCD	-0.00168	-0.00229	-0.00291	-0.00479	-0.00270	-0.00354	-0.00728	-0.00334	-0.00043	-0.00354	-0.00854

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

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

Effect	Mean Effect and Test Hours										
	225	2500	5500	8500	11500	13500	14500	15000	15500	16000	16500
AVERAGE	1.01104	1.02625	1.08082	1.15843	1.17688	1.22354	1.24781	1.24501	1.26762	1.26979	1.25969
A	-0.00126	0.01500	0.00707	-0.02646	-0.03126	-0.04000	-0.04855	-0.04499	-0.05373	-0.04416	-0.03395
B	0.02874	0.01500	0.02708	0.02479	0.08874	0.09375	0.09145	0.09251	0.09877	0.11709	0.13480
AB	0.00209	0.00750	-0.01085	0.02811	0.00376	0.00082	0.00312	0.00251	0.00875	-0.01416	-0.02688
C	0.01041	-0.03833	0.04210	0.11521	0.11374	0.17043	0.20355	0.20209	0.22418	0.22084	0.20648
AC	0.01041	-0.00917	0.00332	-0.03896	-0.03459	-0.02750	-0.03978	-0.04376	-0.05500	-0.03206	-0.01770
BC	-0.03459	0.00082	0.01082	-0.00271	0.05541	0.05125	0.05273	0.05624	0.06000	0.06669	0.08855
ABC	-0.02459	0.00667	-0.01790	0.02646	0.00374	0.00418	0.00855	0.00209	0.00918	-0.00041	-0.00727
D	0.03876	-0.03290	-0.10625	-0.16814	-0.17291	-0.23832	-0.27187	-0.28166	-0.30543	-0.31709	-0.32813
AD	0.02791	0.03710	0.02667	0.04689	0.04541	0.04710	0.05895	0.06334	0.05625	0.04916	0.05355
BD	-0.02209	-0.02540	-0.00082	0.00314	-0.04459	-0.04915	-0.04855	-0.04916	-0.04625	-0.06209	-0.03270
ABD	0.00376	0.00460	-0.00175	-0.03189	-0.01291	-0.00457	0.00312	0.00084	-0.00292	0.00166	-0.01937
CD	-0.01791	0.00707	-0.01500	-0.06229	-0.05959	-0.10582	-0.12980	-0.12374	-0.15500	-0.16084	-0.18187
ACD	-0.04041	-0.00458	-0.01457	0.00689	-0.01126	-0.01625	-0.01312	-0.00459	-0.00583	-0.01374	0.00395
BCD	0.03459	-0.01208	0.00042	0.00314	-0.05126	-0.05250	-0.05312	-0.05959	-0.05082	-0.08749	-0.05980
ABCD	0.00209	-0.01043	-0.01250	-0.04104	-0.01959	-0.02707	-0.03230	-0.02874	-0.03200	-0.00959	-0.02562

Table 4-5
SNAP-23A N-Leg Statistical Analysis Summary (Microquartz Modules)
(Power Ratio)

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

Effect	Mean Effect and Test Hours										
	225	2500	5500	8500	11500	13500	14500	15000	15500	16000	16500
AVERAGE	1.02756	1.00484	0.95561	0.90799	0.90014	0.87017	0.85609	0.85040	0.84351	0.84274	0.84031
A	0.01202	-0.01382	-0.00425	0.01528	0.02681	0.02278	0.01919	0.01520	0.01726	0.02391	0.02294
B	-0.03430	-0.01342	-0.02408	-0.02685	-0.05964	-0.06665	-0.06369	-0.05405	-0.05649	-0.06476	-0.06204
AB	0.00055	0.00838	0.02135	0.00005	0.00689	0.01007	0.00981	0.01135	0.01316	0.01911	0.02759
C	-0.01930	0.02070	-0.03335	-0.09478	-0.08924	-0.11503	-0.12394	-0.13115	-0.13956	-0.13494	-0.13301
AC	-0.02305	0.00205	-0.00838	0.01802	0.01294	0.01450	0.01591	0.01539	0.01884	0.01049	0.00801
BC	0.02828	0.00450	-0.00600	0.00825	-0.02526	-0.01907	-0.01871	-0.01310	-0.01401	-0.01174	-0.01856
ABC	0.02918	0.00905	0.01797	-0.00805	-0.00799	-0.00005	0.00664	0.00425	0.00209	-0.00126	-0.00474
D	-0.04062	0.05740	0.10157	0.12982	0.13344	0.16115	0.17151	0.18495	0.19121	0.19811	0.19819
AD	-0.02812	-0.01430	-0.01885	-0.02242	-0.02524	-0.02877	-0.02279	-0.02490	-0.02419	-0.02136	-0.01254
BD	0.02830	0.01410	-0.00102	-0.00505	0.01686	0.01675	0.01684	0.01150	0.00531	0.00756	0.00049
ABD	-0.00225	-0.01100	0.00695	0.00990	0.00419	0.00132	-0.00796	-0.01375	-0.01059	-0.00166	0.00016
CD	0.04440	0.02662	0.03330	0.05118	0.05081	0.06002	0.07039	0.06740	0.08354	0.08759	0.09301
ACD	0.04695	0.01287	0.00972	0.00972	0.01179	0.02210	0.02544	0.02359	0.02549	0.02391	0.02059
BCD	-0.03427	0.00412	-0.00475	0.00055	0.02644	0.02638	0.02731	0.02945	0.02459	0.03669	0.02861
ABCD	-0.00848	0.00527	0.00777	0.01520	0.01071	0.01335	0.01166	0.01625	0.01994	0.00226	0.00569

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

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

Effect	Mean Effect and Test Hours										
	225	2500	5500	8500	11500	13500	14500	15000	15500	16000	16500
AVERAGE	1.00386	1.01218	1.01531	1.01114	1.00896	1.00177	0.99947	1.00073	1.00271	1.00761	0.99802
A	0.00814	0.00104	0.00357	0.00311	0.00624	0.00979	0.01395	0.00896	0.01291	0.01021	0.01229
B	0.00189	0.00229	0.00232	-0.00314	-0.00876	-0.00896	-0.01480	-0.01479	-0.01459	-0.00854	-0.00646
AB	-0.00104	0.00061	-0.00313	-0.00396	-0.00209	-0.00771	0.00020	-0.00229	-0.00209	-0.00354	-0.00021
C	0.01644	0.01271	0.01063	-0.00271	-0.01541	-0.01939	-0.02480	-0.02314	-0.02334	-0.03686	-0.02979
AC	0.00021	-0.00811	-0.00562	-0.00439	-0.00209	0.00021	0.00520	0.00106	0.00416	0.00314	0.00311
BC	-0.00854	0.00314	0.00312	-0.00564	-0.01209	-0.01104	-0.01605	-0.01519	-0.01084	-0.00811	-0.01064
ABC	-0.00481	0.00396	0.00187	0.00104	-0.00041	-0.00314	0.00395	0.00061	0.00166	0.00189	-0.00104
D	-0.00229	0.00689	0.00188	0.00854	0.00541	0.00729	0.00270	0.00229	0.00249	0.00311	0.00021
AD	-0.01686	-0.01314	-0.01437	-0.00644	-0.01041	-0.00896	-0.01360	-0.01271	-0.00916	-0.00769	-0.00854
BD	0.00689	0.00311	0.00188	-0.00019	0.00459	0.00979	0.00815	0.00354	0.00584	0.00106	-0.00229
ABD	0.00896	0.00814	0.01063	0.00979	0.00041	-0.00146	-0.00855	-0.00646	-0.00751	-0.00314	-0.00104
CD	-0.00436	-0.00896	-0.00812	0.00104	-0.00541	-0.01479	-0.00605	-0.01396	-0.01541	-0.01146	-0.01981
ACD	0.00271	0.00021	-0.00687	-0.00314	-0.00624	-0.00269	-0.00805	-0.00896	-0.00376	-0.00396	-0.00521
BCD	-0.00104	0.00146	-0.00062	0.00311	0.00876	0.00856	0.01020	0.00479	0.00874	0.00729	0.00104
ABCD	-0.00061	0.00229	0.00562	0.00729	-0.00741	-0.00104	-0.00980	-0.00521	-0.00791	-0.00521	-0.00106

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

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

Effect	Mean Effect and Test Hours										
	225	2500	5500	8500	11500	13500	14500	15000	15500	16000	16500
AVERAGE	0.98907	0.98583	1.01479	1.01635	1.01948	1.02126	1.01906	1.01489	1.02376	1.02218	1.01792
A	0.01979	0.01084	0.01959	0.01730	0.02104	0.03294	0.03645	0.03146	0.03541	0.03064	0.03667
B	0.00604	0.01334	0.00459	-0.00395	-0.01521	-0.01456	-0.03480	-0.02979	-0.02209	-0.01561	-0.01082
AB	-0.01061	-0.00584	-0.01541	-0.01105	0.00021	-0.00749	0.00687	-0.00146	-0.00249	0.00061	0.00335
C	0.00811	-0.00336	0.01334	0.01395	0.02479	0.02041	0.01562	0.01354	0.01834	0.01021	0.01543
AC	0.01896	-0.00584	-0.00916	-0.00480	0.00771	0.00334	0.01480	0.00606	0.01544	0.01064	0.00540
BC	-0.02479	0.00666	0.00334	-0.00355	-0.02354	-0.01666	-0.02145	-0.02269	-0.02206	-0.01561	-0.00960
ABC	-0.01564	-0.00086	-0.00916	0.00270	0.00604	0.00291	0.01437	0.01979	0.01334	0.01146	0.01042
D	-0.01479	-0.03416	-0.05084	-0.04855	-0.08811	-0.10166	-0.09522	-0.10854	-0.11791	-0.11604	-0.11125
AD	-0.01564	-0.01584	-0.01499	-0.00230	-0.00189	-0.00209	-0.01020	-0.00771	0.00249	0.00689	-0.00207
BD	0.01311	0.00166	-0.00249	0.00395	0.00936	0.02041	0.01855	0.01104	0.01249	0.00314	-0.00708
ABD	0.02396	0.01834	0.02666	0.02520	-0.00436	-0.00666	-0.01647	-0.01479	-0.01541	-0.00729	-0.00125
CD	0.00104	-0.01834	-0.05374	-0.04395	-0.07564	-0.09626	-0.07937	-0.09064	-0.09374	-0.09604	-0.10582
ACD	0.01769	-0.00166	-0.00709	-0.01105	-0.01856	-0.01749	-0.02020	-0.01896	-0.01084	-0.00896	-0.01750
BCD	0.00144	0.01084	0.00291	0.01770	0.02769	0.03751	0.03355	0.01729	0.02916	0.03229	0.01500
ABCD	-0.00021	-0.00084	0.01626	0.02230	-0.00189	-0.00376	-0.02762	-0.01439	-0.01624	-0.01729	-0.00333

Table 4-8
SNAP-23A N-Leg Statistical Analysis Summary (Min-K 1301 Modules)
(Power Ratio)

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

Effect	Mean Effect and Test Hours										
	225	2500	5500	8500	11500	13500	14500	15000	15500	16000	16500
<u>AVERAGE</u>	<u>1.01985</u>	<u>1.04049</u>	<u>1.01782</u>	<u>1.00802</u>	<u>1.00305</u>	<u>0.98825</u>	<u>0.98493</u>	<u>0.99217</u>	<u>0.98819</u>	<u>0.99986</u>	<u>0.98452</u>
A	-0.00360	-0.00916	-0.01304	-0.01089	-0.00875	-0.01273	-0.00746	-0.01344	-0.01012	-0.01206	-0.01221
B	-0.00338	-0.01049	-0.00089	-0.00401	-0.00517	-0.00707	0.00191	-0.00236	-0.01042	-0.00499	-0.00366
AB	0.00868	0.00711	0.00834	0.00191	-0.00318	-0.00670	-0.00481	-0.00124	0.00035	-0.00526	-0.00241
C	0.02448	0.03029	0.01089	-0.01646	-0.04808	-0.04910	-0.05656	-0.05051	-0.05435	-0.07306	-0.06436
AC	-0.01927	-0.01031	-0.00204	-0.00289	-0.01087	-0.00117	-0.00239	-0.00259	-0.00607	-0.00414	0.00219
BC	0.00895	-0.00154	0.00246	-0.00886	-0.00285	-0.00888	-0.01361	-0.00946	-0.00263	-0.00416	-0.01301
ABC	0.00655	0.00891	0.01154	-0.00254	-0.00620	-0.00825	-0.00504	-0.01724	-0.00855	-0.00584	-0.01146
D	0.01102	0.05059	0.05401	0.06416	0.09470	0.10955	0.09389	0.10764	0.11562	0.11596	0.10394
AD	-0.01792	-0.01006	-0.01376	-0.01076	-0.02095	-0.01793	-0.01339	-0.01984	-0.02360	-0.02461	-0.01726
BD	-0.00010	0.00386	0.00649	-0.00369	0.00177	0.00147	0.00074	-0.00146	0.00120	0.00106	0.00379
ABD	-0.00700	-0.00294	-0.00489	-0.00556	0.00467	0.00290	-0.00234	-0.00014	-0.00072	-0.00061	-0.00291
CD	-0.01025	0.00209	0.03741	0.04496	0.06072	0.06010	0.06081	0.05739	0.05617	0.06699	0.05884
ACD	-0.01375	0.00179	-0.00711	0.00404	0.00392	0.00997	0.00564	-0.00109	0.00035	-0.00149	0.00464
BCD	-0.00293	-0.00909	-0.00451	-0.01154	-0.00900	-0.01858	-0.01104	-0.00596	-0.00990	-0.01681	-0.01246
ABCD	-0.00038	0.00596	-0.00374	-0.00691	-0.00095	0.00160	0.00019	0.00216	-0.00053	0.00631	0.00034

Table 4-9
SNAP-23A P-Leg Statistical Analysis Summary (Microquartz Modules)
(Seebeck Ratio)

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

Effect	Mean Effect and Test Hours										
	225	2500	5500	8500	11500	13500	14500	15000	15500	16000	16500
AVERAGE	0.96125	0.96500	0.95734	0.95547	0.95641	0.94906	0.94625	0.94328	0.94609	0.94453	0.94172
A	0.11500	0.15187	0.15844	0.15844	0.16344	0.16437	0.16687	0.16469	0.16219	0.16531	0.16594
B	0.01125	0.00563	0.01094	0.00844	0.00594	0.01063	0.01438	0.01219	0.00719	0.00996	0.00594
AB	-0.00625	0.00125	0.00469	0.00594	0.00281	0.00188	-0.00250	0.00156	0.00219	0.00281	0.00094
C	0.01000	0.00813	0.00656	-0.00281	0.00344	0.0	0.00187	0.00094	0.00344	0.00531	0.00719
AC	0.00125	-0.01000	-0.01594	-0.01531	-0.01219	-0.01500	-0.01625	-0.01469	-0.01531	-0.01594	-0.01406
BC	-0.00250	-0.00125	-0.00844	-0.00531	-0.00719	-0.00625	-0.01125	-0.00969	-0.01281	-0.01219	-0.01406
ABC	0.00125	0.00437	0.00656	0.00719	0.00594	0.01125	0.00937	0.01344	0.01094	0.01406	0.01469
D	-0.00313	0.00625	0.00406	0.00656	0.01594	0.01563	0.01938	0.01781	0.01844	0.01719	0.01656
AD	0.00438	0.00687	0.00531	0.00156	0.00406	0.00313	-0.00250	-0.00031	-0.00031	0.00094	0.00281
BD	0.00063	-0.01187	-0.01219	-0.01594	-0.01594	-0.01562	-0.01750	-0.01531	-0.01531	-0.01531	-0.01219
ABD	0.00812	0.01000	0.00906	0.00906	0.01344	0.01938	0.02188	0.02031	0.01844	0.02094	0.01906
CD	-0.00563	-0.00437	-0.00156	-0.00469	-0.00719	-0.00250	0.00125	-0.00281	-0.00531	-0.00281	-0.00219
ACD	-0.00188	-0.00125	-0.00156	0.00031	-0.00281	-0.00125	0.00187	0.00281	0.00719	0.00344	0.00531
BCD	-0.00063	0.0	0.00094	0.00281	-0.00031	0.00250	-0.00063	0.00031	0.00469	0.00219	0.00031
ABCD	0.00062	-0.00062	-0.00156	-0.00719	-0.00719	-0.01125	-0.00875	-0.00781	-0.01281	-0.00976	-0.00969
E	-0.00250	-0.00563	-0.00656	-0.01031	-0.01156	-0.00813	-0.00813	-0.01031	-0.00906	-0.00844	-0.00781
AE	0.02250	0.01250	0.01469	0.01219	0.01031	0.01312	0.01250	0.01156	0.01344	0.01281	0.01219
BE	-0.00125	0.00625	-0.00031	0.00219	0.00031	0.00188	-0.00250	0.00156	0.00594	0.00156	0.00719
ABE	0.00375	-0.00438	-0.00906	-0.01031	-0.00906	-0.00687	-0.00562	-0.00781	-0.01156	-0.00969	-0.01031
CE	-0.00375	-0.00750	-0.00844	-0.00656	-0.00469	-0.00500	-0.00125	-0.00219	-0.00156	-0.00219	-0.00281
ACE	0.00250	0.00062	-0.00594	-0.00406	-0.00656	-0.00750	-0.01313	-0.01156	-0.01731	-0.00844	-0.00906
BCE	-0.00625	-0.00063	-0.00094	0.00094	0.00094	-0.00125	-0.00062	0.00094	-0.00031	0.00031	0.00094
ABCE	0.00750	0.00875	0.01406	0.01344	0.01531	0.00875	0.01375	0.01281	0.01344	0.01156	0.00969
DE	0.00187	0.00437	0.00781	0.01031	0.01156	0.00812	0.00500	0.00469	0.00344	0.00719	0.00406
ADE	0.01187	0.00375	0.00156	0.00031	0.00031	-0.00187	-0.00312	-0.00219	-0.00531	-0.00406	-0.00469
BDE	-0.00688	-0.01000	-0.00844	-0.00719	-0.00656	-0.00312	-0.00063	-0.00469	-0.00281	-0.00531	-0.00469
ABDE	0.01312	0.01312	0.01531	0.01781	0.01656	0.01438	0.01500	0.01469	0.01094	0.01594	0.01656
CDE	0.00313	-0.00875	-0.01156	-0.01344	-0.01781	-0.01375	-0.01562	-0.01469	-0.01406	-0.01281	-0.01344
ACDE	-0.00312	-0.00187	-0.00156	-0.00344	-0.00469	-0.00250	-0.00125	-0.00031	-0.00406	-0.00156	-0.00344
BCDE	-0.00188	0.00437	0.00344	0.00406	0.00531	0.00375	0.00375	0.00469	0.00094	0.00219	0.00156
ABCDE	-0.00562	-0.00000	-0.00406	-0.00594	-0.00531	-0.00500	-0.00813	-0.00719	-0.00406	-0.00406	-0.00594

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

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

Effect	Mean Effect and Test Hours										
	225	2500	5500	8500	11500	13500	14500	15000	15500	16000	16500
AVERAGE	1.26515	1.43359	1.52531	1.77922	1.73578	1.82656	1.93875	1.93281	1.99937	2.08109	2.09515
A	0.47219	0.89406	0.89812	1.13844	0.85031	0.71437	0.64562	0.62625	0.55875	0.41719	0.37969
B	-0.08656	-0.10719	-0.13938	-0.43781	-0.19219	-0.20063	-0.21187	-0.22125	-0.21375	-0.13156	-0.17031
AB	-0.01344	-0.05406	-0.07437	-0.37231	-0.16594	-0.17687	-0.25750	-0.26937	-0.31875	-0.39406	-0.47469
C	0.03406	-0.10656	-0.13938	-0.42406	-0.23906	-0.29875	-0.34750	-0.35938	-0.34937	-0.37781	-0.39031
AC	0.05469	0.01406	0.01938	-0.20156	0.08094	0.10250	0.12437	0.12875	0.12063	0.17219	0.15281
BC	0.00594	0.10281	0.14688	0.43969	0.20094	0.28250	0.33688	0.32125	0.36563	0.39844	0.39281
ABC	0.02531	0.01219	-0.01437	0.22719	0.01594	-0.01875	-0.06250	-0.03437	-0.06437	-0.08406	-0.05531
D	-0.10906	-0.09156	-0.08687	-0.13219	-0.22969	-0.24937	-0.29687	-0.29500	-0.31500	-0.42031	-0.40344
AD	0.04031	-0.04469	-0.06563	-0.06844	0.00281	0.04937	0.08250	0.08312	0.10500	0.16219	0.16969
BD	0.01656	0.00406	-0.03812	-0.05469	-0.04719	-0.11063	-0.14500	-0.14438	-0.17000	-0.21656	-0.25731
ABD	0.04219	0.10719	0.11312	0.16656	0.20031	0.21063	0.27813	0.27500	0.29500	0.33344	0.36156
CD	-0.00781	-0.01531	-0.02563	-0.04219	0.03594	-0.00375	0.01188	0.01625	0.00687	0.05344	0.07219
ACD	-0.02219	0.03281	0.03687	0.03906	-0.02531	-0.06000	-0.08000	-0.09313	-0.11062	-0.17406	-0.19094
BCD	0.06406	0.05656	0.11937	0.16531	0.15219	0.25500	0.31250	0.33438	0.36687	0.39219	0.45406
ABCD	-0.07156	-0.06156	-0.06562	-0.11594	-0.14656	-0.14375	-0.19313	-0.21875	-0.24563	-0.26281	-0.31781
E	0.19969	0.19406	0.16687	0.45844	0.30406	0.29437	0.33313	0.32625	0.32500	0.39594	0.38469
AE	-0.01969	-0.00531	-0.02313	0.20094	-0.07469	-0.19437	-0.25250	-0.24437	-0.24250	-0.26656	-0.22969
BE	-0.10844	-0.07906	-0.11813	-0.38031	-0.13969	-0.10938	-0.15000	-0.14937	-0.17750	-0.20281	-0.20719
ABE	0.03594	0.00031	0.00937	-0.21281	-0.00594	0.10937	0.16313	0.15375	0.19000	0.17219	0.18719
CE	-0.01781	-0.15094	-0.22687	-0.57406	-0.41531	-0.52500	-0.62563	-0.65125	-0.72062	-0.88406	-0.95719
ACE	0.08406	0.08594	0.11187	-0.04906	0.24969	0.36625	0.51500	0.52762	0.67187	0.67844	0.71969
BCE	-0.01469	0.07219	0.08688	0.33219	0.07719	0.06125	0.01250	0.00563	-0.03062	-0.05281	-0.12281
ABCE	0.09344	0.06531	0.06062	0.31219	0.09719	0.08500	0.09938	0.12625	0.17187	0.25219	0.33031
DE	-0.04219	0.01531	0.08062	0.08406	-0.00594	0.03688	-0.00500	0.00563	-0.00875	-0.05406	-0.05781
ADE	0.07594	-0.01406	-0.03313	-0.02219	0.03656	0.09063	0.11813	0.12250	0.14875	0.21594	0.21906
BDE	-0.01281	-0.05781	-0.10813	-0.15844	-0.17094	-0.26937	-0.33437	-0.33250	-0.36375	-0.43531	-0.47344
ABDE	0.02406	0.08156	0.11312	0.16781	0.20656	0.22187	0.26000	0.25812	0.27875	0.34719	0.36969
CDE	0.03031	0.04781	0.01313	0.05406	0.15094	0.13500	0.18000	0.18938	0.21313	0.25969	0.27656
ACDE	0.00219	0.09719	0.11812	0.12531	0.07219	0.05375	0.04437	0.03375	0.00812	-0.03031	-0.06531
BCDE	0.00344	-0.01156	0.03312	0.03656	0.03219	0.09375	0.13687	0.14375	0.16312	0.18344	0.24219
ABCDE	-0.09844	-0.09094	-0.12937	-0.16969	-0.18906	-0.20500	-0.25000	-0.26313	-0.27688	-0.32906	-0.37594

Table 4-11
SNAP-23A P-Leg Statistical Analysis Summary (Microquartz Modules)
(Power Ratio)

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

Effect	Mean Effect and Test Hours										
	225	2500	5500	8500	11500	13500	14500	15000	15500	16000	16500
AVERAGE	0.76083	0.70748	0.65519	0.59553	0.58580	0.55358	0.53133	0.53047	0.52157	0.51936	0.50912
A	-0.12598	-0.24813	-0.20768	-0.19787	-0.14946	-0.10901	-0.09794	-0.09517	-0.08670	-0.06384	-0.06264
B	0.06267	0.03953	0.04181	0.06654	0.04353	0.04659	0.04983	0.05310	0.04738	0.03620	0.03764
AB	-0.00988	0.01096	0.02839	0.06331	0.03824	0.04304	0.05156	0.05480	0.06014	0.07199	0.07523
C	-0.00547	0.05596	0.05312	0.06188	0.04911	0.04474	0.04122	0.04381	0.03934	0.03775	0.04399
AC	-0.01894	-0.03307	-0.03379	-0.03721	-0.02893	-0.01759	-0.01086	-0.01151	-0.00683	-0.01009	-0.00914
BC	-0.01279	-0.04728	-0.06873	-0.09524	-0.07742	-0.09636	-0.11081	-0.10321	-0.11252	-0.11935	-0.11716
ABC	-0.00397	0.02192	0.03381	0.01277	0.03212	0.04262	0.05269	0.04809	0.05086	0.05706	0.05068
D	0.05614	0.05932	0.05718	0.07137	0.10442	0.11430	0.12162	0.11980	0.12055	0.13339	0.12371
AD	-0.02538	-0.00703	-0.00721	-0.02567	-0.03764	-0.05020	-0.06238	-0.05800	-0.05894	-0.06202	-0.05501
BD	0.00102	-0.00812	-0.00124	0.00127	-0.00568	-0.00423	-0.00683	-0.00557	-0.00374	-0.00281	-0.00257
ABD	-0.01641	-0.02029	-0.01563	-0.01737	-0.01907	-0.00510	-0.00926	-0.00820	-0.01018	-0.00347	-0.00281
CD	-0.00422	0.00996	0.00284	0.01073	-0.00641	0.00633	0.01346	0.00679	0.01148	0.01594	0.01246
ACD	0.01193	-0.01162	-0.00454	-0.00061	0.00626	0.00598	0.00588	0.01129	0.01386	0.01020	0.01389
BCD	-0.04817	-0.03858	-0.05041	-0.05837	-0.05006	-0.05592	-0.06419	-0.07056	-0.06751	-0.06049	-0.07002
ABCD	0.04978	0.03182	0.02881	0.02689	0.02948	0.01990	0.02806	0.03461	0.03447	0.02662	0.03089
E	-0.12354	-0.10814	-0.07593	-0.10297	-0.09639	-0.08220	-0.07846	-0.07646	-0.07085	-0.07461	-0.06831
AE	0.07368	0.06338	0.04963	0.02324	0.04904	0.06387	0.06159	0.05709	0.05371	0.05023	0.03966
BE	0.07091	0.04329	0.04119	0.06656	0.04486	0.03695	0.03957	0.04589	0.05486	0.05176	0.06229
ABE	-0.03312	-0.02141	-0.02364	-0.00873	-0.02673	-0.04095	-0.04576	-0.04974	-0.05932	-0.05310	-0.06412
CE	0.01817	0.07704	0.09966	0.14827	0.13903	0.15012	0.15868	0.16318	0.16425	0.17416	0.18087
ACE	-0.05203	-0.07501	-0.09283	-0.09407	-0.12751	-0.13730	-0.15899	-0.15997	-0.16276	-0.15852	-0.16072
BCE	0.00709	-0.00627	-0.00889	-0.02031	0.00133	0.00820	0.02026	0.02360	0.02686	0.02306	0.03197
ABCE	-0.04156	-0.01634	-0.00838	-0.03414	-0.00823	-0.02035	-0.01964	-0.02523	-0.03075	-0.03403	-0.04359
DE	0.02463	-0.00717	-0.02506	-0.02167	0.00002	-0.00934	-0.00399	-0.01114	-0.00819	-0.00530	-0.01049
ADE	-0.02697	0.00751	0.01658	0.00269	-0.00664	-0.01554	-0.01944	-0.01571	-0.02368	-0.02621	-0.02346
BDE	-0.00129	0.02507	0.03682	0.05438	0.05769	0.07121	0.07691	0.06604	0.07075	0.07785	0.07703
ABDE	0.00506	-0.01963	-0.02539	-0.03176	-0.04389	-0.04776	-0.04487	-0.03886	-0.04424	-0.04936	-0.04551
CDE	-0.01588	-0.01643	-0.00874	-0.02048	-0.04583	-0.03391	-0.03998	-0.03938	-0.04341	-0.03570	-0.04332
ACDE	0.00369	-0.03373	-0.03721	-0.02602	-0.01957	-0.02041	-0.02156	-0.01955	-0.01758	-0.02049	-0.01313
BCDE	-0.00343	0.00646	-0.01059	-0.00513	0.00369	-0.00134	-0.00113	-0.00113	-0.00428	0.00163	-0.00554
ABCDE	0.03739	0.02408	0.03149	0.02043	0.02243	0.02044	0.01542	0.01777	0.01881	0.01984	0.02317

Table 4-12
SNAP-23A P-Leg Statistical Analysis Summary (Min-K 1301 Modules)
(Seebeck Ratio)

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

Effect	Mean Effect and Test Hours										
	225	2500	5500	8500	11500	13500	14500	15000	15500	16000	16500
AVERAGE	0.96922	1.00719	1.00375	0.98516	0.97562	0.96250	0.95500	0.95375	0.95500	0.95937	0.94969
A	0.09219	0.14062	0.14625	0.13031	0.13250	0.12062	0.12125	0.12000	0.12375	0.12500	0.11937
B	0.00469	0.00687	0.00625	0.00031	0.00375	0.00312	0.00375	0.00500	0.00500	0.00625	0.00687
AB	-0.00156	-0.00188	-0.00250	0.00031	0.00250	0.00500	0.00750	0.00500	0.00875	0.00500	0.00437
C	0.01156	0.01750	-0.00937	-0.03531	-0.05625	-0.06250	-0.06937	-0.07875	-0.07312	-0.09187	-0.08500
AC	0.00031	-0.01125	-0.02187	-0.02531	-0.01875	-0.02437	-0.01437	-0.01625	-0.01812	-0.01687	-0.01500
BC	0.00031	0.00250	0.00562	0.00719	0.01250	0.01062	0.01062	0.01375	0.01562	0.01437	0.01750
ABC	-0.00094	-0.00125	0.00312	0.00719	0.01000	0.01000	0.01062	0.00875	0.01312	0.00937	0.01000
D	0.00094	0.00312	-0.00875	-0.00656	-0.00813	-0.00438	-0.01375	-0.01563	-0.01437	-0.00375	-0.00938
AD	-0.00156	-0.00313	-0.00625	-0.00531	-0.00312	0.00250	0.00375	0.00187	0.00188	0.00250	0.00162
BD	-0.00406	-0.00188	0.00125	-0.00031	-0.00687	-0.00500	-0.01125	-0.01063	-0.00937	-0.01125	-0.01437
ABD	0.00094	0.00187	-0.00125	-0.00156	-0.00188	-0.00437	-0.00375	-0.00062	-0.00312	0.00250	0.00313
CD	0.00531	-0.00250	-0.00812	-0.00094	0.00312	-0.00437	-0.00562	0.00188	-0.00500	0.00062	0.00125
ACD	0.00281	0.00375	-0.00188	0.00031	0.00187	0.01000	0.00563	0.00938	0.00750	0.01062	0.00625
BCD	0.00281	-0.00250	-0.00188	-0.00219	-0.00187	0.00000	-0.00687	-0.00813	-0.00625	-0.00812	-0.00875
ABCD	-0.00219	-0.00125	-0.00313	-0.00344	-0.00562	-0.00688	-0.00312	-0.00313	-0.00625	-0.00312	-0.00125
E	0.00719	0.01312	0.01750	0.02156	0.01875	0.01687	0.01750	0.02000	0.01250	0.01250	0.01688
AE	0.00844	-0.00313	-0.00375	-0.00344	-0.00500	-0.00625	-0.00375	-0.00500	-0.00625	-0.00625	-0.00312
BE	0.00344	0.00063	-0.00125	0.00156	0.00875	0.00625	0.00625	0.01000	0.00750	0.00500	0.00687
ABE	0.00469	-0.00062	-0.00000	0.00156	0.00250	0.00187	-0.00250	-0.00250	-0.00125	-0.00125	-0.00563
CE	0.00031	-0.00375	-0.00313	-0.00156	-0.00250	0.00187	-0.00062	-0.00375	0.00063	0.00062	0.00250
ACE	0.00156	-0.00000	0.00187	-0.00156	-0.00250	-0.00875	-0.00563	-0.00375	-0.00438	-0.00688	-0.00250
BCE	-0.00594	-0.00375	-0.00313	0.00094	0.00125	0.00625	0.00687	0.00625	0.00687	0.00438	0.00750
ABCE	0.00531	-0.00500	-0.00313	-0.00406	-0.00375	-0.00062	-0.00812	-0.00625	-0.00562	-0.00813	-0.01000
DE	0.00344	0.00687	0.00500	0.00844	0.00812	0.00625	0.00750	0.00938	0.01062	0.01000	0.01062
ADE	0.00094	-0.00188	-0.00000	0.00719	0.00562	0.00688	0.00500	0.00437	0.00437	0.00625	0.00562
BDE	-0.00906	-0.00313	-0.00500	-0.00781	-0.01063	-0.01563	-0.01250	-0.01313	-0.00938	-0.01250	-0.01188
ABDE	0.01094	0.00812	0.01000	0.00844	0.01188	0.00625	0.01000	0.00937	0.00937	0.01125	0.01062
CDE	0.00281	0.00375	0.00188	0.00656	0.00813	0.00375	0.00688	0.00938	0.01125	0.00813	0.01125
ACDE	-0.00469	-0.00250	-0.00187	0.00031	0.00187	0.00188	0.00363	-0.00062	0.00375	0.00062	0.00125
BCDE	-0.00219	-0.00625	-0.00937	-0.00719	-0.01437	-0.01312	-0.01437	-0.01312	-0.01250	-0.01313	-0.01125
ABCDE	0.00281	0.00250	-0.00062	0.00406	0.00688	0.00125	0.01188	0.00938	0.00750	0.00937	0.01125

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

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

Effect	Mean Effect and Test Hours										
	225	2500	5500	8500	11500	13500	14500	15000	15500	16000	16500
AVERAGE	1.08515	1.14141	1.13922	1.09312	1.07344	1.05719	1.04250	1.03875	1.04875	1.04547	1.03781
A	0.37469	0.51344	0.46531	0.39125	0.33812	0.30687	0.29250	0.29062	0.29437	0.28844	0.27500
B	-0.05781	-0.03156	-0.04219	-0.05500	-0.05437	-0.05937	-0.06125	-0.05438	-0.05937	-0.05781	-0.06125
AB	-0.01719	-0.01969	-0.03156	-0.03000	-0.03312	-0.03437	-0.02875	-0.02750	-0.02625	-0.02781	-0.02562
C	-0.00719	-0.06844	-0.06781	-0.06938	-0.05937	-0.06063	-0.05187	-0.07063	-0.05312	-0.07469	-0.07189
AC	0.02594	-0.09031	-0.12719	-0.10938	-0.10187	-0.09187	-0.07937	-0.08000	-0.08250	-0.07594	-0.06250
BC	0.04094	0.01219	-0.00219	-0.01312	0.00562	-0.00063	0.00188	0.01000	0.00625	0.00281	0.01375
ABC	-0.02219	-0.01344	-0.01531	-0.02812	-0.01938	-0.02687	-0.02062	-0.02562	-0.01437	-0.02844	-0.02562
D	-0.11531	-0.10344	-0.11969	-0.10250	-0.12437	-0.10562	-0.11062	-0.11188	-0.11937	-0.10406	-0.11437
AD	-0.05719	-0.06656	-0.07031	-0.05875	-0.05937	-0.05312	-0.03687	-0.04250	-0.04250	-0.04031	-0.05250
BD	0.02031	0.00844	0.01469	0.01000	0.00562	0.01063	0.00188	0.00500	0.00625	0.00594	-0.00125
ABD	-0.00781	0.00906	0.00781	0.01125	0.01812	0.01563	0.00813	0.01063	0.01438	0.02469	0.02188
CD	0.03469	0.00156	-0.04344	-0.02187	-0.01312	-0.02062	-0.02875	-0.01375	-0.03125	-0.03469	-0.02937
ACD	0.00156	-0.00406	-0.02781	-0.01313	-0.00438	0.00062	-0.00500	0.00313	0.00687	0.01031	0.00750
BCD	-0.04344	-0.02156	-0.01031	-0.00187	-0.00437	0.00187	-0.00125	0.00062	-0.00188	-0.00844	-0.00875
ABCD	0.03469	0.01156	0.01656	0.01938	0.01438	0.01312	0.01500	0.01375	0.00500	0.01906	0.01438
E	0.06344	0.00219	0.01031	0.00875	0.00312	-0.00187	-0.00125	0.00188	-0.01188	-0.00781	0.0
AE	0.00656	-0.01344	-0.00656	-0.01125	-0.01062	-0.01687	-0.01625	-0.01875	-0.02125	-0.02281	-0.02188
BE	-0.03594	-0.00844	-0.00656	0.00000	-0.00062	-0.00312	-0.00500	-0.00125	0.0	-0.00656	-0.00562
ABE	0.00094	0.00969	0.00281	0.00000	0.01063	0.00938	0.01500	0.00938	0.01438	0.01094	0.01125
CE	-0.02031	-0.01656	-0.00969	-0.01187	-0.00438	-0.00062	-0.00812	-0.01125	-0.00625	0.00031	-0.01250
ACE	0.01906	-0.00469	-0.01031	-0.00188	0.00562	0.00813	-0.00312	0.00563	-0.00437	-0.00094	0.00063
BCE	0.00906	-0.00219	-0.00781	-0.00812	-0.00937	-0.00063	-0.00187	-0.00563	-0.00563	-0.00969	-0.00562
ABCE	-0.05531	-0.03156	-0.01469	-0.01312	-0.02187	-0.00688	-0.01187	-0.01375	-0.01250	-0.01594	-0.01875
DE	-0.01594	0.01469	0.01219	0.02125	0.01812	0.01063	0.00937	0.01875	0.01875	0.00844	0.01750
ADE	0.05344	0.04781	0.03281	0.04250	0.04062	0.03563	0.03312	0.03188	0.03437	0.03219	0.03812
BDE	0.01094	-0.00719	-0.00469	-0.00625	-0.01188	-0.01563	-0.01313	-0.00813	-0.00187	-0.00906	-0.00313
ABDE	-0.00344	-0.00281	0.00219	-0.01250	-0.01187	-0.01312	-0.01188	-0.01625	-0.01750	-0.01531	-0.01875
CDE	0.00781	0.00219	0.00719	0.01188	0.01062	-0.00063	0.00625	0.00687	0.01063	0.00156	0.01250
ACDE	-0.02656	-0.00719	-0.00844	-0.00687	-0.00063	-0.00437	-0.00500	-0.01250	-0.01000	-0.01094	-0.00687
BCDE	0.01344	0.00531	0.00656	0.01687	0.00688	0.00188	-0.00125	0.00125	0.00125	0.00281	-0.00062
ABCDE	0.04781	0.01219	-0.00031	-0.00438	-0.00937	-0.01187	-0.00500	-0.01312	-0.00812	-0.00719	-0.01125

Table 4-14
SNAP-23A P-Leg Statistical Analysis Summary (Min-K 1301 Modules)
(Power Ratio)

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

Effect	Mean Effect and Test Hours										
	225	2500	5500	8500	11500	13500	14500	15000	15500	16000	16500
AVERAGE	0.88781	0.91612	0.90581	0.90355	0.90015	0.88769	0.88542	0.88617	0.88043	0.89082	0.87875
A	-0.14286	-0.15714	-0.10444	-0.07458	-0.03811	-0.03330	-0.02356	-0.02446	-0.01849	-0.01316	-0.01086
B	0.04612	0.03392	0.04072	0.04301	0.04821	0.05076	0.05495	0.05204	0.04424	0.05719	0.06121
AB	0.00495	0.00410	0.01213	0.01726	0.02298	0.02888	0.02921	0.02441	0.02824	0.02333	0.02048
C	0.02564	0.07054	0.02161	-0.01649	-0.06139	-0.06840	-0.08802	-0.08966	-0.09313	-0.10764	-0.09644
AC	-0.02149	0.03544	0.05764	0.04418	0.05537	0.03734	0.04751	0.04306	0.04239	0.03984	0.03051
BC	-0.03200	-0.00595	0.00986	0.01889	0.01358	0.01423	0.01223	0.01074	0.01848	0.01807	0.01479
ABC	0.01947	0.01380	0.01992	0.03639	0.03651	0.04186	0.03844	0.03969	0.03751	0.04188	0.04137
D	0.08146	0.07820	0.07309	0.06616	0.08314	0.07383	0.06365	0.07101	0.06752	0.07494	0.06352
AD	0.02734	0.02378	0.02553	0.02318	0.02702	0.03499	0.02576	0.02714	0.02639	0.02738	0.03534
BD	-0.01745	-0.00559	-0.00556	-0.00416	-0.01083	-0.01135	-0.01630	-0.01874	-0.01484	-0.01877	-0.01892
ABD	0.01062	-0.00026	-0.00209	-0.00666	-0.01171	-0.01339	-0.00726	-0.00359	-0.00997	-0.00876	-0.00557
CD	-0.01299	-0.00080	0.02156	0.01764	0.01717	0.00876	0.01140	0.01411	0.01531	0.02949	0.02711
ACD	0.00099	0.01635	0.01884	0.01152	0.00974	0.01825	0.01456	0.01521	0.00791	0.00861	0.00253
BCD	0.04155	0.01514	0.01046	0.00316	0.00311	0.00234	-0.00780	-0.01269	-0.00698	-0.00277	-0.00531
ABCD	-0.03627	-0.01556	-0.01878	-0.01929	-0.01910	-0.01928	-0.01391	-0.01241	-0.01163	-0.01798	-0.01056
E	-0.03601	0.01957	0.02212	0.02916	0.02910	0.02942	0.03105	0.03221	0.03038	0.02763	0.02706
AE	0.01426	0.00023	-0.00377	0.00083	-0.00384	0.00034	0.00379	0.00411	0.00248	0.00559	0.01051
BE	0.02960	0.01304	0.00547	0.00457	0.02089	0.01720	0.02035	0.02316	0.01764	0.01792	0.02102
ABE	0.00483	-0.01011	-0.00269	0.00477	-0.00368	-0.00409	-0.01644	-0.01146	-0.01196	-0.00969	-0.01766
CE	0.01561	0.00588	-0.00109	0.00697	-0.00051	0.00624	0.00558	0.00381	0.00672	0.00243	0.00757
ACE	-0.00841	0.00335	0.01217	-0.00116	-0.00698	-0.02083	-0.00659	-0.01016	-0.00236	-0.00938	-0.01298
BCE	-0.02572	-0.01099	-0.00104	0.00786	0.00692	0.01116	0.01373	0.01266	0.01601	0.01497	0.01821
ABCE	0.04970	0.01689	0.00559	0.00286	0.01214	0.00440	-0.00336	0.00161	0.00168	-0.00042	-0.00147
DE	0.02056	0.01331	0.00639	0.00467	0.00606	0.00794	0.01152	0.00681	0.01009	0.01674	0.01061
ADE	-0.04211	-0.04054	-0.02514	-0.02031	-0.02232	-0.01585	-0.01736	-0.01646	-0.01858	-0.01467	-0.01957
BDE	-0.02055	-0.00210	-0.00666	-0.01244	-0.01067	-0.01619	-0.01237	-0.01829	-0.01749	-0.01584	-0.02073
ABDE	0.02072	0.01335	0.01398	0.02356	0.02796	0.01983	0.02456	0.02876	0.02908	0.03132	0.03267
CDE	-0.00024	0.00266	-0.00629	-0.00164	0.00273	0.00467	0.00567	0.00931	0.00906	0.01122	0.02864
ACDE	0.00874	-0.00066	0.00537	0.00768	0.00461	0.00661	0.00739	0.01041	0.01696	0.01123	0.00947
BCDE	-0.01170	-0.01328	-0.02154	-0.02823	-0.03261	-0.02590	-0.02627	-0.02304	-0.02356	-0.02592	-0.02082
ABCOE	-0.02258	-0.00040	0.00284	0.01517	0.02440	-0.01444	0.02726	0.02974	0.02164	0.02517	0.03078

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

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

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

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

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

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

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

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

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

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

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

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

Figure 4-20.

Comparison of Average Power Ratio for Various
Combinations of P-Legs and Thermal Insulations

4.4 CONTINUATION TESTING ON RELATED DEVICES

4.4.1 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 4-15 and shown graphically in Figure 4-20.

Analysis of recent data indicates that both Seebeck voltage and internal resistance appear to be stabilizing with time.

4.4.2 Converter 23P-2

Long-term test of converter 23P-2 continued during the quarter. Performance data is summarized in Table 4-16. Normalized performance curves are shown in Figure 4-21; data is normalized to $T_h = 1070^\circ\text{F}$, $T_c = 200^\circ\text{F}$. Initial and current 23P-2 experimental-to-theoretical performance ratios are presented in Table 4-17. Analysis of recent data indicates that:

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

Table 4-15
Six-Couple Module 23A3 N-leg Performance Data
(Start of Test: 3/4/65; Current Reading: 12/31/69)

Hours	T _h , °F	T _c , °F	E, mv	R, mo	I, Amps
90	1102	190	114.2	18.8	2.84
481	1104	197	114.3	18.9	2.58
1,034	1100	194	114.5	19.6	2.55
1,655	1100	197	114.3	19.8	2.64
5,065	1100	191	114.5	21.3	2.58
11,252	1100	190	114.5	24.4	2.48
17,732	1095	193	114.0	26.0	2.35
23,000	1095	190	112.5	25.4	2.36
29,136	1100	191	111.5	25.6	2.38
35,694	1096	193	111.0	30.3	2.26
37,779	1103	184	110.5	27.7	2.33
39,262	1100	193	108.5	28.4	2.29
42,292	1097	193	108.0	28.4	2.29

Key

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

Table 4-16
Converter 23P-2 Performance Data

Date	Hours	T_h (°F)	T_c (°F)	E_x (volt)	I_x (amp)	R_x (ohm)	P_x (watt)	E_n (volt)	R_n (ohm)	P_n (watt)
7/23/65	48	1071	194	49.9	2.89	8.61	72.3	49.6	8.66	71.0
8/2/65	288	1070	201	50.0	2.70	9.25	67.6	50.0	9.24	67.8
8/16/65	624	1080	202	50.8	2.67	9.51	67.8	50.2	9.39	67.2
Installed into System No. 1										
9/3/65	1,030	1075	200	51.0	2.62	9.73	66.8	50.7	9.68	66.3
10/5/65	1,805	1040	201	49.0	2.58	9.59	63.2	51.1	9.90	66.4
11/30/65	3,065	1030	203	48.5	2.56	9.47	62.1	51.0	9.87	66.8
2/2/66	4,679	1030	200	48.3	2.60	9.30	62.8	51.0	9.73	66.9
5/14/66	7,095	1023	204	47.6	2.60	9.15	61.9	51.0	9.60	67.5
8/12/66	9,183	1008	203	46.8	2.57	9.11	60.1	51.2	9.74	67.1
9/2/66	9,757	Shutdown because of heater failure								
2/19/68	9,757	Put back on test								
2/29/68	10,009	1060 (est.)	186	50.6	2.66	9.59	66.8	50.7	9.86	65.2
6/28/68	12,600	1066	199	50.6	2.73	9.34	68.3	50.8	9.39	68.5
10/1/68	14,884	1076	201	50.9	2.78	9.32	69.5	50.5	9.25	69.1
12/31/68	17,069	1073	201	50.6	2.79	9.18	69.8	50.4	9.14	69.7
3/31/69	19,232	1075	205	50.8	2.79	9.25	69.7	50.7	9.14	70.2
6/26/69	21,316	1078	205	50.6	2.78	9.23	69.5	50.3	9.10	69.6
10/1/69	23,640	1078	207	50.3	2.74	9.23	68.6	50.1	9.08	69.1

Key:

- T_h — Average hot electrode temperature
- T_c — Average cold electrode temperature
- E_x — Experimental instantaneous open circuit (Seebeck) voltage
- I_x — Experimental load current
- R_x — Experimental internal resistance
- P_x — Experimental output power
- E_n — Normalized Seebeck voltage
- R_n — Normalized internal resistance
- P_n — Normalized output power

Table 4-17
SNAP-23 Converter P-2 BOL Performance Data
(Ratio of Experimental-to-Theoretical Values)

	Time Evaluated	Seebeck Ratio	Resistance Ratio
Thermopile	48	0.97	1.00
	14,884	0.99	1.07
	19,232	0.99	1.06
	23,640	0.98	1.05
	25,831	0.97	1.05
Typical N-Leg	48	1.03	1.00
	14,884	1.01	0.95
	19,232	1.01	0.95
	23,640	0.99	0.93
	25,831	0.98	0.93
Typical P-Leg	48	0.95	1.10
	14,884	0.98	1.25
	19,232	0.98	1.21
	23,640	0.97	1.19
	25,831	0.97	1.19

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

APPENDIX A

TEST PLAN AND PROCEDURE: FIRE SAFETY EVALUATION

1.0 TEST OBJECTIVE AND SCOPE

The objective of the Fire Safety Evaluation is to determine the overall thermal conductance of the SNAP-23A PMC-2 converter as a function of temperature during and after postulated 1475°F and 1850°F fire transient conditions. To meet the objective of the evaluation a special test module will be assembled which will be an adequate mechanical and thermal representation of the SNAP-23A PMC-2 converter and a test stand will be provided which simulates the desired temperature/time profiles and measures the steady-state thermal conductance of the module. The module data will then be analyzed to determine the relative thermal conductance on a full-size converter scale.

2.0 DESCRIPTION OF TEST MODULE

The module is shown in Figure A-1 and described in Table A-1. It consists of a six-couple segment of the converter contained in a thin wall stainless steel tube. The tube and components are sized to preserve cold frame length, spacing between the T/E legs, internal couple electrical connections, and the distance between hot frame and cold frame. The mass of cold frame and thermal insulation per couple existing in the converter is also maintained in the module. The module cold frame design duplicates the converter wire and spacer washer arrangement to support the follower springs. The contact pressure between the converter cold frame and outer case, resulting from a shrink-fit, is simulated by bolting the cold frame to the outer case. The tube wall is as thin as practical from mechanical strength and fabricability considerations to most nearly approximate the low percentage of total heat input conducted through the converter and covers. A pinch-off tube is provided so that converter processing can be simulated. Thermocouples are mounted in the outer case and hot frame to monitor hot and cold interface temperatures.

Figure A-1.
Six-couple Fire Module

Key

1. Tube
2. Hot Frame
3. Outer Case
4. Cold Frame
5. Insulator
6. Tubulation Fitting
7. Pinch-off Tube
8. Sheathed Thermocouple
9. Support Wire
- 10.
11. Bolt
12. Support Wire
13. Follower Spring
14. Follower
15. Thermoelectric Couple
16. Hot Button
17. Hot Electrode
18. Min-K-1301 Powdered Insulation

Table A -1
Module Design Summary

Module Length:	2.93" nominal
Module Diameter:	1.86" nominal
No. Couples:	Six
Couple Type:	PMC-2 design or equivalent
Thermal Insulation:	a) Min-K 1301 (powdered) packed into voids around T/E legs. b) Microquartz (pad) at outer wall adjacent to cold frame.
Cold Frame:	Aluminum Type 2024-T4
Hot Frame and Cylindrical Wall:	Stainless steel type 304
Outside Case (End Cover):	Inconel 625
Couple Hardware:	Identical to PMC-2 design
Module Orientation During Test:	Axis horizontal
Backfill Gas	Argon (10 psia at BOL conditions)

3.0 TEST EQUIPMENT

The primary item of test equipment is the module test stand (shown in Figure A-2 with the module mounted in position). The test stand consists of a cylindrical cold side heater block, an Armco* iron thermal conductivity standard with calibrated differential thermocouple wires (constantan) attached at a fixed spacing, and a cold side heat sink. Heaters are affixed to the standard and cold side heater block to vary the hot and cold end temperatures (artificial cooling will be provided on the cold side to assure temperature simulation). Guard heaters are used to minimize radial temperature drops (and hence radial heat losses from the standard and the module). The test modules will be bolted to the test stand with foil placed at the interfaces to minimize interface thermal resistance.

Variable transformers will be used to control heater power. Watts-transducers or Wattmeters will be used to measure heater power. The test stand and hermetically sealed module will be placed in a bell jar containing a low thermal conductivity gas (argon) to minimize extraneous heat loss.

4.0 TEST SUMMARY

The test program consists of the series of tests presented in Table A-2. The first test utilizes a dummy module whose thermal conductance versus temperature, in addition being similar to that of the six-couple module, can be calculated with a relatively high degree of accuracy. This initial test is necessary to adequately calibrate the test stand over the anticipated range of temperatures. This test run will also verify the transient response capability of the test stand and establish the data acquisition technique for future tests. The second test utilizes an instrumented module to verify that hot frame (T_{HF}) to hot junction (T_H) and cold junction (T_C) to outer case (T_{OC}) temperature drops in the module are similar to those expected in the PMC-2 converter. Following these calibration tests, module tests will be conducted in which the module will be heated to nominal PMC-2 BOL conditions. After a stable BOL thermal conductance measurement has been made, the test stand heaters and cold side coolant will then be adjusted such that hot and cold side temperatures will achieve the desired steady-state and

* Tradename Armco Steel Corp., Middletown, Ohio

Table A-2
Fire-Safety Test Summary

Type of Test	Test Vehicle	Number of Tests
Fixture Checkout	Dummy Fire Module	1
Module Checkout	Instrumented Fire Module	1
Fire-transient	Fire Module	A minimum of 1

transient temperature profiles. Since the fixture must come to thermal equilibrium for a conductance measurement to be made, the heaters and coolant will be adjusted such that temperature holds are achieved at outer case temperatures of approximately 400°F and 600°F with hot frame temperatures corresponding to the predicted values. The duration of these holds will be kept as short as possible. Above the hold at 600°F, it is anticipated that changes within the converter will develop at a rapid rate and hence the transient must proceed from this level along the predicted transient profile without interruption until a point is reached in the post-fire portion of the transient where a hold for a conductance measurement would not compromise the validity of the test. At a minimum, holds would be made during the post-fire or cool-down periods at approximately the same cold side temperatures where the earlier measurements had been made. Since the converter fire-safety evaluation is intended to provide an understanding of converter damage mechanisms as well as effective conductance values, a thorough visual inspection of the module internal components will be performed following each test.

The first module test will be conducted with a temperature/time profile corresponding to a 1475°F fire transient. Unless the test yields sufficient data for a complete analysis of the converter, this information will then be factored into the second module test which will use predicted profiles for a 1850°F fire. One other test may be run to validate the updated temperature/time profiles.

Figure A-2. Fire Module Test Stand

5.0 TEST PROCEDURES

5.1 Fixture Calibration Test

1. Insert dummy module in test stand.
2. Install test stand assembly in bell jar.
3. Evacuate bell jar to $<20\mu\text{Hg}$.
4. Backfill bell jar to 2 psia with argon.
5. Stabilize module at nominal PMC-2 BOL conditions ($T_{\text{HF}} = 1050^\circ\text{F}$, $T_{\text{OC}} = 155^\circ\text{F}$).
When thermal equilibrium is achieved, record T_{HF} , T_{OC} , ΔT_{STD} , radial temperature drops, heater power, backfill gas pressure, coolant mass flow rate, and coolant inlet and outlet temperatures.
6. Experimentally determine heater power and coolant flow rate versus time curves required to follow the 1475°F fire transient (see Figure A-3).
7. Experimentally determine heater power and coolant flow rate versus time curves required to follow the 1850°F fire transient (see Figure A-4).
8. Experimentally determine heater power and coolant flow rate required to achieve thermal equilibrium at $T_{\text{OC}} = 400^\circ\text{F}$, 600°F in steps (6) and (7) above.

NOTE: Continuously record T_{HF} , T_{OC} , ΔT_{STD} , radial temperature drops, heater power, coolant mass flow rate, and coolant inlet and outlet temperatures as a function of time in steps (6) through (8) above.

Figure A-3.

Calculated Response of SNAP-23A Generator
Components During 1475°F Half Hour Fire

Figure A-4.

Calculated Response of SNAP-23A Generator
Components During 1850°F Half Hour Fire

5.2 Instrumented Module Test

1. Assemble instrumented module with 2 instrumented cold caps and 2 instrumented hot caps. (Rather than attempting to install header feedthroughs, instrumentation wires will exit the module through the processing port.)
2. Insert instrumented module in test stand prior to processing.
3. Install test stand assembly in bell jar.
4. Process module in bell jar, blanking off bell jar (after backfilling with argon to 10 psig) instead of sealing processing port by pinchoff after completion of processing.
5. Stabilize module at PMC-2 BOL conditions ($T_{HF} = 1050^{\circ}\text{F}$, $T_{OC} = 155^{\circ}\text{F}$).
When thermal equilibrium is achieved, record T_{HF} , T_H , T_C , T_{OC} , ΔT_{STD} , radial temperature drops, heater power, backfill gas pressure, and coolant data.

5.3 Module Test (1475°F fire transient)

1. Insert processed, pinch-off module in test stand.
2. Install test stand assembly in bell jar.
3. Evacuate bell jar.
4. Backfill bell jar to 2 psia with argon.
5. Stabilize module at PMC-2 BOL conditions ($T_{HF} = 1050^{\circ}\text{F}$, $T_{OC} = 155^{\circ}\text{F}$).
When thermal equilibrium is achieved, record T_{HF} , T_{OC} , ΔT_{STD} , radial temperature drops, heater power, backfill gas pressure, and coolant data.

NOTE: In the following steps, continuously record T_{HF} , T_{OC} , T_{STD} , radial temperature drops, heater power, and coolant data.

6. Adjust heater power and coolant flow rate appropriately to follow the hot frame and outer case temperature transients shown in Figure A-3.
7. When the outer case temperature reaches approximately 400°F, adjust heater power and coolant flow rate appropriately to achieve a thermal equilibrium at that point in time on the transient curves.
8. As soon as thermal equilibrium is reached, readjust heater power and coolant flow rate to continue along the transient curves until the outer case temperature reaches approximately 600°F. At this point, once again readjust heater power and coolant flow rate to achieve a thermal equilibrium (at T_{OC} of approximately 600°F).
9. As soon as thermal equilibrium is reached, readjust heater power and coolant flow rate to continue along the transient curves until the outer case temperature has once again reached 600°F during the post-fire cool-down portion of the transient. At this point, readjust heater power and coolant flow rate to achieve a thermal equilibrium.
10. As soon as thermal equilibrium is reached, readjust heater power and coolant flow rate to continue along the post-fire portion of the transient curves until the outer case temperature reaches approximately 400°F. (In the event the transient does not reach 400°F, the outer case temperature will be adjusted to 400°F after completion of the transient). At this point, readjust heater power and coolant flow rate to achieve a thermal equilibrium.

5.4 Module Test (1850°F fire transient)

Procedure is identical to that in Section 5.3 except for substitution of appropriate transient curves (Figure A-4).

6.0 DATA ANALYSIS

6.1 Fixture Calibration Test

Heat flow through thermal standard (Q'_S) will be calculated on the basis of observed differential temperature (ΔT_{STD}) and measured geometry of the standard. This heat flow will be corrected for radial losses and then compared to that calculated to be flowing through the dummy module (Q'_D) on the basis of observed temperatures (including radial drops) and the module's geometry and thermal conductance as a function of temperature. If the thermal guarding of the test stand is adequate, the two values of heat flux should agree; otherwise, the heat flux through the standard will be calibrated in subsequent measurements by multiplying it by the ratio Q'_S/A'_D .

6.2 Instrumented Module Test

Observed module cold end temperature drop ($T_C - T_{OC}$) will be compared with that observed at similar BOL conditions on full-scale converters. Similar analysis will be performed for the hot end temperature drop ($T_{HF} - T_H$).

6.3 Module Tests

The thermal conductance of the module will be calculated on the basis of the following formula:

$$\bar{K}_m = \frac{Q'_S}{(\text{Cross-sectional area of module}) (T_{HF} - T_{OC})} .$$

The conductance will be calculated at the following equilibrium test points:

1. BOL conditions
2. $T_{OC} \cong 400^\circ\text{F}$ (during fire)
3. $T_{OC} \cong 600^\circ\text{F}$ (during fire)
4. $T_{OC} \cong 600^\circ\text{F}$ (post-fire)
5. $T_{OC} \cong 400^\circ\text{F}$ (post-fire)

The above module conductance values will then be correlated to full-scale converter performance on the basis of an analytically determined correlation factor.

APPENDIX B SNAP-23A FIRE TEST RAW DATA

A. 1850°F DUMMY TEST (Figure B-1)

- Hot End at 1055°F
Cold End at 155°F

Standard $\Delta T/C$ Readings:

6-7	0.465 mv	$T_{HF} = 1051^{\circ}\text{F}$
8-9	0.927	$T_{CF} = 156^{\circ}\text{F}$
6-8	0.354	
7-9	0.108	

Standard Heater Setting: 85% one 140 VAC variac

- Time: 18:15
Ramp to 400°F

- Hot End at 1100°F
Cold End at 400°F

Standard $\Delta T/C$ Readings:

6-7	0.300 mv	$T_{HF} = 1098^{\circ}\text{F}$
8-9	0.790	$T_{CF} = 382^{\circ}\text{F}$
6-8	0.368	
7-9	0.123	

Standard Heater Setting: 56% two 120 VAC variacs

- Time: 21:00
Ramp to 600°F
- Hot End at 1110°F
Cold End at 600°F

Standard $\Delta T/C$ Readings:

6-7	0.241 mv	$T_{HF} = 1085^{\circ}F$
8-9	0.726	$T_{CF} = 578^{\circ}F$
6-8	0.364	
7-9	0.120	

Standard Heater Settings: 56% two 120 VAC variacs

6. Time: 21:28
Ramp to Peak

During ramp to peak the following data was noted:

$T_C^{\circ}F$	$T_H^{\circ}F$	Hittman Curve $T_H^{\circ}F$
1400	1267	1250
1580	1390	1290
1680	1488	1330
1745	1555	1370

Discrepancy due to poor mechanical contact between hot frame and iron standard.

B. 1475°F DUMMY TEST RUN (Figure B-2)

1. Hot End at 1055°F
Cold End at 155°F

Standard $\Delta T/C$ Readings:

6-7	0.431 mv	$T_{HF} = 1051.3^{\circ}F$
8-9	0.987	$T_{CF} = 158^{\circ}F$
6-8	0.427	
7-9	0.128	

Standard Heater Setting: 45% on 2-140 VAC variacs

2. Time: 12:45
Ramp to 400°F
3. Hot End at 1055°F
Cold End at 400°F

Standard $\Delta T/C$ Readings:

6-7	0.321	$T_{HF} = 1039.7^{\circ}\text{F}$
8-9	0.840	$T_{CF} = 400^{\circ}\text{F}$
6-8	0.395	
7-9	0.124	

Standard Heater Setting: 50% on 2-140 VAC variacs

4. Time: 2:55
Ramp to 600°F

5. Hot End at 1055°F
Cold End at 600°F

Standard $\Delta T/C$ Readings:

6-7	0.261	$T_{HF} = 1058.7^{\circ}\text{F}$
8-9	0.772	$T_{CF} = 595^{\circ}\text{F}$
6-8	0.385	
7-9	0.123	

Standard Heater Settings: 49.5% on 2-140 VAC variacs

6. Time: 5:30 p.m. 11/3/69
Ramp to End of Test

Recording power on Mosley Strip Chart
Hot End Heater at setting of Step 5.

C. INSTRUMENTED MODULE THERMOCOUPLE LAYOUT

STANDARD

ANALYSIS FORM 1038A																		
Processing Data for Instrumented Module																		
	Time	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
		Pressure Cold Frame Hot Frame Hot Button #5 Hot Button #1 Cold Elec-trode #2 Hot Button #3 Cold Elec-trode #4 Cold Frame Power Hot Frame Power Water Flow G.P. Hr. Average Hot Average Cold																
1	11/15/69	14:35	Microns	Back Fill with Argon 2psig														
2		14:40		Pump for 30 minutes														
3		15:15	4	Blank Off														
4		15:16	5															
5		15:17	6															
6		15:18		Pump for 30 minutes														
7		16:00		Back Fill with Argon 2psig - Increase temps to 1011°F and 187°F														
8																		
9	(Not Stable)	17:15	2psig	148	1049	1005	1017	190	1017	187		40.0	67.0	0.5	1013	189		
10		17:30	2psig	145	1047	1002	1015	183	1014	181		44.0	69.0	0.5	1010	182		
11	11/16/69	09:30	2psig	148	1048	1005	1017	186	1016	184		44.0	69.0	0.5	1013	185		
12		10:00		148	1047	1005	1016	186	1016	184		44.0	69.0	0.5	1013	185		
13				155	1050													
14		11:00	Test shut down	and remove from bell jar.														
15																		
16																		
17	B-5		Temp:	Cold T = 38°F (Cold Frame to Cold Electrode)														
18				Hot T = 36°F (Hot Frame to Hot Electrode)														
19																		
20																		
21																		
22																		
23																		
24																		
25																		
26																		
27																		
28																		
29																		
30																		
31																		
32																		
33																		
34																		
35																		
36																		

D. 1475°F FIRE TEST (Figure B-3)

1. Hot End at 1055°F

Cold End at 155°F

Standard $\Delta T/C$ Readings:

6-7	1.288 mv	$T_H^F = 1052.6^\circ F$
8-9	1.181	$T_C^F = 160^\circ F$
6-8	0.140	
7-9	0.033	

Standard Heater Setting: 136 VAC on variac

Reaching Equilibrium:

Hot External	Standard	
1064.0°F	32.17 mv	18:56
1056.6	31.85	19:07 variac at 131 VAC
1055.4	31.82	19:09 increased to 133 VAC
1053.7	31.76	19:15
1052.7	31.75	19:18
1052.4	31.78	19.21 increased to 136 VAC
1052.4	31.78 = 1105°F	19:24
		19:26 data taken

2. Time: 19:27 11/19/69

Ramp to 400°F

Standard $\Delta T/C$ Readings:

6-7	1.080	$T_H^F = 1057^\circ F$
8-9	1.011	$T_C^F = 395^\circ F$
6-8	0.104	
7-9	0.034	

Standard Heater Setting: 136 volt VAC on variac

Reaching Equilibrium:

Hot External	Standard	Time	Variac
1057.5°F	31.47	19:41	120
1055.8	31.31	19:44	120
		19:45	130
1051.5	31.26	19:51	136
1051.9	31.32	19:55	136
1054.5	31.41	20:04	136
1056.2	31.45	20:08	136
		20:12	Reading

4. Time: 20:15

Ramp to 600°F

5. Hot End at 1070°F

Cold End at 600°F

Standard $\Delta T/C$ Readings:

6-7	0.856 mv	$T_{HF} = 1071.5^\circ F$
8-9	0.779	$T_{CF} = 595^\circ F$
6-8	0.100	
7-9	0.023	

Standard Heater Setting: 130 VAC on variac

Reaching Equilibrium: (600°F Hold)

<u>Hot External</u>	<u>Standard</u>	<u>Time</u>	<u>Variac</u>
1066.8°F	31.62	20:25	130
1071.0	31.58	20:32	130
1071.7	31.56	20:38	130
1071.6	31.52	20:41	130
1071.4	31.52	20:42	Data

6. Time: 20:43

Ramp over top and cool down to 600°F

Air flow decreased from 30 psig on regulator to 25 psig.

Downward ramp was slow by approximately 60°F on the portion of curve.

T cold holding at 21:18 -

Reaching Equilibrium:

<u>Hot External</u>	<u>Standard</u>	<u>Time</u>	<u>Variac</u>
1082.0°F	31.89	21:20	130
1081.0	31.88	21:22	130
1077.0	31.82	21:26	130
1075.0	31.75	21:31	130
1073.0	31.68	21:36	130
1071.7	31.62	21:40	130
1069.2	31.54	21:51	130
		21:52	Data

6-7	0.970	$T_H^F = 1069.8^\circ F$
8-9	0.897	$T_C^F = 595^\circ F$
6-8	0.099	
7-9	0.025	

7. Cooling to 400°F

Time: 21:55 at 400 21:59

Hot External	Standard	Time	Variac
1063.2°F	31.46	22:00	130
1057.6	31.45	22:04	136
1055.4	31.45	22:08	136
1054.1	31.43	22:12	136

6-7	1.198	$T_H^F = 1053.9^\circ F$
8-9	1.135	$T_C^F = 400^\circ F$
6-8	0.093	
7-9	0.031	

8. Temperature Calculations

T6 = 1100°F	=32.720	$T_H^F = 1052.6^\circ F$
	1.288	
T7 = 1060	=31.432	$T_C^F = 160^\circ F$
T8 = 1100	=32.72	
	1.18	
T9 = 1063	=31.54	

T6 = 1107	=32.95	$T_H^F = 1057^\circ F$
	-1.08	
T7 = 1074	=31.87	$T_C^F = 395^\circ F$
T8 = 1107	=32.95	
	-1.01	
T9 = 1076	=31.94	

T6 = 1121°F = 33.37 .86	T _H ^F = 1071.5°F
T7 = 1093 = 32.51	T _C ^F = 595°F
T8 = 1121 = 33.57 .78	
T9 = 1096 = 32.59	
<hr/>	
T6 = 1120 = 33.37 -.97	T _H ^F = 1069.8°F
T7 = 1090 = 32.40	T _C ^F = 595°F
T8 = 1120 = 33.37 -.90	
T9 = 1092 = 32.47	
<hr/>	
T6 = 1104 = 32.86 -1.20	T _H ^F = 1053.9°F
T7 = 1067 = 31.66	T _C ^F = 400°F
T8 = 1104 = 32.86 1.13	
T9 = 1069 = 31.73	
<hr/>	

E. DUMMY DUMMY TEST (24 November 1969)

Replaced module with a cylinder of Min-K. Control cold end heater block and Armco iron standard at 1050°F and measure heat flow through Armco iron standard with middle guard heater de-energized and energized:

Middle Guard De-Energized

T Cold = 1057.1°F	
T6 = 1055.7	
T7 = 1050.6	13:25 (Time)
T8 = 1053.6	
T9 = Open	
T6 = 1041.8	
T7 = 1040.6	
T8 = 1042.2	13:34
T9 = 1040.5	

T6 = 1044.6	
T7 = 1042.7	13:41
T8 = 1044.8	Variac set at 127 VAC
T9 = 1047.6	

T6 = 1042.9	
T7 = 1041.8	13:51
T8 = 1043.0	Increased variac to 130 VAC
T9 = 1041.6	

T6 = 1045.4	
T7 = 1043.1	13:57
T8 = 1045.5	Decreased variac to 128 VAC
T9 = 1042.9	

T6 = 1045.5	
T7 = 1043.5	
T8 = 1045.6	14:05
T9 = 1043.4	

T6 = 1045.6	
T7 = 1043.8	
T8 = 1046.0	14:10
T9 = 1044.7	

T6 = 1047.7	
T7 = 1046.0	
T8 = 1047.9	14:18
T9 = 1045.9	

T6 = 1049.3	
T7 = 1047.7	
T8 = 1049.7	14:23
T9 = 1047.7	

T6 = 1049.0		6-7	0.054 mv	CE = 1056°F
T7 = 1047.4		8-9	0.059	
T8 = 1049.4	14:28	6-8	0.003	
T9 = 1047.4		7-9	0.007	

Energized Middle Guard Heater - 14:30

T6 = 1049.5		T6 = 1051.0	14:56
T7 = 1047.7		T7 = 1049.2	
T8 = 1049.8	14:45	T8 = 1051.2 (1056°F CF)	
T9 = 1047.9			

Middle Guard Energized

T Cold = 1057.2°F	15:20
T6 = 1055.0	
T7 = 1053.4	
T8 = 1053.2	
T9 = 1053.7	

T6 = 1058.7		
T7 = 1057.3		
T8 = 1058.6	15:45	$T_C^F = 1056.9^{\circ}F$
T9 = 1057.2		

T6 = 1060.5		
T7 = 1059.2		
T8 = 1060.6	16:00	$T_C^F = 1057.6^{\circ}F$
T9 = 1059.3		

Cooled down to 155°F - Mid-guard De-energized. Time: 17:15

T6 = 1065.6		
T7 = 1063.4		
T8 = 1065.2	17:15	$T_C^F = 156.6^{\circ}F$
T9 = 1063.7		

T6 = 1066.2		
T7 = 1064.0		
T8 = 1065.5	17:20	$T_C^F = 156.2^{\circ}F$
T9 = 1064.1		

Holding dummy at 155°F cold
1050°F hot

Time: 17:25

T6 = 1067.4		
T7 = 1065.2		
T8 = 1062.6		$T_C^F = 155.0^{\circ}F$
T9 = 1066.2		

Time: 17:30

T6 = 1068.1		
T7 = 1066.0		
T8 = 1067.6		$T_C^F = 155.8^{\circ}F$
T9 = 1066.3		

Time: 17:32

Energized Mid-Guard Heater

Time: 15:05

T6 = 1065.5		
T7 = 1063.0		
T8 = 1064.0		$T_C^F = 155.8^{\circ}F$
T9 = 1063.5		

Time: 18:10

T6 = 1065.0
 T7 = 1063.1
 T8 = 1065.2
 T9 = 1063.6

F. 1475°F FIRE TEST REPEAT

155°F and 1050°F Starting Point

Cold end not responding.

Steady data recorded at following condition:

T_C = 210°F (temperature decreasing 187.3 when lower guard is off)

T_H = 1000°F

6-7 = 1.196
 8-9 = 1.039
 6-8 = 0.017
 7-9 = 0.136

13:48

6-7 = 1.194
 8-9 = 1.040
 6-8 = 0.131
 7-9 = 0.017

14:06

T_H = 1000°F

T_C = 182°F

T6 = 1054.5
 T7 = 1017.2
 T8 = 1050.6
 T9 = 1018.1

Control of cold end unsuitable - test terminated.

G.
ANALYSIS FORM 1038A

FILE
SEC.
DATE SHEET NO.

SNAP-23A

1850°F FIRE TEST (FIG B-4)

ANALYSIS FORM 1038A

SNAP-23A

1850°F FIRE TEST (FIG B-4)

		Data Cases Analyzed				Temp °F				Hot Frame		Cold Frame		Variac		6-7		6-8		7-9	
		A	B	C	D	T6	T7	T8	T9	F	G	H	J	K	L	M	N	O	P	R	
1	11:00		1111	1062	1105	1064	1046	165		178-					1.571	1.310	.195	.071			
2	11:10		1112	1063	1106	1066	1048	165		178-					1.564	1.300	.193	.072			
3	11:20		1115	1066	1110	1068	1052	166		178-					1.581	1.336	.178	.069			
4	6 Dec 69 11:30		1120	1071	1114	1073	1058	168		178-					1.565	1.329	.170	.065			
5			1133	1086	1129	1088	1073	171		176-					1.550	1.316	.169	.067			
6	9 Dec 69 11:55		1108	1060	1102	1062	1038	161		165					1.544	1.370	.167	.060			
7	Auto Temps.																				
8																					
9	9 Dec 12:02	Ramp to 400°F																			
10	12:08	At 400°F & Holding																			
11																					
12	12:24		1125	1084	1120	1082	1068	398		165					1.383	1.156	.167	.060			
13	12:31		1129	1086	1125	1088	1075	397		165					1.380	1.153	.169	.058			
14	12:37		1132	1089	1128	1091	1077	398		165					1.373	1.147	.166	.060			
15	12:48		1137	1096	1133	1097	1083	398		165					1.374	1.146	.166	.060			
16	12:57		1141	1096	1136	1100	1088	400		165					1.375	1.148	.166	.060			
17	13:04		1143	1102	1139	1103	1089	400		165					1.379	1.151	.160	.060			
18	Up to 600°F and Holding																				
19	13:16		1148	1110	1142	1112	1102	600		165					1.250	1.025	.159	.055			
20	13:20		1152	1116	1148	1118	1106	599		165					1.218	0.994	.167	.057			
21	13:25		1154	1118	1150	1119	1112	599		165					1.206	0.985	.170	.054			
22	13:30		1158	1121	1153	1124	1116	600		165					1.204	0.978	.170	.054			
23	13:35		1160	1125	1157	1127	1119	600		165					1.200	0.974	.169	.057			
24	13:40		1163	1127	1159	1130	1122	600		165					1.199	0.973	.170	.057			
25	13:46		1165	1129	1161	1131	1124	600		165					1.198	0.972	.169	.056			
26	13:51		1168	1131	1164	1133	1125	600		165					1.200	0.972	.170	.058			
27	13:56		1170	1133	1165	1136	1128	600		165					1.204	0.976	.171	.056			
28	14:00		1171	1135	1167	1137	1129	600		165					1.206	0.978	.170	.060			
29	14:05		1173	1137	1168	1138	1131	602		165					1.200	0.983	.168	.061			
30	Ramp over top 14:06	Up Ramp																			
31	Down to 600°F & Holding																				
32	14:56		1192	1148	1187	1152	1136	596		165					1.385	1.119	.184	.089			
33	15:00		1191	1146	1185	1148	1131	594		165					1.473	1.201	.182	.090			
34	15:05		1188	1142	1182	1144	1125	595							1.519	1.248	.182	.090			
35	15:10		1186	1138	1180	1140	1122	598		165					1.540	1.269	.182	.091			
36	15:15		1182	1135	1177	1137	1119	598							1.551	1.277	.183	.091			

B-14

G. SNAP-23A
1850°F FIRE TEST (FIG B-4)

Temp °F

			T6	T7	T8	T9	Hot Frame	Cold Frame	Variac		6-7	8-9	6-8	7-9	
		A	B	C	D	E	F	G	H	J	K	L	M	N	O
1	9 Dec 69	15:20	1178	1129	1173	1132	1116	598		165		1.556	1.280	.185	.090
2		15:25	1176	1128	1171	1132	1113	599		165		1.558	1.285	.182	.092
3		15:35	1173	1125	1168	1128	1110	599		165		1.564	1.289	.182	.092
4		15:40	1172	1124	1166	1126	1108	600		165		1.568	1.284	.184	.091
5		15:45	1170	1121	1165	1125	1106	600		165		1.567	1.284	.184	.091
6		15:50	1168	1120	1163	1122	1106	598		165		1.568	1.294	.185	.090
7		15:55	1168	1118	1162	1122	1104	600		165		1.569	1.297	.183	.093
8		16:00	1166	1118	1160	1120	1103	599		165		1.571	1.299	.183	.091
9		16:08	Down to 400°F (CF)							165					
10		16:15	1158	1102	1152	1106	1082	402		165		1.765	1.481	.184	.102
11		16:25	1152	1096	1146	1099	1076	400		165		1.785	1.499	.185	.101
12		16:30	1148	1092	1142	1094	1072	402		165		1.793	1.506	.184	.101
13		16:35	1144	1089	1138	1091	1067	401		165		1.799	1.515	.184	.101
14		16:45	1139	1084	1133	1086	1065	402		165		1.795	1.514	.183	.098
15		16:50	1136	1080	1131	1084	1061	402		165		1.793	1.513	.182	.097
16		16:55	1133	1077	1128	1079	1056	402		165		1.790	1.513	.181	.096
17		17:00	1130	1073	1125	1077	1055	402		165		1.789	1.514	.180	.096
18		17:05	1129	1072	1124	1075	1054	401		165		1.788	1.514	.180	.094
19		17:10	1127	1070	1121	1074	1052	400		165		1.787	1.513	.182	.093
20		17:11	Down to 155°F (CF)												
21															
22															
23															
24	9 Dec 69	22:30	1054	990	1048	994	960	202				1.995	1.721	.175	.100
25															
26		Cool Down with CO ₂ - 155° CF													
27															
28		22:35	1053	991	1049	994	958	154				2.009	1.735	.174	.100
29		22:50	1053	989	1048	992	952	162				2.067	1.799	.169	.101
30		23:00	1053	988	1047	991	951	164				2.065	1.797	.168	.099
31															
32		Power Off													
33															
34															
35															
36															

H.

Second 1475 °F Test (Retest of 19-Nov-69 Data)

FIG B-5

FILE

SEC.

DATE Dec. 3, 1969 SHEET NO. 1

ANALYSIS FORM 1038A

ANALYSIS FORM 1038A											DATE DEC. 3, 1963												
	Time	Temp. °F					Hot Frame	Cold Frame	Variac Setting	Voltage													
		A T6	B T7	C T8	D T9	E				F	G	H	J	K	L	6-7 M	8-9 N	6-8 O	7-9 P	R			
1	1050 °F	15:13	1132	1075	1126	1076	1050	170	180														
2	and	15:16	1128	1079	1122	1080	1054	156	170														
3	155 °F	15:19	1124	1079	1117	1079	1056	156	170														
4		15:25	1114	1073	1108	1074	1058	154	170														
5		15:30	1108	1068	1102	1068	1050	156	175														
6		15:36	1106	1063	1100	1063	1045	153	175														
7		15:40	1105	1062	1100	1062	1045	157	178														
8			NEW METERS																				
9		15:43	1108	1064	1103	1065	1046	155	178						1.428	1.219	.176	.032					
10		15:50	1108	1064	1103	1064	1042	156	178						1.436	1.228	.180	.030					
11		15:53	1109	1064	1103	1065	1044	157	178						1.440	1.230	.180	.028					
12		15:55	RAMP TO 400 °F - CF																				
13																							
14																							
15	400 °F	16:15	1116	1076	1111	1077	1064	402	178						1.305	1.086	.177	.038					
16	UP RAMP	16:20	1120	1080	1115	1081	1066	402	178						1.279	1.064	.193	.027					
17		16:25	1124	1084	1119	1085	1070	402	178						1.285	1.070	.187	.031					
18		16:30	1128	1088	1122	1089	1074	403	178						1.292	1.075	.187	.031					
19		16:35	1130	1090	1125	1091	1076	402	178						1.291	1.074	.189	.032					
20		17:00	1141	1102	1135	1103	1090	402	178						1.287	1.070	.188	.033					
21		17:10	1143	1104	1138	1105	1092	402	178						1.295	1.071	.188	.032					
22		17:15	1145	1106	1140	1107	1093	402	178						1.297	1.081	.188	.031					
23		17:25	1148	1109	1143	1110	1097	402	178						1.303	1.087	.187	.031					
24		17:30	1149	1110	1144	1111	1097	402	178						1.303	1.087	.186	.031					
25		17:35	1150	1111	1145	1112	1098	402	178						1.301	1.085	.187	.029					
26		17:40	1151	1112	1146	1113	1098	402	178						1.299	1.084	.188	.028					
27		17:40	UP RAMP TO 600 °F																				
28																							
29																							
30	600 °F	17:50	1154	1118	1148	1119	1109	604	178						1.190	0.972	.187	.034					
31	UP RAMP	18:05	1162	1128	1157	1129	1121	604	178						1.145	0.922	.180	.033					
32		18:25	1169	1136	1165	1137	1132	605	178						1.143	0.933	.177	.035					
33		18:35	1175	1140	1170	1141	1137	605	178						1.172	0.961	.179	.035					
34		18:45	1180	1145	1175	1146	1144	606	178						1.142	0.968	.182	.033					
35		18:55	1184	1149	1179	1150	1149	606	178						1.187	0.972	.182	.033					
36																							

B-16

H. 1475 °F Fire Test (Retest of 19-Nov-69 Data)

ANALYSIS FORM 1038A

FILE

SEC.

DATE Dec. 3, 1969 SHEET NO. 2

ANALYSIS FORM 1038A																		
		Temp. °F							Voltage									
Time		T6	T7	T8	T9	Hot Frame	Cold Frame	Variac Setting										
		A	B	C	D	E	F	G	H	J	K	L	6-7	8-9	6-8	7-9	P	R
1	600 °F	19:00	1187	1151	1181	1152	1151	605	178				1.192	0.977	.182	.032		
2	UP RAMP	19:10	1189	1154	1184	1155	1154	600	178				1.187	0.975	.182	.032		
3		19:10			UP RAMP - 1475 °F					HF = 1161 °F		CF = 1197 °F						
4		19:45		Stop	at 600 °F		CF Temp.											
5																		
6																		
7	600 °F	20:00	1212	1173	1207	1174	1175	604	178				1.328	1.080	.194	.057		
8	DOWN RAMP	20:20	1207	1168	1201	1169	1171	602	178				1.319	1.074	.191	.056		
9		20:25	1207	1168	1202	1169	1172	604	178				1.334	1.089	.193	.054		
10		20:30	1208	1168	1202	1170	1172	604	178				1.335	1.089	.194	.053		
11		20:30		DOWN TO 400 °F -				COLD	FRAME									
12																		
13																		
14	400 °F	20:50	1202	1157	1196	1159	1158	405	178				1.504	1.252	.197	.056		
15	DOWN RAMP	21:00	1199	1153	1193	1155	1154	406	178				1.519	1.277	.192	.052		
16		21:10	1197	1151	1191	1153	1152	406	178				1.514	1.277	.187	.053		
17		21:10		DOWN TO 155 °F -				COLD	FRAME									
18																		
19																		
20	155 °F	21:45	1181	1131	1175	1132	1128	191	178				1.681	1.440	.190	.053		
21	: AGAIN	21:50	1180	1130	1174	1131	1126	190	178				1.681	1.439	.189	.052		
22																		
23		21:50		ALL POWER OFF														
24																		
25																		
26																		
27																		
28																		
29																		
30																		
31																		
32																		
33																		
34																		
35																		
36																		

B-17