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**SNAP-23A PROGRAM
PHASE I
THERMOELECTRIC CONVERTER
DEVELOPMENT PROGRAM**

MASTER

QUARTERLY REPORT NO. 2

RECEIVED BY BIE SEP 14 1967

3M Isotope Power Products
MINNESOTA MINING & MANUFACTURING CO.
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SNAP-23A PROGRAM PHASE I

THERMOELECTRIC CONVERTER DEVELOPMENT PROGRAM

QUARTERLY REPORT NO. 2

April 1, 1967 through June 30, 1967

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FOREWORD

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

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

The SNAP-23A development effort is directed toward the design, fabrication, and test of a thermoelectric converter design to be used as a component in the 60-watt SNAP-23A Terrestrial Radioisotope Power Supply System. This document reports progress for this effort from the period 1 April through 30 June 1967.

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

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

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

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SECTION 1.0
SUMMARY

1.0 SUMMARY

During this quarter the milestone effort completed was the release of the Experimental Mockup Converter design. A summary of this design is given in paragraph 3.2.

Other significant highlights occurring during this period are summarized below:

- Design analysis and design change release of the Experimental Mockup Converter to achieve a thermal match with an optimized system design.
- Converter/system mechanical interface design finalized.
- "Program Plan", Vol. I and II, MMM 3824-0005 submitted.
- "Quality Control Plan" MMM 3824-0001 — preliminary was submitted to system contractor and AEC for comments and review.
- Design completed for the 10-couple module.
- Process and Test Stations (converter and 10-couple module) designed.

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SECTION 2.0

TASK I – PROGRAM MANAGEMENT

2.0 TASK I-PROGRAM MANAGEMENT

2.1 LIAISON

Extensive coordination and liaison activities were performed throughout the reporting period with Westinghouse Astronuclear Laboratory (WANL) to further develop the definitive interface between the 3M developed SNAP-23A thermoelectric converter and the Westinghouse developed SNAP-23A radioisotope power supply.

Efforts this quarter were concerned with parametric analysis and resolution of mechanical, thermal, electrical and instrumentation interface design details necessary to complete the design and integration of the Experimental Mockup Converter.

On the basis of the joint parametric analysis conducted on the converter by 3M and on the system by Westinghouse, agreement was reached on the Experimental Mockup Converter design parameters. The final converter design contains 264-couples and achieves a thermal match with the optimized SNAP-23A system.

An agreement was reached with Westinghouse and the AEC concerning the three SNAP-23A Experimental Mockup Converters as follows:

Converter No. 1 – To be shipped to Westinghouse for system integration testing (performance) prior to design of the Prototype Mockup Converter and system. The converter may be subjected to shock and vibration test as part of the SNAP-23A system.

Converter No. 2 — To be shock and vibration tested, then placed on long-term performance test; all testing to be conducted by 3M.

Converter No. 3 — To be tested to determine optimum stability conditioning time based on initial performance characteristics which will be used to establish acceptance criteria for Prototype Mockup Converter design. The converter will then be subjected to long-term performance and temperature excursion test; all testing to be conducted at 3M.

2.2 DOCUMENTATION AND REPORTS

The following documents were published during the second quarter.

- SNAP-23A Program Plan, Volumes I and II, Report No. MMM 3824-0005
- Quarterly Report No. 1, Report No. MMM 3824-0006, dated May 22, 1967
- Monthly Report - April 1967, Report No. MMM 3824-0007
- Monthly Report - May 1967, Report No. MMM 3824-0008

2.3 EFFORT PLANNED FOR NEXT QUARTER

During the forthcoming quarter, 3M and Westinghouse will continue liaison efforts with emphasis on preparation for test integration of the first Experimental Mockup Converter and system, and on planning for design of the Prototype Mockup Converter. Major scheduled efforts anticipated for the third quarter include:

- Complete final assembly of Experimental Mockup Converter, EMC-1, ready for final processing and acceptance test.
- Complete final assembly and processing of twelve 10-couple module units.
- Initiate long-term performance testing activity on twelve 10-couple module units.

- Continue short-term thermoelectric couple performance testing activities in the bell jar test apparatus.
- Complete final assembly of converter process and test station.
- Initiate effort on thermoelectric material recharacterization.

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SECTION 3.0
TASK II-60-WATT CONVERTER DEVELOPMENT

3.0 TASK II-60-WATT CONVERTER DEVELOPMENT

3.1 INTRODUCTION

The objective of this task is to design, develop, fabricate and test a thermoelectric converter that will interface with the SNAP-23A power supply system. As a component of the system, the converter is required to produce 60 watts under ten-year end-of-life (EOL) temperature conditions.

A major share of the design effort this quarter was spent in re-evaluating the SNAP-23 converter design, both analytically and by physical examination of parts from disassembled units which had been long-term performance tested and applying this re-evaluation to the present design.

Under Phase I of this program two distinct converter designs will be prepared. The effort covered in this report is for the first of these, the Experimental Mockup Converter. During this quarter the design was completed and the drawings released. A summary of this design is presented in paragraph 3.2 of this section of this report.

3.2 DESIGN SUMMARY

3.2.1 SNAP-23A EXPERIMENTAL MOCKUP CONVERTER

The SNAP-23A Experimental Mockup Converter design (Figure 3-1 and Tables 3-1 and 3-2) is based upon and similar to that of the SNAP-23 converter. The primary reason SNAP-23 converter technology was used as the baseline for the Experimental Mockup Converter was satisfactory SNAP-23 converter performance.

Table 3-1. SNAP-23A Experimental Mockup Converter
Parts and Materials

Item	Quantity	Part Title	Material
1	1	Outer Case	Stainless Steel
2	1	Support Cone	Stainless Steel
3	1	Hot Frame	Stainless Steel
4	1	Ring, Lower Rain Cover	Stainless Steel
5	40	Insulation Strip, Electrical	Boron Nitride
6	40	Pin, Anchor	Stainless Steel
7	1	Thermal Insulation Block	Johns-Manville Min-K 1301 (Molded Form)
8	1	Thermal Insulation for Support Cone	Johns-Manville Micro Quartz (formed at assembly)
9	1	Thermal Insulation for Couples	Johns-Manville Min-K 1301 (Powdered Form)
10	1	Min-K Thermal Insulation for Lower Cover	Johns-Manville Micro Quartz
11	1	Power Output Header	Eimac Division of Varian
12	1	Cold Frame	Aluminum
13	264	Hot Junction Electrode	Copper
14	528	Hot Junction Button	Mild Steel
15	264	P-Leg	(See Table 3-3)
16	264	N-Leg	(See Table 3-3)
17	264	Jumper Wire	Copper
18	264	Cold Cap, P-Leg	Copper
19	264	Cold Cap, N-Leg	Copper
20	528	Follower	Hardcoated Aluminum
21	528	Insulating Washer	Mica
22	528	Follower Spring	Stainless Steel
23	528	Support Washer	Steel
24	40	Support Wire	Steel

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Table 3-2. SNAP-23A Experimental Mockup Converter Parameters

Converter Parameter	Terminology	Units	Nominal Value	
			BOL	EOL
Electrical				
Power Output	P	watts	80.5	60.24
Voltage, Open Circuit	E	volts	53.51	41.29
Voltage, Load	V _L	volts	24	23.86
Overall Efficiency	N	percent	8.0	7.8
Thermal				
Total Heat Input	Q _T	watts	1006.4	771.5
Shunt Heat Loss	Q _L	watts	78.4	59.9
Temp., Hot Junction	T _H	°F	1085	900
Temp., Cold Junction	T _C	°F	191	174
Temp., P-leg Segment	T _{SP}	°F	568.5	489
Temp., N-leg Segment	T _{SN}	°F	406.4	349.2
Temp. Drop, Hot Frame to Hot Junction	---	°F	40	40
Temp. Drop, Cold Junction to Fin Base	---	°F	30	30
Configuration				
Heat Rejection Method	---	----	Cooling fins	
Hot Side Heat Transfer	---	----	Conduction	
Converter Weight	---	pounds	35	
Number of Couples	N _C	----	264	
Number of Couple Rows, Vertical	---	----	40	
Number of Couple Rows, Radial	---	----	7	
Contact Pressure	---	psi	250	
Fill Gas	---	----	Xenon	
Fill Gas Pressure	---	psia	25	

The major areas of difference between the SNAP-23 converter and the SNAP-23A Experimental Mockup Converter include couple geometry and number, electrical insulation and method of attachment, follower springs, support cone, hot frame, outer case and power output header. These are discussed in detail in paragraph 3.2.1.1 through paragraph 3.2.1.7.

The primary parameters which influenced the design changes listed above are operating temperatures, 60-watt power output requirements at the end of 10-year design life, and dynamic load considerations. In addition, information gained from the SNAP-23 converter post-test analysis was integrated into the SNAP-23A Experimental Mockup Converter design.

The SNAP-23 converter was a 252-couple design while the final iteration of the SNAP-23A Experimental Mockup Converter is a 264-couple design (the initial SNAP-23A Experimental Mockup Converter design was 280-couples but was redesigned to meet changed SNAP-23A system requirements – refer to paragraph 3.2.1.1 for details). Thermoelectric couple leg characteristics (Table 3-3) which did not change from the SNAP-23 converter (leg geometry is the same for both the SNAP-23A Experimental Mockup Converter 264- and 280-couple designs) include N and P leg diameters, leg hot and cold segment materials, and cold segment to total leg length ratios. The same leg manufacturing method (segmenting by pressing of the two segment materials simultaneously) will also be used.

3.2.1.1 264-Couple Design

Based on Westinghouse proposed system temperature and heat input data, the SNAP-23A Experimental Mockup Converter was initially a 280-couple design (discussed in SNAP-23A Program Quarterly Report No. 1 (MMM 3824-0006). The 280-couple design was reanalyzed to determine the number of couples to be removed to obtain a closer system thermal match and reduce fuel requirements when new temperatures and heat input rate conditions (couple cold junction temperature at BOL (beginning-of-life) and EOL (end-of-life) and average couple hot junction temperature) were established as the result of a 3M couple parametric study (paragraph 3.3.2.1) and system contractor thermal analyses.

Table 3-3. SNAP-23A Experimental Mockup Converter
Thermoelectric Couple Parameters

Characteristic	P-Leg	N-Leg
Thermoelectric Material, Hot Segment Cold Segment	M-76 (PbSn)Te M-29 (BiSb) 2T3	M-10 (PbTe) M-13 (PbTe)
Leg Dimensions, inch Hot Segment Length Cold Segment Length Total Leg Length Diameter	$L_{HP} = 0.213$ $L_{CP} = 0.114$ $L_P = 0.327$ $D_P = 0.187$	$L_{HN} = 0.359$ $L_{CN} = 0.120$ $L_N = 0.479$ $D_N = 0.187$
Ratio Cold Segment Length to Total Leg Length	$\frac{L_{CP}}{L_P} = 0.350$	$\frac{L_{CN}}{L_N} = 0.250$
Ratio, inch^{-1} Leg Length/Area	$\frac{L_P}{A_P} = 11.91$	$\frac{L_N}{A_N} = 17.44$
Fabrication Method	Segments Simultaneously Powder-Pressed	Segments Simultaneously Powder-Pressed

The present couple design is a 264-couple configuration. As can be noted in Table 3-2, the number of vertical rows when multiplied by the number of radial rows equals 280. The 16 couples have been removed from the top radial row in a symmetrical pattern. Parts necessary to span the voids of the 16-couples have been designed and released. The 264-couple configuration is discussed in detail in paragraph 3.3.2.2 of this report.

3.2.1.2 Electrical Insulation and Method of Attachment

The boron nitride strips (Figure 3-1- (5)), which electrically insulate the couples from the hot frame (3), were redesigned due to a cracking problem uncovered during the SNAP-23 converter P-1 post-test analysis. To correct this problem both the method of anchoring the strips and the strip thickness were changed.

The method of anchoring the strip to the hot frame was changed from a shallow surface lug to a through pin to eliminate bending stresses at the anchor point. The anchor pin is located at a point on the hot frame (6) such that the relative motion (vertical direction) between the boron nitride strips and the cold frame (12) is minimized (refer to paragraph 3.3.2.4 for detailed analysis).

The thickness of the strips was increased to resist the friction force created by the difference in thermal coefficient of expansion between the boron nitride and stainless steel hot frame (refer to paragraph 3.3.2.5 for detailed analysis). The strip is now twice as thick in the region of the couples and approximately four times as thick at the upper end of the strips to permit the pin type anchor.

3.2.1.3 Follower Springs

The follower springs (22) have undergone a redesign as a result of the increased thickness of the boron nitride strips. Of the three possibilities for absorbing this increased thickness, a follower spring change appeared the most feasible. Increasing the outside diameter of the converter had the disadvantage of changing an established interface dimension. However, it was necessary to increase the inside diameter of the cold frame (12) to make room for the couples. Since shortening the follower (20) decreases the heat transfer efficiency from the follower to the cold frame, the increase in boron nitride strip thickness was

offset by shortening the follower springs. Although the new springs have less working space than the previous springs, an improvement in spring rate and working length ratio was realized by changing the spring material and using the maximum allowable stress recommended by Associated Spring Corp. for a static spring application. Refer to paragraph 3.3.1.1 for the detailed design analysis.

3.2.1.4 Support Cone

A structural analysis of the support cone appeared in the first quarterly report. The SNAP-23A Experimental Mockup Converter support cone (2) was structurally stiffened as a result of the converter having to withstand system imposed acceleration loads which are twice the acceleration forces specified in MIL-Std-810A. When the system is vibrated per MIL-Std-810A, the converter is subjected to increased vibration amplitudes as a result of being attached to a truss rod supported fuel capsule which vibrates at approximately twice the specification amplitudes. The fin type heat rejection system, which is clamped to the outer case (1), imposes an additional load on the support cone. Stiffening of the support cone was accomplished by increasing the cone thickness from 0.016 to 0.025 inch and increasing the section of the integral inner and outer ring.

3.2.1.5 Hot Frame

The hot frame changes, while not readily apparent in Figure 3-1, primarily involve the threaded attaching web which is referred to as the "jacking base" in the hot frame analysis presented in the first quarterly report. The jacking base thickness was increased from 0.25 inch (SNAP-23 thickness) to 0.75 inch in anticipation of high removal forces necessary for separating the converter from the system heat input speed. The boron nitride strip anchor pin has replaced the 0.030 inch high lug, that previously held each strip. The hot frame is 0.790 inch larger in diameter than the previous hot frame.

3.2.1.6 Outer Case

The outer case (1) configuration has changed appreciably as a result of system integration. An inner ring was added to provide positive positioning of the cold frame with respect to the outer case, a spacer being placed between the ring and

cold frame at each attaching bolt. An external flange at the bottom of the outer case is for the purpose of attaching a system rain shield, the shield being made of rubber so that the converter is not subjected to lateral loads by the system container during lateral vibration. The external flange at the top of the outer case is the mating surface for a rain cover. Wall thickness adjacent to the cold frame and between the fin locating shoulders was increased from 0.030 to 0.045 inch for machining and assembly purposes. During one stage of the design a tapered wall was considered for this thin section. (Refer to paragraph 3.2.2 of SNAP-23A Program Quarterly Report No.1 for more detailed information.)

3.2.1.7 Power Output Header

The electrical header for the SNAP-23 converter was a gland type connector made by Conax Corporation which was welded to the converter outer case. A hermetic seal was effected by squeezing a flexible sealing ring around each power lead; the sealing ring being trapped between a compression nut and the metal connector body. Although a hermetic seal was demonstrated for static application, it was decided not to use this connector for the SNAP-23A Experimental Mockup Converter primarily for two reasons. First, it was believed that vibration might cause the compression nut to loosen and secondly, the sealing ring long life resiliency characteristics were unknown.

The connector selected for the SNAP-23A Experimental Mockup Converter power output header is an Eimac Corporation hermetic connector. The header has hollow pins through which the power leads pass. The pins are flared to form a well for solder which hermetically seals the power leads; the soldering being done on the external side of the converter.

3.2.2 PROCESS AND TEST STATION

The objective in designing the process and test station was to design a unit which will meet the test requirements of the SNAP-23A converters. Following an iteration of these test requirements, the test and process station design will be discussed.

3.2.2.1 Process and Test Station Requirements

The process and test station is designed to incorporate the following required features:

- A controller will be incorporated to insure constant temperature conditions; this controller will be portable to facilitate its use on other test stations.
- Rotary switches with digital readout will allow temperatures to be read manually. Both I/C and C/A type thermocouple instrumentation outputs will be read. These rotary switches will also allow both open and closed circuit voltage measurements.
- The external load will be electronic with high resolution.
- The load current shall be measured with a calibrated shunt having an accuracy of ± 0.25 percent.
- All gas pressure readouts will be in voltage via a pressure transducer.
- Input power will be available for strip chart display filtered to 0.1 percent ripple.
- A resetable hour meter will be incorporated to record time.
- A water flow meter with line pressure regulation and in/out temperature measurement will be used to control cold side temperature.
- All connections to air and water services will be disconnectable.
- The test station will be portable for use within the laboratory and at the dynamic testing facility.
- The test converter will be mounted to the test station in such a way that it can be conveniently removed from the panel and mounted for dynamic testing.
- The leads will be of sufficient length to permit mounting the converter on the dynamic testing station without disconnection.

- The thermoelectric converter leads will allow quick disconnect from the test station.
- Components will be arranged and spaced to permit easy performance of processing operations.
- Short term test temperature and power input will be monitored on strict chart recorders.
- Long term test temperature and power input will be monitored on data acquisition system.
- The heat source will provide simulation of the isotopic heat source thermal profile, minimum heat loss to the atmosphere to facilitate converter efficiency measurement, and a base which will act as a shock and vibration adapter.

3.2.2.2 Process and Test Station Design

The Process and Test Station design is discussed through four main areas.

1. Heat Source Simulator Design

The heat source simulator is designed to provide a minimum of 1000 watts to the converter with a temperature gradient along the converter hot frame of approximately 30°F. The heat source simulator will consist primarily of a hot block containing six main heaters and two auxiliary heaters, the lower end attachment and the upper end attachment.

The hot block mates with the converter hot frame taking into consideration the possibility of thermal stress and allowing a thermal gradient to be established. The six main heaters are uniformly spaced and inclined to the vertical axis. One auxiliary heater will be placed on the top of the block and another on the bottom of the block to regulate variations in heat load thermal conductivity and heat losses from the hot block. The lower end attachment will be bolted to the hot block to

provide a mounting surface for the shock and vibration fixture and to hold in place the electrical insulation and busbars which are required for connection of the electrical firerods.

The upper end attachment will be designed to provide a method of clamping the simulator to the hot frame without exceeding the maximum specified contact pressure on the hot frame.

2. Water Jacket Design

The objective in designing a water cooled jacket is to provide a heat sink which will achieve a minimum of 1000 watts capacity at a temperature of approximately 180°F. The water jacket will be comprised of inner and outer cylindrical shells. The inner shell will mate with the external surface of the converter and will contain slots machined for the flow path. The outer shell will be welded to the inner shell along with two brackets and two tubes to form an enclosed sealed unit. The inner and outer shells of the water jacket are shown in Figure 3-2. The water jacket is designed to be easily attached and easily removed from the converter outer case.

3. Cabinet and Electrical Hardware

The process and test station cabinet and modular panel are designed to house all electrical hardware. The test station console (shown in Figure 3-3) consists of six modular panels mounted into a commercial cabinet. They will provide the main power supply, the auxiliary power supply, two readout panels, load control and water jacket control. The temperature controller will be added as a separate unit for temporary use.

4. Test Fixture Design

The test fixture is designed for mounting the SNAP-23A converter with simulator and water jacket to the test console. The fixture will effectively insulate the simulator for efficiency measurements. The test

Figure 3-2. P&TS Water Jacket Inner and Outer Shell

Figure 3-3. Process and Test Station Console

fixture will consist of a large tube with flange and mounting brackets. The converter with simulator and water jacket will be mounted on the brackets; the bottom of the tube will then be packed with thermal insulation and the flange attached.

3.3 SNAP-23A EXPERIMENTAL MOCKUP CONVERTER DETAILED ENGINEERING DESCRIPTIONS AND DESIGN ANALYSES

3.3.1 DETAILED ENGINEERING DESCRIPTIONS

3.3.1.1 Follower Spring and Follower

Follower Spring

During the design stage of the SNAP-23A Experimental Mockup Converter (hereinafter referred to as the SNAP-23A EMC) it was decided to maintain the SNAP-23 converter radial distance from the inside diameter of the outer case to the outside diameter of the hot frame and hold all part dimensions between these two points. The only changes anticipated were minor changes in the P and N leg length (Figure 3-1 (15) (16)) which were to be offset by a corresponding change in the cold cap (18, 19) length. However, the post-test analysis of the SNAP-23 converter revealed a boron nitride strip (5) cracking problem. A stress analysis of the boron nitride strips (paragraph 3.3.2. 5) resulted in a new boron nitride strip design having a significantly thicker section in the radial direction. To allow for this increased dimension the follower springs were redesigned and shortened. Although the new springs have less working space, an improvement in spring rate and working length ratio was realized by changing the spring material and using the maximum allowable stress recommended by Associated Spring Corporation for a static spring application.

To insure adequate working space in the hot condition, the analysis includes calculation of the hot condition dimensions of all parts that affect the working space. The parts are identified in Figure 3-4 and the hot and cold condition dimensions given in Table 3-4.

Figure 3-4. Thermoelectric Couple - Follower Layout

Dimension i , the spring working space, will be determined for both the hot and cold condition.

From Figure 3-4, it is noted that

$$i = l - a - b + c - d - e + f - g - h - j - k$$

Separating the positive and negative terms,

$$i_{\max} = (l + c + f)_{\max} - (a + b + d + e + g + h + j + k)_{\min}$$

Substituting the maximum and minimum values from Table 3-4,

$$i_{\max} = 0.683$$

Solving for minimum working space,

$$i_{\min} = (l + c + f)_{\min} - (a + b + d + e + g + h + j + k)_{\max}$$

The part names and corresponding dimensions for the cold and hot conditions are tabulated in Table 3-4.

Table 3-4. Thermoelectric Couple – Follower Layout Dimensions

Dimension	Part Name	Length Cold (L_c)	Thermal Coefficient of Expansion	Length Hot (L_h)
a	Hot frame outside radius	1.895 to 1.894	1.04×10^{-5}	1.916 to 1.915
b	Boron nitride overall thickness	0.327 to 0.323	1.14×10^{-6}	0.327 to 0.323
c	Boron nitride recess depth	0.038 to 0.032	1.14×10^{-6}	0.0380 to 0.0320
d	Hot junction electrode	0.052 to 0.042	1.04×10^{-5}	0.052 to 0.042
e	Hot junction button	0.031 to 0.029	1.04×10^{-5}	0.031 to 0.029
f	Hot junction button recess depth	0.016 to 0.014	1.04×10^{-5}	0.016 to 0.014
g	Couple	0.690 to 0.666	1.04×10^{-5}	0.694 to 0.670
h	Follower	0.940 to 0.937	1.29×10^{-5}	0.941 to 0.938
i	Follower Spring	To be determined	--	--
j	Insulation Washer	0.019 to 0.009	disregard	0.019 to 0.009
k	Support Washer	0.030 to 0.028	1.04×10^{-5}	0.030 to 0.028
l	Radial distance from center of the converter spring retaining pin in cold frame	4.557 to 4.547	1.29×10^{-5}	4.562 to 4.552

Substituting the appropriate values from Table 3-4,

$$l_{\min} = 0.609$$

$$l_{\text{avg}} = \frac{l_{\max} + l_{\min}}{2}$$

$$l_{\text{avg}} = 0.646$$

To determine the length of the working space in the hot condition, it is necessary to calculate the thermal expansion of each dimension and repeat the calculations for $l_{\max}$, $l_{\min}$, and l_{avg} using the hot dimension for each part. A typical calculation is shown below.

For the a dimension,

$$\Delta a = (\Delta T) a \alpha$$

where

Δa = thermal expansion of dimension a in inches

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

α = thermal coefficient of expansion for the stainless steel hot frame in inches per inch - °F

Substituting appropriate values from Table 3-4 and using temperatures of 1140 and 75°F for the hot and cold condition respectively,

$$\Delta a = 0.02099$$

Letting a_h be the hot length designation for a,

$$a_h = a + \Delta a = 1.91599$$

The hot lengths for the various parts are tabulated in Table 3-4.

Substituting Table 3-4 values in $l_{\max}$, $l_{\min}$, and l_{avg} equations, the hot working space is as follows:

$$l_{\max \text{ hot}} = 0.6612$$

$$l_{\min \text{ hot}} = 0.5872$$

$$l_{\text{avg hot}} = 0.6242$$

It can be noted that the average hot working space of 0.6242 inches is less than the average cold working space of 0.6460 inches. Likewise, the hot maximum and minimum working space dimensions are correspondingly smaller. For design purposes the spring solid height will be made slightly less than the hot minimum working space of 0.5872 inches. The working length of the spring will be equal to the average hot working space of 0.6242 inches. Since allowable working stress varies with the wire diameter, the Gibson Division of Associated Spring Corporation was consulted for this value for 316 stainless steel at 300°F. 316 stainless steel has a higher working stress than the 18-8 series steel used in the SNAP-23 converters. As with most spring designs involving limited working space and minimum desired spring rate, several trial and error type calculations are necessary. The final iteration from which drawing spring dimensions were established is shown as follows:

Maximum Allowable Stress	167,000 psi
Total Coils	17
Active Coils	15
Mean Diameter	0.180 inch
Wire Diameter	0.031 inch
Load at 0.624 inch	7.1 pounds

$$K = \frac{d^4 G}{8 N D^3}$$

where

K = spring rate in lbs per inch

d = wire diameter in inches

N = number of active coils

D = mean diameter in inches

G = torsional modulus of rigidity which for steel wire averages 11, 500, 000

Substituting and calculating we find:

$$K = 15.18 \text{ lbs/in}$$

To develop the desired couple contact pressure, it is necessary for the spring to exert 7.1 pounds at its working length of 0.624 inch. With a spring rate of 15.18 pounds per inch, the deflection from free length to loaded length for a 7.1 pound load, P is

$$\text{Deflection} = \frac{P}{K} = \frac{7.1}{15.18} = 0.468 \text{ inch}$$

Then,

$$\text{Free length} = \text{deflection} + \text{loaded length} = 0.468 + 0.624 = 1.092 \text{ in.}$$

$$\begin{aligned} \text{Solid height} &= \text{total coils} \times \text{wire diameter} = 17 \times 0.031 = 0.527 \\ &= 17 \times 0.031 = 0.527 \text{ inch} \end{aligned}$$

$$\begin{aligned} \text{Maximum deflection} &= \text{free length} - \text{solid height} \\ \text{or free length to solid} &= 1.092 - 0.527 = 0.565 \text{ inch} \end{aligned}$$

$$\begin{aligned} \text{Spring load, } P_{\text{max}}, \text{ at solid height} &= \text{Maximum deflection} \times K \\ &= 0.565 \times 15.18 = 8.572 \text{ lbs} \end{aligned}$$

$$S = \frac{2.55 P_{\max} D W}{d^3}$$

where

W = a stress magnification factor related to the ratio of Mean Diameter to Wire Diameter. For a $\frac{D}{d}$ of 5.8, W = 1.27

S = stress at solid height in psi

Substituting,

$$S = \frac{2.55 (8.572) (0.180) (1.27)}{(0.031)^3}$$

$$S = 167,000 \text{ psi}$$

Since this stress, which is equal to the maximum allowable stress, occurs at the solid height, the spring will not take a set if accidentally compressed to the solid height. The stress at the working load of 7.1 pounds is 138,000 psi.

Follower

Four design reviews were held on the follower during this quarter. These reviews were necessary to establish a method of manufacture and an end product acceptable to both vendor manufacture and design criteria. This part requires two grinding operations, a minimum plating depth, and a surface finish on a spherical surface which requires arbitration. This part has been released for production.

3.3.1.2 Instrumentation Components

Instrumentation Matrix

In order to pinpoint location, material type and size, function, replaceability, and type of attachment, a preliminary instrumentation matrix was established. In addition, a preliminary instrumentation drawing was completed giving location

and description of the instrumentation. This matrix was jointly reviewed with Westinghouse; additions were suggested and evaluated by 3M and the system contractor. The instrumentation drawing is now in its final form and is illustrated in Figure 3-5.

Headers

The Experimental Mockup Converter instrumentation headers will be of the same type (Eimac Corporation hermetic connectors) and were selected for the same reasons as the power output header described in paragraph 3.2.1.7 of this report. They will, however, differ in several areas other than size from the power output header. First, the feedthrough pins will be swedged on the end to provide a good fit for welding because three different wire diameters will be going through the pins. Secondly, the pins will be insulated so that the wire will touch the feedthrough in only one place to prevent measurement error due to thermal losses. Figure 3-6 shows a typical instrumentation header.

Gas Sampling Assembly

Liaison work was conducted with the gas sampling valve and pressure transducer vendors this quarter. It was decided that in order to hold fin size reduction to a minimum the gas sampling valve would be altered. The alteration consisted of choosing a valve without its standard input and output tubes which allows greater flexibility in valve location. Tube dimensions, integrity, and physical shape will be controlled by 3M. To accommodate a pressure transducer with minimum obstruction, the pressure transducer standard adapter was removed. This configuration was forwarded to the test department and has been approved.

3.3.1.3 Fasteners

To assure absolute containment during shock and vibration all screws are of the wire cap screw type. All bolts will be wired unless lock nuts are provided.

INSTRUMENTATION LEGEND									
7/C	LOCATION	NO.	HEADER	RECD	WIRE	EXTERNAL WIRE	ATTACH		
NO	NO	NO	NO	NO	NO	NO	MENT		
1	H.F. RI	-	6	A	CHL	PD 39 5070	CDSW		
2	H.F. R2I	-	6	B	AL	CHL			
3	H.F. RI	-	6	C	CHL				
4	H.F. R2I	-	6	D	CHL	PD 39 5070	CDSW		
5	H.F. RI	-	8	A	CONST	PD 39 5067	STAKE		
6	H.F. R2I	-	4	N	CONST	PD 39 5067	STAKE		
7	H.F. R3	-	16	B	CONST	*PD 39 5071	TIG WELD		
8	H.F. R2I	-	16	C	CONST	*PD 39 5071	TIG WELD		
9	H.F. R14	-	9	N	CHL	PD 39 5070	CDSW		
10	H.F. R34	-	9	P	CHL	PD 39 5070			
11	H.C. RI	A1	2	2	N	*PD 39 5071			
12	H.C. R2I	A1	9	4	P				
13	H.C. RI	A2	2	2	P				
14	H.C. R2I	A2	9	4	P				
15	H.C. R3	A7	3	2	P				
16	H.C. R2B	A7	12	7	N				
17	H.C. R3	A8	3	3	A				
18	H.C. R2B	A8	12	7	B				
19	H.C. R14	A13	7	4	R				
20	H.C. R34	A13	13	8	D				
21	H.C. R14	A14	7	4	E				
22	H.C. R34	A14	13	8	S				
23	G.C. RI	A1	17	2	D				
24	G.C. R2I	A1	10	4	E				
25	G.C. RI	A2	17	2	S				
26	G.C. R2I	A2	10	4	S				
27	G.C. R3	A7	4	3	B				
28	G.C. R2B	A7	11	7	G				
29	G.C. R3	A8	4	3	C				
30	G.C. R2B	A8	11	7	D				
31	G.C. R14	A13	5	3	R				
32	G.C. R34	A13	15	8	F				
33	G.C. R14	A14	5	3	E				
34	G.C. R34	A14	15	8	G				
35	C.F. R14	A14	6	3	L				
36	C.F. R34	A1	14	8	H				
37	C.F. R14	A14	6	3	S				
38	C.F. R34	A1	14	8	V	PD 39 5071	MECH		
39	S.C. RI		2	2	T	PD 39 5072	CDSW		
40	S.C. R2I		7	2	S				
41	S.C. RI		2	2	F				
42	S.C. R2I		7	2	F				
43	S.C. RI		2	2	H				
44	S.C. R2I		7	2	V				
45	G.C. RI		2	2	V				
46	G.C. R2I		7	2	V				
47	G.C. R3	A1 A2	3	3	V				
48	G.C. R2B	A1 A2	7	7	V				
49	G.C. R3	A7 A8	3	3	V				
50	G.C. R2B	A7 A8	7	7	V				
51	G.C. R3	A14	3	3	X				
52	G.C. R2B	A14	7	7	CONST	PD 39 5072			
53	L.C. RI		9	9	CHL	PD 39 5070			
54	L.C. R2I		9	9	R				
55	L.C. RI		9	9	F				
56	L.C. R2I		9	9	F				
57	L.C. RI		9	9	D				
58	L.C. R2I		9	9	N				
59	L.C. RI		9	9	V				
60	L.C. R2I		9	9	S				
61	L.C. RI		9	9	D				
62	L.C. R2I		9	9	M	PD 39 5070	CDSW		
63	G.C. RI	A1	1	1	A	CU	PD 39 5022	BRAZE	+VOLTAGE TAP (24V)
64	G.C. R2I	A1	1	1	B	CU	PD 39 5022	BRAZE	-VOLTAGE TAP (24V)
65	G.C. R3	A1	8	4	V	IRON	*PD 39 5071	BRAZE	-VOLTAGE PROBE (24V)
66	G.C. R2I	A1	1	1	C	CU	PD 39 5022	BRAZE	CENTER TAP

TABLE NO 1		
RECEPTACLE NO	MS NUMBER	DWG NUMBER
1	MS3102A 20 4S	PD 39 5043 3
2 3 4 7 #8	MS3102A 24 415 SW	5043 1
5	MS3102A 16S P	5043 4
6 #9	MS 3 02A 24 414 SK	5043 2

TABLE NO 2	
HA	LWG NUMBER
1	PD 39 5031
2 3 4 5 7 8 9	C PD 39 5036
4	C PD 39 5045

LEGEND CODE	
RI	ROW 1 ETC
AI	AXIAL ROW 1 ETC
H.F.	HOT FRAME
H.C.	HOT CAP
C.C.	COLD CAP
C.F.	COLD FRAME
S.C.	SUPPORT CONE
O.C.	OUTER CASE
L.C.	LOWER COVER
CDSW	SPOTWELD
MECH	MECHANICAL
AL	ALUMEL
CHR	CHROMEL
CONST	CONSTANTAN
CU	COPPER

4. PIN A IS USED FOR GROUND N RECEPTABLES
 *1 AND 5 REFER TO DWG PD 39 5043 SHIT 1
 3. PIN 2 IS USED FOR GROUND N RECEPTABLES
 *2 3 4 6 7 AND 8 REFER TO DWG PD 39 5043 SHIT 2
 2. FOR INTERNAL WIRING OF 7/C NOS (1) THRU (34)
 AND (63) THRU (66) REFER TO DWG PD-39-1364 (SCHEMATIC)
 *1 WIRE FROM HEADER TRANSITION TERM VAL TO
 RECEPTACLE ONLY
 NOTES

Figure 3-5. Instrumentation Matrix

BLANK

Figure 3-6. Instrumentation Header

3.3.1.4 Converter-System Design Detail

Several design interface problems were mutually resolved during 3M/WANL interface meetings. The bottom of the outer case was extended downward approximately 1/4-inch to provide a one-inch space between the lower rain shield and the bottom of the fins as shown in Figure 3-7.

Figure 3-7. Converter-System Interface Detail

This one-inch space is required for the free convection air flow as well as wrench clearance for the fin clamping bolt.

The lower rain shield consists of a flat sheet of rubber, clamped to the lower flange on the outer case, to provide a flexible connection between the converter and system container. A rigid rain shield would subject the converter to side loads during lateral vibration of the system when the heavy fuel capsule deflects relative to the container. In order to prevent possible mating problems 3M offered to fabricate the clamping ring for the rubber rain shield. One method of sealing each clamping screw is by means of an O-ring type cap screw as shown in Figure 3-7.

Figure 3-8 shows the fuel capsule spud bolted to the converter hot frame. The large threaded hole in the jacking base portion of the hot frame is for converter removal.

The thickness of the jacking base will be 0.75 inch and jacking threads 2-12 will be provided so that a 10,000 lb. jacking force can be exerted in the hot condition. A 50 in-lb torque limit on the jacking threads was established.

Figure 3-8. Fuel Capsule Spud with Hot Frame

It is anticipated that a maximum spud temperature of 500°F to 600°F at time of assembly will be specified for assembly purposes to avoid thermal shock to the thermoelectric material. Westinghouse stated that cooling the spud just prior to assembly should not be a problem.

3.3.2 DETAILED DESIGN ANALYSES

3.3.2.1 Converter Parametric Study

A converter parametric study, which would serve as a basis for designing both the heat input and heat rejection system, was conducted for Westinghouse. The relationship of fin base temperature and geometry to total heat input rate for 60 watts power at the EOL point were the primary parameters. Couple geometry and hot junction temperature at BOL were also determined in the study.

Converter Parametric Study Basis and Assumptions

1. An optimum converter design would be established for five EOL fin base temperatures varying from 130 to 200 degrees F for a power output of 60 watts at 24 volts.
2. Primary computer program which establishes couple geometry (used for EOL design)
3. Secondary computer program which evaluates converter performance of a given design for conformance to the given specifications (used for BOL evaluation)
4. Simultaneously pressed P and N leg materials are

N leg hot segment	PbTe
N leg cold segment	PbTe
P leg hot segment	PbTe - SnTe
P leg cold segment	(BiSb) ₂ Te ₃
5. Temperature difference between leg cold junction and fin base to be 30 degrees F.
6. Temperature difference between leg cold junction at BOL and leg cold junction at EOL to be 30 degrees F.
7. Average hot junction temperature at BOL not to exceed 1075 degrees F.

8. Total heat input rate to converter at EOL is 78.2 percent of total heat input rate at BOL.
9. P-and N-leg diameter - - - - 0.187 inch
10. No heat is lost in axial (vertical) direction from upper and lower covers.
11. Heat losses (Q_L) at BOL and EOL are determined on basis of SNAP-23 design as given in Figure 4-1 of the SNAP-23 Program Parametric Study MMM 3418-33. A mathematical equation fit to the Figure 4-1 curve is

$$Q_L = 0.1097 (T_H - T_C - 600) + 46.11$$

where

Q_L = converter heat loss rate in watts

T_H = couple hot junction temperature in degrees F

T_C = couple cold junction temperature in degrees F

Converter Performance and Geometry Calculations

The procedure for calculating couple geometry and converter performance is the given in the appendix of the first quarterly report. A portion of the EOL data, which is convenient in selecting a design, is shown in curve form. Cold frame outside diameter and hot frame inside diameter at the start of taper (small end) are based on seven layers of couples, the horizontal chordal spacing between couples at the cold frame inside diameter being held to the same dimension as used in the two SNAP-23 converters. In addition, the radial distances from the hot frame outside diameter to the cold frame inside and outside diameters were kept the same as in the two SNAP-23 converters. The terminology used in the tabulations and curves is defined as follows:

L_P	= length of P leg in inches
L_{CP}	= length of P leg cold segment in inches
L_N	= length of N leg in inches
L_{CN}	= length of N leg cold segment in inches
E	= open circuit voltage in volts
V	= load voltage in volts
Q_L	= shunt heat loss rate in watts
Q_T	= total heat input rate in watts
N	= overall efficiency in percent
P	= power output in watts
I	= current in amperes
N	= number of couples

Table 3-5 lists the component geometries for five different EOL cold junction temperatures. Each temperature represents an optimized design.

Table 3-5. Component Geometries for Various EOL Cold Junction Temperatures

L_P	L_{CP}	L_N	L_{CN}	N	T_C EOL	Cold Frame O.D.	Hot Frame I.D. at Start of Taper (Small End)
0.336	0.118	0.481	0.144	263	160	8.716	2.767
0.331	0.116	0.469	0.141	266	170	8.716	2.767
0.319	0.112	0.446	0.134	272	190	8.843	2.894
0.309	0.108	0.442	0.111	276	210	8.976	3.027
0.297	0.104	0.420	0.105	283	230	9.116	3.167

Table 3-6 lists the converter performance characteristics at BOL.

Table 3-6. SNAP-23A Experimental Mockup Converter Performance Characteristics at BOL

Converter Performance Characteristics at BOL									
N	E	V	I	P	T_H	T_C	Q_L	Q_T	η
263	53.31	24	3.226	77.42	1075	190	78	969.2	7.99
266	53.51	24	3.23	77.64	1075	200	77	984.8	7.88
272	53.82	24	3.26	78.26	1075	220	74	1018.9	7.68
276	53.02	24	3.23	77.41	1075	240	72	1032.5	7.50
283	52.26	24	3.18	76.35	1075	260	70	1043.1	7.32

Table 3-7 lists the converter performance characteristics at EOL.

Table 3-7. SNAP-23A Experimental Mockup Converter Performance Characteristics at EOL

Converter Performance Characteristics at EOL									
N	E	V	I	P	T _H	T _C	Q _L	Q _T	η
263	41.48	24	2.5	60	890	160	61	759.6	7.89
266	41.58	24	2.5	60	890	170	59	768.8	7.80
272	41.67	24	2.5	60	890	190	57	790.6	7.58
276	41.84	24	2.5	60	900	210	56	806.4	7.44
283	41.74	24	2.5	60	900	230	55	833.4	7.19

In selecting a design it is convenient to have three of the EOL parameters presented in curve form. Overall efficiency, total heat input rate, and number of couples are plotted against couple cold junction temperature and are shown in Figures 3-9, 3-10, and 3-11 respectively.

3.3.2.2 264-Couple Design

The initial SNAP-23A Experimental Mockup Converter (EMC) 280-couple design was based on the temperature and heat input data specified in "Performance Requirements for SNAP-23A 60-Watt Thermoelectric Converter", dated 30 November 1966 (which is incorporated in contract AT(30-1)-3824, dated 1 February 1967) and in "WANL-3M Interface Document, SNAP-23A-Phase I", WANL-SS-001, February 1967.

However, a subsequent heat source and radiator design and system thermal analyses by the system contractor in conjunction with the 3M converter parametric data (included in SNAP-23A Program Quarterly Report No. 1-MMM3824-0006) showed that the heat rejection system could operate at a lower temperature. From the initial 280-couple design the couple cold junction temperature was reduced from 180°F to 174°F at EOL and from 210°F to 191°F at BOL.

Figure 3-9. Overall Efficiency vs Cold Junction Temperature for EOL Conditions

Figure 3-10. Total Head Input Rate vs Cold Junction Temperature for EOL Conditions

Figure 3-11. Number of Couples vs Cold Junction Temperature for EOL Conditions

In addition, during the system contractor heat source design analyses the heat input spud diameter was increased which improved the temperature gradient along the heat spud; thereby, increasing the average couple hot junction temperature (the arithmetical average of the couple temperatures at the top and bottom of the converter) from a maximum of 1075°F to 1085°F.

In view of the new temperature and heat input rate conditions established by the system contractor, the 280-couple design was adjusted to obtain a closer system thermal match and reduce fuel requirements. A summary of the operating parameters for the 280-couple (initial) design and the 262-couple (adjusted) design is presented in Tables 3-8 and 3-9. The procedure used to determine the 264-couple (adjusted) design is described in the following paragraphs.

From the converter parametric study, the corresponding heat input to the Experimental Mockup Converter for 174°F (EOL cold junction temperature) is 773 watts. The corresponding heat input to the Experimental Mockup Converter at BOL, as specified for the system is 1002 watts. In order to successfully integrate the converter into the system, it was requested that 3M reduce the number of couples without dimensionally changing other converter parts if the 60-watt power requirement at EOL could be met with the 773-watt heat input to the converter.

Two computer programs were used to arrive at the number of couples (as described in Quarterly Report No. 1, Appendix E). The converter design computer program was used to calculate the number of couples and couple hot junction temperature at EOL for a maximum efficiency operating condition. The design was then evaluated at BOL by means of the converter parametric computer program, with critical parameters consisting of heat input to converter, couple hot junction temperature, and P-leg cold segment temperature. P-leg cold segment temperature is limited to a maximum value of 600°F. To avoid exceeding this 600°F temperature as well as the maximum average hot junction temperature of 1085°F, the converter must be able to absorb the heat input of 1002 watts which consists of heat input to couples plus converter heat losses. The converter was evaluated at a load voltage of 24 volts, the point at which the converter has its maximum heat absorption capacity under specified operating conditions.

Table 3-8. SNAP-23A Experimental Mockup Converter
EOL Operating Parameters

EOL Conditions	Initial Couple Design		Adjusted Couple Design	
	280-Couples	System Parameters**	264-Couples	System Parameters*
Converter heat losses	58.2 watts	--	59.9 watts	--
Temperature cold junction	180°F	180°F	174°F	174°F
Temperature hot junction	890°F	--	900°F	--
Total heat input to converter	796 watts	781 watts	771.5 watts	773 watts
Overall efficiency	7.7 percent	7.7 percent	7.8 percent	--
Load voltage	24.7	24 ± 1	23.9	24 ± 1
Open circuit voltage	42.8	--	41.3	--
Power output	61.4 watts	60 watts min	60.2 watts	60 watts min.

*Supplied by Westinghouse

**Listed in "Performance Requirements for SNAP-23A 60-Watt Thermoelectric Converter", dated November 30, 1966, incorporated in Contract AT(30-1)-3824, dated February 1, 1967.

Table 3-9. SNAP-23A Experimental Mockup Converter
BOL Operating Parameters

EOL Conditions	Initial Couple Design		Adjusted Couple Design	
	280-Couples	System Parameters**	264-Couples	System Parameters*
Converter heat losses	75.2 watts	--	78.4 watts	--
Temperature cold junction	210°F	--	191°F	191°F
Temperature hot junction	1075°F	1075°F	1085°F	1085°F
Total heat input to converter	1030 watts	989 watts	1006 watts	1002 watts
Efficiency	7.7 percent	--	8.0 percent	--
Load voltage	24	24 ± 1	24	Regulated to 24
Open circuit voltage	55.2	--	53.5	--
Power output	79.3 watts	60 watts min	80.5 watts	60 watts min
P-leg cold segment temperature	573°F	--	586°F	--

*Supplied by Westinghouse

**Listed in "Performance Requirements for SNAP-23A 60-Watt Thermoelectric Converter", dated November 30, 1966, incorporated in Contract AT(30-1)-3824, dated February 1, 1967.

The computer analysis showed that 16 couples should be removed from the 280-couple configuration to obtain a system heat balance at the specified temperatures.

As shown in Table 3-8 using the 264-couple design, the P-leg cold segment temperature of 568°F is below the maximum allowable temperature of 600°F. This tabulation also shows that the 264-couple design has the capacity to absorb 1006 watts total heat input rate, which is slightly greater than the system heat output rate of 1002 watts.

These analyses show that the 264-couple converter design should meet system specifications since the P-leg cold segment temperature and couple hot junction temperature are not expected to exceed the maximum allowable limits of 600°F and 1085°F, respectively.

Leg geometry, the same for both the 264- and 280-couple design, is shown in Table 3-3.

3.3.2.3 Upper and Lower Surface Temperature Analysis

The SNAP-23A Experimental Mockup Converter is designed on the basis that all shunt heat losses are confined to a radial or horizontal direction with respect to the vertical axis of the converter. With the converter mounted on the heat spud, converter performance characteristics are based on an adiabatic (perfectly insulated) boundary for all exposed support cone, lower cover, hot frame, assembly bolt, and assembly washer surfaces. Surface temperatures at intermediate points along the exposed surfaces can be calculated after the heat flow rates along the paths are determined. The intermediate temperatures must be known for estimating yield stresses and are also of value when estimating external converter heat flow in the vertical direction. Therefore, this analyses is concerned with the intermediate temperature calculations. Figure 3-12 shows the system interface temperature and the calculated intermediate temperatures. Also shown is the direction of heat flow in the upper and lower converter surfaces, the upper surface consisting of the upper hot frame cylinder and support cone.

Upper Surface

As noted in Figure 3-12, the hot frame temperature at the thick threaded section is 1110°F at BOL. Starting at this point, the heat travels upward through the thin

Figure 3-12. Experimental Mockup Converter Anticipated Surface Temperatures

walled cylindrical portion of the hot frame (referred to as upper hot frame cylinder in Figure 3-13) after which the heat moves radially outward through the thin walled support cone. The final temperature at the outer ring of the support cone is 161°F at BOL.* The thermal resistance of each portion of this series circuit must be calculated before heat flow rate and the intermediate temperature at the hot frame/support cone junction can be determined. The thermal resistance of the upper hot frame cylinder is calculated with reference to Figure 3-13, which shows the dimensions.

Figure 3-13. Sketch Showing the Upper Hot Frame Cylinder Dimensions

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

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

where t = wall thickness in feet

D_M = mean cylinder diameter in feet

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

ℓ = cylinder length in feet

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

$$R_f = 12.16 \text{ hr-}^\circ\text{F/Btu}$$

A textbook formula is not available for calculating the thermal resistance of the support cone and is therefore derived as follows. The formula is derived with reference to Figure 3-14.

Figure 3-14. Support Cone Thermal Resistance Calculation Parameters

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

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

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

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

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

Substituting and separating variables,

$$\int_{\ell_o}^0 \frac{d\ell}{\frac{r_2 - r_1}{\ell_o} \ell + r_1} = \int_{T_2}^{T_1} \frac{-t \, 2\pi k \, dT}{q}$$

Integrating,

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

Solving for q ,

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

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

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

Equating and letting support cone resistance be designated as R_s ,

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

From which:

$$R_s = \frac{l_o}{r_2 - r_1} \cdot \frac{1}{t 2\pi k} l_n \frac{r_2}{r_1}$$

The numerical values for the above resistance equation terms are shown in Figure 3-15.

Figure 3-15. Sketch Showing Support Cone Thermal Resistance Numerical Values

Letting k equal 11.2 and substituting the numerical values from Figure 3-15,

$$R_s = 5.86 \frac{\text{hr-}^\circ\text{F}}{\text{Btu}}$$

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

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

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

$$q = 52.7 \frac{\text{Btu}}{\text{hr}} \text{ or } 15.4 \text{ watts}$$

The intermediate temperature, T_2 , is found from the relation

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

or

$$T_2 = 470^\circ\text{F at BOL}$$

When EOL temperature (925° and 144°F) are substituted for T_1 and T_3 in the above equations, the heat flow rate is 43.3 Btu per hour (12.7 watts) and T_2 is equal to 398°F.

Lower Surface

The lower cover forms the lower converter surface as noted in Figure 3-16. Heat travels radially outward, with the exception of the short cylindrical section in the lower cover, from the lower hot frame - lower cover junction to the lower cover - outer case junction. Two intermediate temperatures will be calculated. The first intermediate temperature, designated as T_2 , is at the top of the short cylindrical section in the lower cover. The second intermediate temperature, designated as T_3 , is at the bottom of the short cylindrical section. For the analysis the lower cover is divided into an inner disc, an outer disc and a short cylinder. Figure 3-16 shows the dimensions of each section.

Figure 3-16. Lower Rain Cover Ring (Cross Section Sketch)

Letting R_i be the thermal resistance of the inner disc,

$$R_i = \frac{1}{t \, 2\pi k} \, \ell_n \frac{r_2}{r_1}$$

where t = disc thickness in feet

k = thermal conductivity for stainless steel and is equal to
11.2 Btu-ft/ft²-hr-°F

r_1 = inner radius of disc in feet

r_2 = outer radius of disc in feet

Letting R_c be the resistance of the short cylinder,

$$R_c = \frac{\ell}{t_c \pi D_M k}$$

where t_c = wall thickness in feet

l = cylinder length in feet

D_M = mean cylinder diameter in feet

k = thermal conductivity

Substituting and noting that $D_M = \frac{2(r_2 + r_3)}{2} = r_2 + r_3$,

$$R_c = 1.07 \frac{\text{hr-}^\circ\text{F}}{\text{Btu}}$$

Letting R_o be the thermal resistance of the outer disc,

$$R_o = \frac{1}{t \cdot 2\pi k} \cdot l \cdot \frac{r_4}{r_3}$$

Substituting the numerical values from Figure 3-16,

$$R_o = 5.5 \frac{\text{hr-}^\circ\text{F}}{\text{Btu}}$$

Since the lower cover sections form a series circuit, the heat flow rate in the cover is given by the relation

$$q = \frac{T_1 - T_4}{R_i + R_c + R_o}$$

where T_1^* is the temperature at junction of lower cover and hot frame and is equal to 1140°F at BOL. T_4 is the temperature at junction of lower cover and outer case and is equal to 161°F at BOL.

*This temperature is assumed to be the same as hot frame temperature at point of physical contact with spud because of the unknown radiation heat exchange across the narrow air gap.

The intermediate temperature, T_2 , is found from the relation

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

$$T_2 = 906^\circ\text{F at BOL}$$

The intermediate temperature, T_3 , is found from the relation

$$q = \frac{T_2 - T_3}{R_c}$$

$$T_3 = 785^\circ\text{F at BOL}$$

When EOL temperature (955° and 144°F) are substituted for T_1 and T_4 in the above equations, the heat flow rate is 94 Btu per hour (27.5 watts) and the intermediate temperatures, T_2 and T_3 , are 761° and 661°F respectively.

3.3.2.4 Couple Alignment Analysis (Figures 3-17 and 3-18)

Couple alignment was a major design consideration because proper operation of the thermoelectric legs and couples depends on the leg being positioned such that good contact is maintained at all times between the leg hot end and hot junction button (Figure 3-1, (14) or (15) and (16)). The couple hot junction is a flat, butt type joint and any loss of edge contact due to cocking would decrease the thermal heat transfer area and increase electrical contact resistance.

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

Thermal expansion of the boron nitride strips in the vertical (axial direction) is negligible compared to the hot frame expansion. Since the hot junction end of the legs must follow the boron nitride strips during thermal expansion, it is desirable

Figure 3-17. Sketch Showing Thermoelectric Couple Alignment Parameters

Figure 3-18. Support Cone Sketch Showing Dimension Parameters

that the strips be anchored to the hot frame at a point that has no relative motion with respect to the cold frame which guides the cold junction end of the legs. The cold frame expands a small amount in the vertical direction with respect to the boron nitride strips. To distribute the misalignment evenly between the upper and lower couples, the vertical midpoint of the cold frame (Figure 3-17) is the point selected as having zero relative motion with respect to the boron nitride anchoring point on the hot frame.

The boron nitride anchor point was found by iterative type calculations. The final calculations which located the anchor point shown in Figure 3-17 are presented in this analysis.

The welded joint between the support cone and hot frame is selected as the fixed reference point. All parts move downward with respect to this fixed reference point. The distance of the cold frame midpoint from the fixed reference point is the summation of dimensions a, b, and c. It is desirable that the combined thermal expansion of dimensions a, b, and c equals the thermal expansion of dimension f. The expansion of the support cone in the downward direction (change in dimension a) is complicated by the two thickened rings which act as stiffeners for the thin (0.025 inches thick) section of the cone. The outer ring, being cooler, does not expand at the same rate as the inner ring and the thin portion and, therefore, the cone angle changes during thermal expansion. This change in cone angle causes a considerable increase in dimension (a) compared to a simple linear expansion. The expanded dimension (a) is found by first calculating the expansion of the rings and thin section separately and then reassembling the three pieces to form a cone with a steeper angle. The support cone will be analyzed with reference to Figure 3-18 which shows the dimensions involved in the calculation of an expanded a dimension.

The expanded length for each dimension must be calculated before dimension a can be determined for the hot condition. Table 3-10 lists the dimensions in the cold condition.

Table 3-10. Couple Alignment Cold Condition Dimensions

Dimension	Length - Cold	Average Temp Hot (°F)	Thermal Coefficient of Expansion
a	1.694	---	----
g	0.344	580	0.99×10^{-5}
h	2.116	580	0.99×10^{-5}
i	4.339	160	0.96×10^{-5}
j	0.12	160	0.96×10^{-5}
k	2.665	370	0.99×10^{-5}

A typical calculation is shown below:

For the g dimension,

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

where

Δg = thermal expansion of dimension g in inches

ΔT = temperature differential between hot conditions and room temperature
in $^{\circ}\text{F}$

α = thermal coefficient of expansion for the stainless steel support cone
in inches per inch- $^{\circ}\text{F}$

Substituting the appropriate values from Table 3-10 and assuming a 75°F room temperature,

$$\Delta g = 0.00172$$

Letting g_h be the hot length designation for g ,

$$g_h = g + \Delta g = 0.34572$$

The hot lengths for the various dimensions, with the exception of dimension a which is to be determined, are tabulated in Table 3-11.

Table 3-11. Couple Alignment Hot Condition Dimensions

Dimension	Length (Hot)
g_h	0.34572
h_h	2.12658
i_h	4.34254
j_h	0.12010
k_h	2.67286

Letting a_h be the hot length designation for (a) and noting the right triangle dimensional relationship in Figure 3-18,

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

Substituting the corresponding values from Table 3-11,

$$a_h = 1.72032$$

The change in the a dimension is

$$\Delta a = a_h - a = 0.2632$$

The hot lengths for dimensions b, c, d, and e in Figure 3-17 are found by the same equation used for calculating g_h . Results are tabulated in Table 3-12.

Table 3-12. Couple Alignment Hot and Cold Condition Dimensions

Dimension	Cold Length	Hot Length	Change in Length	Average Hot Temp (°F)	Thermal Coefficient of Expansion
b	1.812	1.81348	0.00148	160	0.96×10^{-5}
c	1.876	1.87830	0.00230	170	1.29×10^{-5}
d	2.687	2.70852	0.02152	845	1.04×10^{-5}
e	0.75	0.75807	0.00807	1110	1.04×10^{-5}

It is noticed in Figure 3-17 that the boron nitride anchor point (f) is directly in line with a point on the hot frame equal to a distance $d + e$ from the fixed reference point.

or $f = d + e$

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

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

Substituting the values for Δd and Δe from Table 3-12,

$$\Delta f = 0.02959$$

For there to be no appreciable relative motion between the anchor point and the cold frame midpoint, the combined expansion of dimensions a, b, c must be approximately equal to Δf or

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

From Table 3-12 and the calculation for Δa ,

$$\Delta a + \Delta b + \Delta c = 0.03010$$

Since the difference between 0.03010 and 0.02959 represents the relative motion between the boron nitride anchor point and the cold frame midpoint, this relative motion being 0.00051 inch, it is seen that for negligible relative motion the anchor point should be approximately 3.437 inches (this is $d + e$ as shown in Figure 3-17 for the cold condition) from the fixed reference point.

3.3.2.5 Electrical Insulation (Boron Nitride Strip) Stress Analysis

As stated previously the post-test analysis of the SNAP-23 converter revealed the electrical insulation (boron nitride strips) had cracked in every thin section area. Cracking is caused by high tensile stresses indirectly created by the difference in the thermal coefficient of expansion between the boron nitride and the stainless steel hot frame. Were it not for the high frictional force between the two parts, the boron nitride would be free to expand since only the upper end is anchored to the hot frame. The combined force of 14 follower springs (each spring exerts a 7.1 pound force) acting on one boron nitride strip, when multiplied by the coefficient of friction for boron nitride against stainless steel at elevated temperatures, induces a high longitudinal tensile force in the strip. The method of anchoring the strip to the hot frame was changed from a shallow surface leg to a through pin. Figure 3-19 shows the anchoring method used in the two SNAP-23 converters.

Figure 3-19. SNAP-23 Converter Electrical Insulation (Boron Nitride Strip) Anchoring Method

It is noticed in Figure 3-19 that the anchor lug opposes the surface friction force. Since the retaining force of the anchor lug acted very close to the mating surface (lug was approximately 0.030 inches high), the eccentric longitudinal loading on the strip produced a bending stress in the strip which was considerably greater than the tensile stress. The thermal expansion of the boron nitride strip with respect to the hot frame is discussed in paragraph 3.3.2.4. Figure 3-17 of the alignment analysis shows the through pin anchor with respect to the cold frame. Figure 3-20 shows the improved through pin anchoring method.

The two cross sectional areas which will be analyzed for tensile stress are Section A-A and B-B shown in Figure 3-20.

1. Section A-A

Friction force, which is also the tensile force in the strip, is equal to the coefficient of friction multiplied by the combined force of 14 follower springs. Expressed mathematically,

$$F = fN$$

Figure 3-20. SNAP-23A Experimental Mockup Converter
Electrical Insulation (Boron Nitride Strip)
Anchoring Method

where

F = friction force in pounds

f = coefficient of friction of boron nitride against stainless steel at 1100°F. This value is taken from Figure 3-21 and is equal to 0.30. Figure 3-21 shows IN102. For this analysis the frictional characteristics of stainless steel (converter hot frame material) are expected to be similar to that of IN102.

N = Normal force of follower springs which exert 7.1 pounds per spring.

Substituting,

$$F = 30 \text{ lbs.}$$

The cross sectional area, A_A , of Section A-A is

$$A_A = 0.267 \times 0.254 - 0.224 \times 0.038$$

$$A_A = 0.05931 \text{ sq. in.}$$

The tensile stress, S_A , in Section A-A is given by the relation

$$S_A = \frac{F}{A_A}$$

Substituting,

$$S_A = 506 \text{ lbs. per sq. in.}$$

Figure 3-21. Static Friction Coefficient vs Temperature for Boron Nitride on IN102

2. Section B-B

The same tensile force, F , also acts at Section B-B. The cross sectional area, A_B , of Section B-B is:

$$A_B = 0.0633 \text{ sq. in.}$$

The tensile stress, S_B , in Section B-B is

$$S_B = \frac{F}{A_B} K$$

where K is a stress concentration factor and is equal to approximately 2.

Substituting,

$$S_B = \frac{30 \times 2}{0.0633}$$

$$S_B = 948 \text{ lbs. per sq. in.}$$

The following tabulation lists the ultimate tensile strength* for boron nitride at various temperatures (Table 3-13).

In this application, the boron nitride is machined so that the long direction is perpendicular to the axis in which the boron nitride is pressed. From the tabulation it can be seen that the ultimate tensile strength for a direction perpendicular to press at 1100°F is 1725 psi. Therefore, the stress of 506 psi in Section A-A is well below the breaking stress, whereas the 948 psi stress in Section B-B allows a safety factor of approximately 1.8.

*Carborundum Co., Latrobe, Pa.

Table 3-13. Tensile Strength for Boron Nitride at Various Temperatures

Temperature (°F)	Ultimate Tensile Strength Parallel to Press (psi)	Ultimate Tensile Strength Perpendicular to Press (psi)
75	5,750	9,000
200	4,800	6,250
400	3,750	4,600
600	2,900	3,500
800	2,250	2,650
1,000	1,700	2,000
1,200	1,250	1,450
1,400	900	1,000
1,600	750	750
2,000	550	550

3.4 FABRICATION AND ASSEMBLY

Principal manufacturing efforts this quarter for the Experimental Mockup Converters consisted of planning, scheduling, vendor qualification, and procurement activities. Part drawings were released by design to production. Purchase requisitions for materials or parts were issued for all of the parts released. No outstanding parts procurement problems were identified at the end of this quarter.

Ninety-five percent of the electrical components for the Process and Test Station cabinets have been ordered.

A preliminary Parts Release Requirements Listing was developed for the two Prototype Mockup Converters.

3.5 TEST AND ANALYSIS

During the second quarter, the major test and analysis effort directly related to Task II involved assistance to the design of the Process and Test Station described in paragraph 3.2.2. Other test and analysis work included post-test analysis of the SNAP-23 Converter P-1 module, bell jar tests and 10-couple module tests. These are a part of the Task III effort and therefore, discussed in paragraphs 4.2, 4.3 and 4.4 of this report.

3.6 RELIABILITY

3.6.1 GENERAL

During the second quarter, Task II reliability efforts consisted primarily of Experimental Mockup Converter drawing reviews and investigation of the converter electrical insulation system. In addition, a reliability analysis was conducted as a part of the Task III SNAP-23 converter post-test analysis (paragraph 4.2).

During this period, all of the Experimental Mockup Converter drawings were completed and released for production and ninety percent have been reviewed for both Failure Mode and Effect Analysis (FMEA) and detail hardware. Piece-part (detail) drawings which effect SNAP-23A converter-system interface dimensions were reviewed to determine their compliance with the required configuration.

The SNAP-23A Reliability Plan was completed and a preliminary draft was forwarded to Westinghouse and the AEC review prior to publication.

3.6.2 ELECTRICAL INSULATION SYSTEM INVESTIGATION

The converter Failure Mode and Effect Analysis review indicated that short circuits to the outer case are a primary potential failure mode. To preclude failures by this mode, a high potential test was conducted on the converter cold junction follower hardcoat insulation, this being the converter part subject to the greatest stress and therefore most susceptible to breakdown.

The objectives of the test were to evaluate:

1. The inherent insulation strength of the follower insulation.
2. If the test current would be destructive to the follower insulation in the event of insulation failure.

The followers tested were of the SNAP-21 configuration which has the same geometry and hardcoat finish used on the SNAP-23A. The advantage of the configuration used was that the spherical end was not hardcoated and could be used as a contact during the test.

Each follower was placed on the test fixture (as shown in Figure 3-22) with the uninsulated area extending beyond the foil electrode. A pointed electrode was then held against the spherical surface while the follower was pressed against the foil and rolled at least one revolution.

Test 1

A sample of six followers was picked for the test. This total sample was first tested with V_1 at 500 volts open circuit and R_1 at 1.5 megohms with no indication of breakdown.

Test 2

For the next test, R_1 was set at 20 megohms and one follower was tested with V_1 at 600, 800, and 1600 volts open circuit. Partial breakdown occurred at some points at 600 and 800 volts but was continuous at 1600 volts. During partial breakdown, the voltmeter would drop to approximately 500 volts but no short circuits through the insulation could be found, nor could any be developed.

Test 3

Another follower was then chosen and subjected to the following series of tests in the order listed.

Figure 3-22. Follower Insulation Test Fixture

<u>R₁</u>	<u>V₁ open</u>	<u>Result</u>
20 meg	1600	Continuous partial breakdown to V ₁ = 500
1.5 meg	1600	Continuous partial breakdown to V ₁ = 500
0.25 meg	800	No breakdown
0.25 meg	1600	Continuous partial breakdown to V ₁ = 500

The follower breakdown points on Test 3 were obvious in a visual examination at X40 magnification. They appeared as pits through the hardcoat to the base metal. These pits were also found on the sample of Test 2 but were much smaller; none were found on the other samples.

The aluminum foil of the test fixture was also examined under a microscope to determine if it had been pitted or splattered with the follower material. The only defect found was severe dimpling in the area which had been used in testing. However, this condition was reproduced in another area of the foil by simply rolling a follower over the surface a number of times.

The conclusions drawn from this test are:

1. The inherent insulation strength of the hardcoat finish is approximately 500 volts. This is in agreement with calculated values which give 800 volts for a perfect finish.
2. The tester current does affect the size of the flaw left in the insulation when breakdown occurs. However, the flaw produced by 250 times normal current, which will occur in converter testing did not result in breakdown at less than 500 volts.

3.7 QUALITY CONTROL

The objective of this effort is to plan, implement and conduct a quality control program in general accordance with MIL-Q-9858A and consistent with the SNAP-23A Program.

The SNAP-23A "Quality Control Plan" MMM 3824-0001 was prepared and submitted in draft form to Westinghouse and the AEC for review and comment.

The Westinghouse Phase I Product Assurance Plan (WANL-(SS)-003) was reviewed and comments were issued to Westinghouse. A meeting between 3M and Westinghouse Quality Control representatives was held at Pittsburgh to resolve outstanding comments.

A meeting was held at Pittsburgh between 3M and WANL Quality Control personnel, to resolve 3M and Westinghouse comments on their respective Quality Plans. In general, agreement was reached and minor revisions were suggested for each plan. The 3M plan was revised to include the recording of variable interface characteristics of the converter as determined from the WANL/3M interface drawing.

A standard procedure was developed by 3M which defines methods for obtaining joint WANL/3M concurrence on interface affected characteristics when deviated. This procedure for non-conforming material will utilize TWX to effect prompt transmittal to WANL and return receipt by 3M.

Quality Control has been working in close liaison with Design Engineering in preparation of the SNAP-23A drawings and with the Manufacturing Group to review and provide quality control requirements to manufacturing flow plans, process routing sheets and purchase documents.

Surveys were conducted on several prospective vendors to evaluate their quality capability and performance. This survey activity is a continuous process while establishing additional approved vendors to satisfy the program requirements.

Effort was conducted by Quality Control personnel to establish new measurement techniques and develop equipment. Effort relating to the thermoelectric legs and couple inspection methods is discussed in section 4.5.

SECTION 4.0

TASK III – THERMOELECTRIC COUPLE DEVELOPMENT

4.0 TASK III—THERMOELECTRIC COUPLE DEVELOPMENT

4.1 INTRODUCTION

The thermoelectric couple development program is being conducted concurrently with the baseline converter development program. This effort is intended to meet the following goals:

- Identify problem areas related to ten-year life thermoelectric leg stability.
- Develop alternate constructional features to eliminate problem areas.
- Test proposed alternates as candidate design inputs to the converter design effort.
- Document and record test data, methods, and test detail so that valid test analyses and conclusions may be generated for the converter design.

In order to meet these objectives, the thermoelectric couple improvement program is being conducted through three distinct approaches:

- Post-test analysis of SNAP-23 converter and module.
- Bell jar testing to verify ingradient thermoelectric performance with respect to design objectives and specifications and to qualify new concepts for long-term performance evaluation.

- 10-couple module testing for long-term performance evaluation of promising variables investigated in the bell jar tests.

The work performed during the quarter for each of these approaches is described in the following paragraphs. Specifically these efforts included:

- R vs L measurements for SNAP-23 Converter P-1 and Module A-2 thermoelectric legs
- Metallographic, emission spectrographic, and microprobe analysis for SNAP-23 units
- Verification of bell jar fixture capabilities
- Completion of bell jar test plan
- 10-couple module leak rate calculations
- Evaluation of soft-sealant feedthrough design for 10-couple modules
- Calculation of 10-couple module extraneous resistance
- Recalculation of 10-couple module insulation requirements
- Reliability analysis of potential failure modes
- Development of total resistance measuring equipment

Each of these areas is discussed in detail in this section.

4.2 POST-TEST ANALYSIS

4.2.1 INTRODUCTION

The prime objective of the SNAP-23 6-couple Module A-2 and 252-couple prototype Converter P-1 post-test analysis is to attempt to clarify or establish potential failure or degrading mechanisms within the converter and module. Both of these devices contain technology which was developed during the SNAP-23 Program which is considered as the baseline technology for SNAP-23A.

The principle areas of investigation include: thermoelectric performance changes, P-leg hot junction contact resistance, metallurgical changes within thermoelectric couple hardware, cold end thermal impedance gas environment, and chemical-physical changes in the thermal insulation.

Progress during the reporting period includes performance evaluation, dimensional analysis, device disassembly, and analyses of individual materials and components. At the end of the period all work was completed with the exception of the detailed analytical tests (microprobe and metallographic) on the individual thermoelectric leg specimens. All work will be completed and a final report issued during the next quarter. Status of the analysis is tabulated in Table 4-1 and interim results are described in the following paragraphs.

4.2.2 PERFORMANCE EVALUATION

An important part of the post-test analysis is to conduct a thorough evaluation of the device performance history. This evaluation is conducted for two reasons:

- 1) Performance data will be correlated with post-test data so that valid conclusions can be drawn.
- 2) Problem areas identified during the device testing will be examined closely in the post-test examination.

The data for Converter P-1 and Module A-1 are summarized in the following paragraphs.

Table 4-1. Post-Test Analysis Status

Test or Analysis	Module A-2	Converter P-1
Performance Evaluation	D	D
Gas Analysis	C	C
Leak Test	C	C
Resistance Tests (in-pile)	C	C
Disassembly	C	C
Dimensional Survey	--	D
Visual Inspection	C	C
Photographs	C	C
Thermoelectric Leg Analysis		
a. Dimensional	C	C
b. Resistivity	C	C
c. Seebeck	C	I
d. Microprobe	I	I
e. Metallographic	I	I
Final Report	I*	I*

Nomenclature: C Completed

I In-Progress

D Test completed, data factored into SNAP-23A
Experimental Mockup Design

*Awaiting completion of all tests and summary evaluation of all individual analyses.

4.2.2.1 SNAP-23 Prototype Converter P-1

Prototype Converter P-1 contains 252 couples, connected in series, through 1020 steel hot electrode caps and iron-plated copper hot shoes at the hot end, and nickel-plated copper cold caps and jumper wires at the cold end. The thermopile is designed in a cylindrical configuration with the thermoelectric legs positioned between two concentric cylinders. The thermoelectric couples utilize pressure contacts at the hot electrode caps. This pressure contact is provided by a spring and follower arrangement from the cold cap into the aluminum outer cylinder cold frame. The inner cylinder hot frame and converter outer case are constructed of 304 stainless steel. Hot side electrical insulation is boron nitride; internal thermal insulation is powdered Min-K 1301. The followers are aluminum with a hard coat of aluminum oxide. The converter is hermetically sealed and back-filled with xenon gas.

After an initial 1000-hour stability conditioning run-in period, the electrical performance of Converter P-1 has been very stable. The output power decreased during the first 1000 hours. The initial power decrease is suspected to be caused by an increase in contact resistance at the hot end of the P legs.

Converter P-1 has required a gradual increase in input power (increased from approximately 1000 watts to 1070 watts) to maintain constant hot electrode temperatures. It must be noted, however, that this power input includes thermal losses through the test stand which cannot be accurately determined. The appearance of the Min-K 1301 material, removed from the region of the heater in the test stand, indicates that severe degradation of the material occurred. It is therefore probable that all or part of the 70 watts input power increase can be assigned to the test stand. Converter P-1 performance data (experimental) is shown graphically in Figure 4-1.

4.2.2.2 Module A-2

The SNAP-23 Module A-2 contains six thermoelectric couples, connected in series, using the same type of electrode hardware as does the converter. The thermopile is in a parallel plate hot frame-cold frame configuration. The springs, followers, electrical insulation, internal thermal insulation, hot frame, cold frame, and internal atmosphere are of the same material as that used in the converter.

Figure 4-1. SNAP-23 Prototype Converter Performance (3M-39-P1) - Experimental Data

Figure 4-2. SNAP-23 Performance Data - Module A-2

The electrical performance of Module A-2 was more unstable than that of Converter P-1. This may be due, in part, to a lower hot electrode contact pressure and a higher hot electrode temperature within Module A-2. (Module A-2 had 150 psi contact pressure compared with 250 psi for Converter P-1.) Module A-2 performance data is shown graphically in Figure 4-2.

Both the P and N legs, with their electrode hardware, have demonstrated performance instability during operation. Based on individual monitoring of two P legs and two N-legs, the following comments can be made:

- The increase in power output during the first 3000 hours was due to a decrease in resistance within each of the P legs and their hot and cold electrode hardware. It is suspected that the resistance change occurred mainly at the hot electrode contacts.

Figure 4-3. SNAP-23 Module A-2 N- and P-Leg Resistance

- The Seebeck voltages of the P legs have, on the average, decreased approximately 11 millivolts during module operation. The Seebeck voltage change was probably caused by a physical or chemical change within the P legs. It is suspected that the resistivity of the P legs was also decreasing.
- The resistance of the N legs and their hot and cold electrode hardware has increased slowly after the initial 1000 hours of testing. The increase in resistance could be caused by an increase in contact resistance or an increase in N-leg resistivity.

4.2.3 PRELIMINARY RESULTS

In addition to the performance evaluation, several of the initial analyses performed on the SNAP-23 devices yielded data which could be immediately factored into the early SNAP-23A Program effort. Two cases are described in the following paragraphs.

4.2.3.1 Couple Alignment

The dimensional evaluation conducted on SNAP-23 Converter P-1 indicated that some misalignment of thermoelectric legs was present. This was the result of a change in position of the cold frame with respect to the hot frame. The net leg misalignment (Figure 4-4) varied from 0.001 to 0.035 on the samples measured.

Figure 4-4. Couple Misalignment (Exaggerated View)

The performance history indicated that leg misalignment did not affect the observed device performance. Visual observations of the legs indicated that the misalignment did not cause any apparent reduction in the contact area at the hot junction, but that full contact between electrode and leg was maintained by yielding of the thermoelectric material at the hot extremity of the leg.

The exact cause of the physical misalignment has not been determined. The information obtained to date reveals that alignment of the thermoelectric legs to the hot cap is not extremely critical and this factor has been reflected in the choice of dimensional tolerances used in design of the Experimental Mockup Converter.

4.2.3.2 Electrical Insulation

During disassembly of Converter P-1 it was observed that the electrical insulation strips, which were made of boron nitride, had broken at a number of locations. Since these strips were held in place by positioning tabs located on the hot frame surface and by spring pressure from the thermoelectric couple assemblies, no failure of the electrical insulation system occurred.

To prevent reoccurrence of this problem on the SNAP-23A Converter, corrective action was taken as described below and in paragraph 3.3.2.5.

- a) Current design data was obtained from the vendor.
- b) The frictional coefficient was analyzed based upon the SNAP-23A design and on SNAP-27 data.
- c) Based on (a) and (b), the cross sectional area of the SNAP-23A part was increased to provide the required strength.

4.3 BELL JAR TEST EFFORTS

The SNAP-23A bell jar tests are short-term tests designed to verify ingradient thermoelectric performance with respect to design objectives and specifications and to qualify new concepts for long-term performance evaluation in the 10-couple module portion of the development program.

Two bell jar tests using residual SNAP-23 couples were conducted during this quarter to determine the ability of the test fixture to meet SNAP-23A couple test requirements. The first test (1A) indicated that a cold frame heater would be required to achieve SNAP-23A operating temperatures. The heater was installed and a second test (1B) indicated that the equipment now has the required range capability.

A detailed bell jar test plan was completed, and appears in Table 4-2. The following rationale provided the basis for this test plan.

Test No. 1:	This test will provide engineering evaluation of SNAP-23 (1965) thermoelectric materials manufacturing processes compared to current SNAP-23A processes.
Test Nos. 2-4:	These tests will provide thermoelectric property data necessary for updating the leg performance computer program.
Test No. 5:	This test will provide engineering evaluation of couples with SNAP-23A leg geometry.
Test Nos. 6-15:	These tests will provide a comparison of legs manufactured using the baseline technique with those manufactured using the alternate technique. Performance variations both batch-to-batch and within batches will be determined.
Test Nos. 16-17:	These tests provide a comparison of conventional and soft nose P legs in terms of both magnitude and reproducibility of hot contact resistance.
Test No. 18:	This test will serve to identify any short-term contacting problems involved in use of the alternate hot contact cap material with either conventional or soft nose thermoelectric legs.
Test Nos. 19-23:	These tests are designed to provide needed information regarding the short-term effects, if any, of hot contact pressure on hot contact resistance. This information will be used to help determine the alternate hot contact pressure which is to be evaluated on a long-term basis in the 10-couple module test effort.

Table 4-2. Bell Jar Test Plan

KEY:

- SP – Baseline Leg Manufacturing Technique (simultaneously pressed)
- B – Alternate Leg Manufacturing Technique (individually pressed and bonded)
- N – Conventional
- H – Soft Nose
- STP – Short-Term Performance
- CR – Contact Resistance

Test Number	P-Legs	N-Legs	Contact Pressure (psi)	Primary Data Objective
1	SP, N	SP, N	250	STP
2	SP, N	SP, N	250	Seebeck Coefficient
3	SP, N	SP, N	250	Resistivity
4	SP, N	SP, N	250	Thermal Conductivity
5	SP, N	SP, N	250	STP
6	SP, N	SP, N	250	STP
7	B, N	B, N	250	STP
8	SP, N	SP, N	250	STP
9	B, N	B, N	250	STP
10	SP, N	SP, N	250	STP
11	B, N	B, N	250	STP
12	SP, N	SP, N	250	STP
13	B, N	B, N	250	STP
14	SP, N	SP, N	250	STP
15	B, N	B, N	250	STP
16	H		250	CR
17	N		250	CR
18	H, N	N	250	CR
19	H, N	N	100	CR
20	H, N	N	150	CR
21	H, N	N	200	CR
22	H, N	N	300	CR
23	H, N	N	400	CR

4.4 10-COUPLE MODULES

The 10-couple modules provide test vehicles for long-term performance evaluation of the stability characteristics of both the couple baseline design and new concepts qualified from short-term tests in bell jars and permit demonstration of reproducibility in a thermopile configuration.

During the second quarter the design of the 10-couple module was completed and detail drawings were released for procurement and fabrication. The basic 10-couple module can be adapted to incorporate various combinations of SNAP-23A legs, couples and related hardware.

Several aspects of the design were analyzed and investigated during the reporting period. These included the maximum leak rate specification, design of the soft sealant feedthrough, calculation of the extraneous electrical resistance in each of the 5-couple circuits, and determination of the weight of the thermal insulation. These aspects are covered in detail in paragraphs 4.4.1 through 4.4.4 of this section.

4.4.1 MODULE LEAK RATE SPECIFICATION

Since it is desirable to limit the pressure drop or leak rate of the 10-couple module to simulate converter performance requirements, it is necessary to establish requirements and to specify subassembly leak rates of the module to which test-measurements may be compared.

Based upon the assumptions of an allowable drop of 1 psi per year, that leakage varies directly with pressure, that nominal operation is at 10-psig, and that the perfect gas law applies, the allowable leak rate is determined to be 8.41×10^{-8} cc He/sec.

Since a leak is more likely to develop in the electrical feedthroughs and the valve or pressure gage and not at a properly welded joint, the leak rate is divided in half for specifying subassembly leak rates.

Module Base Assembly:	4.2×10^{-8} cc He/sec
Enclosure Plate Assembly:	4.2×10^{-8} cc He/sec

The following calculations are given for the above specified values, with the applicable nomenclature defined as follows:

$$\begin{array}{ll} V = \text{ft}^3 & K = \text{ft}^2 \text{ mole/lb second} \\ T = {}^\circ\text{F absolute (}^\circ\text{R)} & M = \text{molecular weight of gas} \\ t = \text{second} & P_F = \text{pressure, final} \\ R = \text{ft-lb/deg mole} & P_I = \text{pressure, initial} \\ P = \text{lb/ft}^2 & \end{array}$$

One mole of gas at standard temperature of 0°C and one atmosphere pressure has a volume of 22,400 cc. At other than standard conditions, the molar volume is:

$$V_M = V_{\text{STD}} \times \frac{T}{T_{\text{STD}}} \times \frac{P_{\text{STD}}}{P}$$

The amount of gas passing through a small opening (effusion) will depend upon its relative mass*. If two gases pass through the same opening, the time element for each is related by the equation:

$$\frac{t_1}{t_2} = \sqrt{\frac{M_1}{M_2}}$$

The volume of the 10-couple unit is calculated by subtracting the volume of the component parts (cold frame, upper heater block, lower heater block, insulator, elements) from the total volume of the enclosed space; the net volume is determined to be 0.082 ft^3 .

From the assumption that the perfect gas law applies, we have

$$\eta = \frac{PV}{RT}$$

*Scott L. Kittsley, Physical Chemistry (New York: Barnes, Noble, Inc., 1955) College Outline Series, pp 16.

such that

$$\frac{dn}{dt} = \frac{V}{RT} \frac{dP}{dt} = -k (p - p_O) \text{ moles/sec}$$

or

$$\frac{\Delta P_F}{\Delta P_I} = e^{-kRTt/V}$$

Neglecting the effect of packed insulation, the value for K is calculated:

$$K = -\frac{V}{RT_t} \ln \left(\frac{P_F - P_O}{P_I - P_O} \right)$$

Assuming that the effusive gas is Argon, we have

$$R = 53.4 \times \frac{79}{40} = 38.7 \text{ ft-lb/}^\circ\text{R mole,}$$

and for

$$T = 650^\circ\text{F} = 1110^\circ\text{R}$$

and

$$t = 1 \text{ year} = 3.15 \times 10^7 \text{ seconds}$$

$$k = 6.36 \times 10^{-15}$$

This in turn establishes $dn/dt = -k (P - P_O) = 916 \times 10^{-15} \text{ moles/sec.}$

Then, for

$$V_M = 22400 \times \frac{530}{1110} \times \frac{24.7}{14.7} = 27,800 \text{ cc/mole,}$$

The allowable leak rate is $916 \times 10^{-15} \times 27,800 = 25.5 \times 10^{-9}$ cc Ar/sec.

Since measurement is done in cc of helium,

$$\frac{E_{\text{arg}}}{E_{\text{hel}}} = \sqrt{\frac{M_{\text{arg}}}{M_{\text{hel}}}} = \sqrt{\frac{40}{4}} = 3.3$$

Finally, the allowable leak rate is determined to be $25.5 \times 10^{-9} \times 3.3 = 8.41 \times 10^{-8}$ cc He/sec.

4.4.2 EVALUATION OF SOFT-SEALANT FEEDTHROUGH DESIGN

The feedthrough design was evaluated to determine the effect of a teflon sleeve on the sealing ability of the soft-sealant feedthrough.

A diagram of the normal Conax sealing gland is pictured in Figure 4-5. The SNAP-23A design required the use of a sealing gland which is larger than the size normally required for bare wire. Oversizing will accommodate the use of extruded or hollow teflon tubing over the bare wire in order to provide the feedthrough with insulation capable of withstanding a high voltage range.

Two sizes of the same Conax connector design were evaluated to determine their sealing capabilities at different torque levels.

In order to measure leak rate, the Conax gland was welded to a fitting which is mounted in a bell jar. The bell jar was evacuated and helium gas (at 10 psig pressure) supplied to the mounted fitting. The leak rate, if any, was detected on a leak-detector which monitors the bell jar. Figure 4-6 depicts the test apparatus used in this evaluation.

At all torque levels the smaller connector showed signs of leakage during a first test. However, indications were that the sealant was not seating square and there was some evidence that the teflon sleeve may have cracked.

Figure 4-5. Conax Sealing Gland

SCHEMATIC OF TEST APPARATUS

Figure 4-6. Conax Gland Test Apparatus Schematic

Because of the indications of improper sealing, a new gland was used and the test rerun. At torque levels of 15, 20, 25, and 30 ft-lb, there was no indication of leakage at any time during the 10-minute monitoring periods in the second test.

The larger connector showed leak rates ranging from 2.2×10^{-8} cc He/sec after one minute to 1.7×10^{-6} cc He/sec after 15 minutes, at a torque level of 10 ft-lbs. The 15 and 20 foot-pound torque levels showed no leakage in the connectors at any time during the 15 minute monitoring period.

Tests have indicated that the proposed design is satisfactory, provided the sealant or gland is seated properly. An assembly specification will be prepared to assure proper seating.

4.4.3 EXTRANEIOUS ELECTRICAL RESISTANCE

An approximate calculation was made of the electrical resistance in each 5-couple circuit, apart from that of the thermoelectric elements. This resistance is termed "Extraneous" and is calculated for a temperature of approximately 70°F.

The detailed steps of these calculations will not be shown here; the method of calculation involves the determination of the resistance (R) for the given materials from the material resistivity (ρ) and geometry of the parts (length L and area A) according to the relationship:

$$R = \rho \frac{L}{A}$$

Table 4-3 tabulates the calculated extraneous resistance for 5-couple circuit as used in the 10-couple module. Figure 4-7 pictorially shows those items associated with the above resistance values.

4.4.4 WEIGHT OF INSULATION

Previous calculations for the amount of insulation required in the 10-couple modules have been adjusted to reflect the correct expression for packing volume determination. Redetermined insulation requirements incorporate the expression:

$$V = \frac{\pi}{4} D^2 L.$$

Table 4-3. 5-Couple Circuit Extraneous Resistance

Item	Resistance ($\mu\Omega$)	Quantity	Total Resistance ($\mu\Omega$)
P Cap	5.26	5	26.30
N Cap	2.31	5	11.50
Button	3.01	10	30.10
Electrode (including Plating)	20.8	5	104.0
Jumper	206	4	824.0
Preforms (N and P Legs)	1.04	5	5.20
Output Wire	1670	2	3340
Hookup Wire #1	3750	2	7500
Hookup Wire #2	2090	2	4180
Total			16021.1

Approximate extraneous resistance — 16 milliohms

Figure 4-7. Hardware Items and Associated Extraneous Resistance Values

Insulation requirements were determined from these applicable calculations:

Min-K Units

$$\text{Packing Volume:} \quad 171 - 33.6 = 137.4 \text{ in}^3$$

$$\text{Shredded Fill:} \quad \frac{\pi}{4} [(6.0)^2 - (3.25)^2] \times 0.75 = 14.9 \text{ in}^3$$

$$\text{Min-K Volume:} \quad 137.4 - 14.9 = 122.5 \text{ in}^3$$

For a density of 11 lb/ft³ or 0.00636 lb/in³ the weight required is
 $0.00636 \times 122.5 = 0.780 \text{ lb. or } 0.78 \times 454 = 354 \text{ grams.}$

Microquartz Units

$$\text{Packing Volume:} \quad 137.4 \text{ in}^3$$

No insulation retainer is used so volume will increase by 4.68 in³ to
 142.1 in³.

For a density of 4 lb/ft³ or 0.00172 lb/in³ the weight required is
 $0.00172 \times 142.1 = 0.245 \text{ lbs. or } 0.245 \times 454 = 111 \text{ grams.}$

4.4.5 FABRICATION AND ASSEMBLY

Detailed fabrication flow plans for the 10-couple module were completed during the second quarter. The Manufacturing System Instruction and Processing Routings were finalized. Parts procurement and fabrication for the 10-couple module are 90 percent completed. The module thermopile assembly fixture has been ordered and fabricated. This fixture is shown in Figure 4-8.

A special insulating packing tool (Figure 4-9) used to compress the microquartz pads in the thermopile, has been designed and fabricated. This tool was required because of the installed microquartz packing density required and the extremely close nature of the converter components into which it is compressed.

Figure 4-8. 10-Couple Module Assembly Future

Figure 4-9. Special Insulation Packing Tool

Twelve process and test stations have been assembled for the 10-couple module, although one electrical component, the rheostat, is still outstanding from the vendor. A typical process and test station is shown in Figure 4-10.

During the third quarter, completion of all fabrication efforts on the 10-couple module is anticipated.

4.5 THERMOELECTRIC LEGS AND COUPLES

4.5.1 DESIGN

The design effort was concentrated on completion of detailed drawings for the thermoelectric couples (Tables 4-4 and 4-5) to be used in the 10-couple module test program. This comprehensive test effort includes twelve 10-couple modules, each 10-couple module will incorporate various combinations of N and P legs assembled into couples as identified in Table 4-1 of Quarterly Report No. 1 MMM 3824-0006.

The basic program will evaluate N legs and P legs manufactured by two different methods — simultaneous powder pressing of both hot and cold segments into one leg, and individually powder pressing and then bonding the hot and cold segments. In addition, two configurations of P leg hot end contacting methods will be evaluated — conventional and soft nose.

4.5.2 FABRICATION AND ASSEMBLY

Some thermoelectric legs and couples used in the 10-couple module test effort use materials and processes which are common to the SNAP-21 Program (AEC Contract AT(30-1)-3691)). Since the SNAP-21 thermoelectric leg and couple manufacturing was under various stages of development during the reporting period, some of the development effort involved joint SNAP-21 and SNAP-23A participation.

The development effort was applied to satisfying the requirements of the 10-couple module and bell jar test efforts. Manufacturing procedures were established for all couple combinations to be used. Additional procedures for the Experimental Mockup Converter couples, if required, will be developed during the next reporting period.

Figure 4-10. Typical Process and Test Station

Table 4-4. Design Data Leg Material Combinations

Leg Type	Hot Segment	Cold Segment	Hot End Configuration	Fabrication Method	Fabrication Specification
N	XTPM-223	XTPM-13	Conventional	Simultaneously powder pressed	XTPO-189
N	XTPM-223	XTPM-13	Conventional	Individually pressed and bonded	MSI-30701
P	XTPM-222	XTPM-29	Conventional	Individually pressed and bonded	XTPO-193
P	XTPM-222	XTPM-29	Soft Nose XTPM-81	Individually pressed and bonded	XTPO-193
P	XTPM-76	XTPM-29	Conventional	Simultaneously powder pressed	XTPO-189
P	XTPM-76	XTPM-29	Soft Nose XTPM-81	Simultaneously powder pressed	XTPO-217

Table 4-5. Design Data Segmented Leg Dimensions

	Hot Segment	Cold Segment	Hot Contact Material*	Diameter
N-Leg	0.377 in.	0.125 in.	----	0.187 in.
P-Leg	0.232 in.	0.124 in.	----	0.187 in.
P-Leg	0.212 in.	0.124 in.	0.020 in.	0.187 in.

*Soft nose legs.

The development effort is summarized as follows:

Leg Bonding

Fixtures for bonding of individually pressed segments into N and P legs which were developed, evaluated, tested for the SNAP-21 program were adapted for use on SNAP-23A. Manufacturing procedures and bonding techniques according to XTPO-193A have been adopted and will be used for production of the legs to be tested.

Several simultaneously pressed N and P legs were manufactured for the bell jar test effort. No problems were encountered.

Thermoelectric Couple Development

Brazing wires to cold caps: A batch process which was used previously for bonding cold caps and jumper wires in a reducing atmosphere was found to give problems in assembly and positioning of parts. A new method which is based upon the induction-heater-continuous feed method will be used.

Bonding molds will be used for accurate holding and positioning parts. Satisfactory brazing has been demonstrated using No. 1801 eutectic silver solder and introducing it through the locating hole at the top of the cap. No flux was required since a reducing atmosphere was introduced in the heating chamber. Figure 4-11 shows a typical brazed wire to cap assembly. Instrumented caps were brazed by using the same process; these are shown in Figure 4-12.

Soldering Legs to Cold Cap

The use of pure tin as a bonding agent has been established over the past years. Development work was undertaken to establish the machine settings to give the correct process temperature and time cycle and quantity of solder to be used on each leg.

Since the cold segment of the P-leg reacts with the solder, the temperature control and quantity of solder are considered to be critical factors. Settings of power input

Figure 4-11. Typical Brazed Wire to Cold Cap Assembly

Figure 4-12. Instrumented Cold Caps, Brazed

(temperature) and rate of speed through the heating unit were established. A tin will be used: 0.002-inch thick on the N-leg, and approximately 0.005-inch will be used on the P-leg.

A problem arose in the fabrication of instrumented couples. The rather stiff instrumentation wires (thermocouples) caused an external force to be exerted on the cold cap assembly at the instant of bonding to the legs. This resulted in imperfect or incomplete bonds. The problem was alleviated by reducing the instrumentation wire diameter from 26 gage to 30 gage.

4.5.3 RELIABILITY

An investigation was performed to determine the integrity of the solder bond on cold cap assemblies. The break in the solder bond between cold caps and jumper wires was considered a critical failure mode because of the number of these junctions and limited reliability data. The investigation showed that when the copper surface has been degreased, the solder will "wet" to the copper surface thereby indicating that the cleaning process was satisfactory. Gases entrapped within the solder decrease the contact surface by approximately 20 percent. This surface decrease does not affect the integrity of the bond in this application.

4.5.4 QUALITY ASSURANCE

4.5.4.1 General

Development effort was undertaken to improve the test methods and equipment used to evaluate the electrical characteristics of segmented legs. Prior tests used the R vs L method — a total resistivity trace for the entire length of the segmented leg. Measuring equipment was experimentally developed for determination of resistivity of thermoelectric segments, legs and couples, using a direct total resistance measurement technique.

The direct resistance technique, unlike the R vs L method, is nondestructive, and allows 100 percent inspection without the need for tinning or special sample preparation.

Measuring apparatus has been designed to accept all sizes of segments and segmented legs to be used in the SNAP-23A Program. In the case of individually segmented and bonded legs (used in the 10-couple module and bell jar efforts) it is possible to determine by direct measurement the resistivity of individual segments and to evaluate the intersegment bond resistance by subtraction of the sum of the individual measured leg resistances from the total measured resistance of the composite segmented leg. In addition, the apparatus has been adapted to accept SNAP-23A couples for evaluation of contact (cold cap-to-segment) resistance.

The data generated by the evaluation of present batches of thermoelectric materials cannot be readily correlated with historical (R vs L) data to any degree of accuracy. It is postulated that the degree of accuracy acquired with the direct measurement equipment is such that a change in acceptance criteria is possible. In review of this, the data generated from the testing of each material configuration will be statistically evaluated to predict new acceptance limits and the percentage of population within these limits.

4.5.4.2 Leg Inspection Testing Development

Evaluation of Bond Integrity by Historical (R vs L) Method

The R vs L method yields a resistivity (ρ) trace determined by incremental tracing of voltage drop over a thermoelectric leg of known dimensions from the relationship $\rho = EA/IL$. Figure 4-13 illustrates typical resistivity – traces associated with segmented thermoelectric legs, according to the above relationship, where E = measured voltage and I = test current.

The height of the trace increases as the thermoelectric sample is traversed and the resistance, measured as a voltage drop per unit length, increases. In the case of a segmented leg, the difference in resistivity of each segment is identified by a change in slope at the segment point, as indicated by trace #1. Trace #1 is an example of a segmented leg possessing a zero intersegment resistance and is characterized by a sharp knee at the point of slope change. The trace of a segmented leg possessing a finite resistance at the hot-cold segment interface is illustrated in Trace #2.

Figure 4-13. Typical Resistivity Traces for Segmented Thermoelectric Legs

With the use of the R vs L method for the evaluation of intersegment bond integrity, it has been found that the trace yields interface information limited to the actual area of the trace. Additional traces traversed at various radial locations of the same sample may yield different voltage drops, each an indication of the bond condition in the area of the specific trace. It has been further noted that a physical misalignment of the hot and cold segments may cause a discontinuity in the trace which does not represent the actual electrical integrity of the bond.

Direct Total Resistance Measurement Technique

To overcome the problems associated with the evaluation of bond integrity by the R vs L method, a direct total resistance measurement technique was established and measurement equipment has been experimentally developed.

This approach produces a total resistance value for each segmented leg. Assuming that the resistance of the hot segment plus the resistance of the cold segment would equal the total resistance of the segmented leg, any variation in total resistance would be the value introduced by the bond resistance.

A direct-resistance device was designed using a direct-current power source and voltage probes which contacted the test specimen at each end at the centerline. The current probes contact each end of the thermoelectric leg in an annular pattern centrally located from the voltage probes as illustrated in Figure 4-14.

Figure 4-14. Direct Resistance Measurement Schematic

The voltage probe is a spring-loaded needle which breaks through the surface of each end of the segmented leg to eliminate spurious readings caused by a possible oxide film. A mechanical attachment is utilized to locate the centerline of the segmented leg concentric to the centerline of the voltage and current probes. The sample is retained by a spring pressure sufficient to force the annular current probes through any oxide film.

In the case of a specific segmented leg type, the area and the length are constants, causing no change in the resistivity values for segmented legs of the same type. Therefore, discounting end effects caused by the short length elements (an assumption valid for samples of the same length, diameter, density and material), the total resistance may be evaluated by application of Ohms Law ($R = E/I$) such that, for a test current of one ampere, the resistance is directly proportional to the measured voltage.

Application

Tests conducted on over 300 samples using the direct resistance measurement technique yielded reproducible resistance readings within ± 2 percent. Resolution of the resistance variations was found to be accurate enough to predict the physical strength of the bond (on individually segmented and bonded legs) between the hot and cold segments and to indicate temperature variations used to perform the bonding operation.

Following the development of preliminary methods and apparatus, effort was continued to improve the testing methods used to evaluate the electrical resistance of thermoelectric segments, segmented legs and couples.

When using the relationship, $\rho = EA/IL$ for the evaluation of the resistivity of a conductive material, a measurement error is introduced by any nonuniformity in the sample since the current distribution is a function of sample geometry. Theoretically, current flow should be parallel to the longitudinal axis of the conductor in any increment of an infinitely long conductor. However, in a conductor of finite length, the current distribution is distorted at the ends of the conductor. Thus, for a true resistivity measurement, it is necessary to establish a correction factor for each geometric configuration. This was done by

measuring the resistivity of a standard material, of known (published) resistivity, having the same geometry as the thermoelectric material in question. These samples were evaluated on the direct resistance equipment at a constant current and the results were plotted with respect to sample length. Using this technique, the correction factors for specific thermoelectric sample geometries were developed. With the correction factors, the direct resistance measurements can be converted to resistivity.

The test fixture has been adapted to accommodate all types of legs and couples under evaluation on SNAP-23A. Tests have been made; results are being evaluated and new limits will be established.

Use of a direct-current power source for testing of thermoelectric legs and couples containing heat pump materials resulted in errors due to thermal effects in the sample. The total resistance of samples of this type were successfully tested using an alternating-current power source. The existing a-c current supplies used for the R vs L apparatus can be used for this test. The Dana amplifiers presently used can also be used where higher sensitivity is required. A Dana model 5500 a-c voltmeter was selected as the readout device on this system and has been ordered.

Future Development

This fixture will be refined for direct resistance testing to better adapt it to rapid, continuous production application.

Assembly and testing of new Seebeck fixtures, which are under development, will be initiated during the next reporting period. This fixture incorporates a temperature regulated cold block and will facilitate immediate establishment and control of the temperature gradient across the sample. Problems encountered with thermal shock to the thermoelectric samples tested with the device are presently under investigation.

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

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

No effort was expended on this task during this quarter.

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