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SYSTEM DESIGN AND TEST
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SNAP 10A POWER CONVERSION

SYSTEM DESIGN AND TEST

(Title Unclassified)

By

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I. INTRODUCTION

SNAP 10A was designed to produce 500 electrical watts continuously for 1 year in a space environment. A compact nuclear reactor is the heat source and the heat is converted directly into electricity by means of a thermoelectric (TE) power conversion system. Development of a power conversion system which would meet the requirements listed in Table 1 was initiated in 1960 and culminated with the successful flight test of the system in the spring of 1965.

The objectives of the TE development program were to develop, fabricate, test, and qualify TE modules for the power conversion system. The principal work areas included (1) design and analysis, (2) developmental engineering and testing, (3) module fabrication, (4) acceptance testing, and (5) qualification testing.

Initial development efforts were directed toward evaluation and test of several module concepts utilizing lead telluride (PbTe) and silicon germanium (SiGe) as the TE material. Three basic concepts were evaluated: (1) a single-loop system using PbTe TE pellets mounted on a NaK tube with a radiator platelet attached to the cold junction of the pellet for heat rejection; (2) a single-loop system similar to (1) but employing SiGe as the TE material; and (3) a two-loop system employing thin washer-type PbTe elements encased between primary and secondary NaK tubes, the secondary NaK loop being used for heat rejection. The SiGe concept was ultimately selected and development efforts on PbTe were then terminated.

The SiGe design, fabrication, and testing portions of the TE program are discussed in this report. The overall design and specifications for the SiGe converter were established by Atomics International (AI). The development and fabrication work was accomplished by the Radio Corporation of America (RCA) under a subcontract from AI.

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TABLE 1
SNAP 10A REQUIREMENTS

Power Output - 581 watts initially and at least 500 watts throughout mission lifetime at the design voltage

Voltage - 28.5 volts at the terminals of the converter

Mission Life - 1 year in space

Efficiency - 1.82% minimum overall based on a NaK inlet temperature of 987°F

Weight - 151 lb maximum including 11 lb for contained NaK

Radiator Size - 65 ft² maximum surface area

Radiator Configuration - conical frustum with a 52-in. maximum base diameter

Reliability - 0.989

Shock Load - two 6-msec shocks of ± 20 g along each of three mutually perpendicular axes

Vibration Load - vibration loads along each of three mutually perpendicular axes consisting of a single sweep at a constant octave sweep rate proceeding from low to high frequency in 5 min of the following magnitude and frequency:

<u>Magnitude</u>	<u>Frequency (cps)</u>
1/4 in. peak to peak	5 to 20
5.0 g	20 to 400
7.5 g	400 to 3000

II. SiGe POWER CONVERSION SYSTEM DESIGN

A. SYSTEM DESCRIPTION

The TE conversion system consisted of 120 modules arranged in a series-parallel mechanical network along the surface of a conical support structure. Figure 1 is a photograph of a module showing its construction. Basically, a module consisted of an equal number of N-type (arsenic-doped) and P-type (boron-doped) SiGe TE elements alternately spaced along the flat surface of a D-shaped stainless steel NaK containment tube. Each element was electrically insulated from the NaK tube by a thin alumina (Al_2O_3) disc. All elements in the module were electrically connected in series by means of a copper strap at the hot end of the element and an aluminum radiator platelet at the cold end.

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Figure 1. SNAP 10A Thermoelectric Module

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An expansion loop was provided in the strap and radiator platelet to accommodate differential thermal expansion between the various materials. The radiator platelet also served to reject waste heat to space.

Three modules were welded in series to form a leg assembly. The three modules were similar in construction but varied in length, number of elements, element spacing and radiator size, due primarily to the conical shape of the system. The module located nearest the reactor heat source was designated an A module and contained 20 TE elements. The second module in the series was designated a B module and contained 24 elements. The third module, located at the base of the conical system, was designated a C module and contained 28 elements. Thus, a leg assembly contained a total of 72 elements electrically connected in series.

Forty leg assemblies arranged in parallel and bolted to the conical support structure comprised the converter assembly. A converter assembly contained a total of 2880 elements or 1440 N and P couples.

The series string of elements in each leg assembly was electrically connected in parallel to an adjacent string by a wire cross-connection at each radiator platelet. Adjoining cross-connected leg pairs were electrically connected in series to form a two-parallel path electrical circuit within the converter.

Figure 2 is a schematic of the paths of heat and current flow for a module. Most of the heat supplied by the NaK flowed through the TE elements and was rejected directly to space by the radiator platelets. The surface of the radiator had a special high emissivity coating to improve its effectiveness in radiating heat.

The Seebeck effect produced a small voltage across each element. The accumulation of the small voltages by connecting elements in series provided the required voltage. The voltage potential caused direct current to flow in the circuit. The current path was through the copper straps, the N and P elements, the radiator platelets and the external load.

B. MODULE CONFIGURATION

The basic objectives of the module design were to achieve the required performance with high reliability and minimum weight.

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Figure 2. Electric and Heat Flow Paths

To achieve maximum performance, the TE hot- and cold-junction temperatures should equal the heat-source and heat-sink temperatures and there should be no power loss in the electrical interconnections. In practice these conditions are not obtainable due to the thermal and electrical impedance in all real materials and interfaces. Further, the brittle nature of TE materials and the required electrical insulation methods of joining the thermoelement to the heat source and heat sink result in a compromise between the minimum impedance system and the allowable stress in the thermoelement.

Design studies resulted in the module configuration shown in Figure 3. For a given TE material and heat-source temperature, this design delivers maximum efficiency and results in a minimum weight system. All interfaces in the

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Figure 3. TE Converter-Radiator Module Assembly

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direction of heat flow were brazed or otherwise metallurgically bonded to minimize the thermal impedances. The utilization of the radiator as part of the electrical current path eliminated the need for electrical insulation at the cold junction and helped increase the temperature differential across the TE material.

To maximize the heat-rejection capability of the radiator and minimize the heat shunting, the outside of the aluminum radiator was coated with a high emissivity material and maintained in a shiny condition on the side facing the NaK tube. The effective emissivity of the NaK tube was kept low by the use of a molybdenum foil wrap coated with gold.

Stresses in the brittle TE material were minimized by making each element essentially independent of the adjacent element so that each could expand and contract when exposed to thermal gradients without imposing large stresses on the TE and adjacent materials. Compensating pads prevented the stresses due to the mismatch in thermal expansion of the materials used at the thermoelement heat source and heat sink interfaces from being transmitted to the SiGe.

The modular concept made possible the performance of acceptance testing at the element level prior to the assembly of the full-size converter and thus ensured stability and manufacturing reproducibility of the assembly.

C. DESIGN PARAMETERS

Table 2 summarizes the nominal design parameters for the SNAP 10A power conversion system. The nominal design point was based on a SiGe alloy composed of 70 at. % Si and 30 at. % Ge. However, a more suitable SiGe alloy composed of 67 at. % Si and 33 at. % Ge was ultimately used.

A weight breakdown of the power conversion system is shown in Table 3. The total weight is 154 lb, including radiator platelets, NaK tubing, and contained NaK. The specific weight of the conversion system is 265 lb/kwe.

D. METHOD OF ANALYSIS

The basic equations and definitions employed in the design and analysis of the power conversion system are given on the following pages. The open-circuit voltage of the TE converter is

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TABLE 2

NOMINAL DESIGN PARAMETERS FOR SNAP 10A POWER
CONVERSION SYSTEM

Electrical

Power output, initial (watts)	581
Closed-circuit voltage (volts)	28.5
Open-circuit voltage, steady-state (volts)	61.7
Current (amp)	20.4
Resistance (ohms)	1.40

Thermal

Heat input (kw)	31.90
Heat rejected (kw)	31.32
Radiator area, at temp (ft ²)	62.5
Radiator fin effectiveness	0.90
Radiator surface emissivity	0.89

Efficiency (%)

Overall	1.82
Carnot (Avg NaK-Avg radiator)	23.8
Device	7.65

Temperatures (°F)

Inlet NaK	987
Outlet NaK	883
Average NaK	935
Maximum hot junction	954
Minimum hot junction	850
Average hot junction	902
Maximum cold junction	656
Minimum cold junction	552
Average cold junction	604
Maximum radiator	655
Minimum radiator	551
Average radiator	603

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TABLE 3
WEIGHT BREAKDOWN OF SNAP 10A POWER
CONVERSION SYSTEM

Component	Weight (lb)
TE Elements (SiGe and W shoes)	36.8
Radiator	32.7
Hot Straps	11.8
Insulators	1.4
NaK Tubes	25.4
Compensating Pads	19.6
Braze Material	2.5
Mounting Brackets	4.8
Miscellaneous Electrical Hardware	7.9
Total (Converter and Radiator, Dry)	142.9
NaK	11.1
Total (Converter and Radiator, Wet)	154.0

$$E_{oc} = \frac{N(|S_N| + |S_P|)(T_{HJ} - T_{CJ})}{n} \quad \dots(1)$$

where

E_{oc} = converter open-circuit voltage (volts)

N = total number of couples

n = number of parallel electrical circuits

S = Seebeck coefficient (volts/°R)

T_{HJ} = hot-junction temperature (°F)

T_{CJ} = cold-junction temperature (°R)

Subscripts N and P refer to N and P TE elements. The absolute value of the Seebeck coefficient is used in Equation 1 with the understanding that the N and P elements are of opposite polarity, i. e., the Seebeck coefficient of the N element is negative and that of the P element is positive.

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The equivalent electrical resistance of the converter is

$$R = \frac{N R_o}{(n)^2} \quad \dots(2)$$

where

R = equivalent electrical resistance of the converter (ohm)

R_o = electrical resistance per couple including contact resistance and electrical straps (ohm/couple).

The electrical current delivered to the external load is

$$I = \frac{E_{oc}}{R + R_L} \quad \dots(3)$$

$$= \frac{E_{oc}}{(M + 1) R}$$

where

I = load current (amp)

R_L = load resistance (ohm)

$M = \frac{R_L}{R}$ = load to converter resistance ratio .

The electrical current flowing through the thermoelectric elements is

$$i = \frac{I}{n} \quad \dots(4)$$

where

i = element current (amp) .

The voltage across the output terminals of the converter is

$$E = E_{oc} - IR \quad \dots(5)$$

$$= \left(\frac{M}{M + 1} \right) E_{oc}$$

where E = terminal voltage (volts).

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The power output of the converter is the product of terminal voltage and current; thus

$$P = EI$$

$$= \left(\frac{M}{(M+1)^2} \right) \left(\frac{E_{oc}^2}{R} \right) \quad \dots(6)$$

where P = power output (watts) .

A more familiar form of the equation for power output is

$$P = N \frac{M}{(M+1)^2} \frac{(S_N + S_p)^2 (T_{HJ} - T_{CJ})^2}{R_o} \quad \dots(7)$$

The power output at matched load conditions ($R_L = R$) is

$$P_{ml} = \frac{N(S_N + S_p)^2 (T_{HJ} - T_{CJ})^2}{4 R_o} \quad \dots(8)$$

where P_{ml} = matched load power output (watts).

The net heat flow across the hot and cold junctions of the TE element is the sum of four heat terms: (1) conduction heat, (2) Peltier heat, (3) Joule heat, and (4) Thomson heat. The Thomson heat is small compared to the other terms and is neglected in the heat balance. The Thomson heat is taken into account indirectly in the Peltier heat by use of a mean value of the Seebeck coefficient over the hot- to cold-junction temperature range. The heat absorbed at the hot junctions is

$$Q_a = N K_o (T_{HJ} - T_{CJ}) + N i (S_N + S_p) T_{HJ} - 1/2 N i^2 R_o \quad \dots(9)$$

where

Q_a = heat input (watts)

K_o = thermal conductance per couple including shunt heat losses (watts/°R) .

The heat rejected at the cold junctions is

$$Q_R = N K_o (T_{HJ} - T_{CJ}) + Ni(S_N + S_p)T_{CJ} + 1/2 N i^2 R_o \quad \dots(10)$$

where Q_R = heat rejected (watts) . The first term in Equations 9 and 10 is the conduction heat, the second is the Peltier heat, and the third term is the Joule heat.

Converter efficiency is the ratio of power output to heat input; thus,

$$\eta = \frac{P}{Q_a}$$

$$= \frac{M(S_N + S_p)^2 (T_{HJ} - T_{CJ})^2 / (M + 1)^2 R_o}{K_o (T_{HJ} - T_{CJ}) + i(S_N + S_p)T_{HJ} - 1/2 i^2 R_o} \quad \dots(11)$$

A more familiar form of the equation for converter efficiency is

$$\eta = \left(\frac{\Delta T}{T_{HJ}} \right) \left[\frac{M}{(M + 1) + \frac{(M + 1)^2}{Z_{eff} T_{HJ}} - \frac{\Delta T}{2 T_{HJ}}} \right] \quad \dots(12)$$

where

$$\Delta T = T_{HJ} - T_{CJ} (^{\circ}R)$$

$$Z_{eff} = \text{effective figure of merit} = \frac{(S_N + S_p)^2}{R_o K_o} (^{\circ}R^{-1})$$

The first term in Equation 12 is the well-known expression for Carnot efficiency and the second term is defined as device efficiency; hence,

$$\eta = \eta'_c \eta_o \quad \dots(13)$$

where

$$\eta_c' = \text{Carnot efficiency} = \frac{\Delta T}{T_{HJ}}$$

$$\eta_D = \text{Device efficiency} = \frac{M}{(M + 1) + \frac{(M + 1)^2}{Z_{\text{eff}} T_{HJ}} - \frac{\Delta T}{2 T_{HJ}}}$$

Radiant heat transfer from the radiator is described by the familiar Stephan-Boltzman equation:

$$Q_R = \eta_f \epsilon \sigma A_R (T_R^4 - T_S^4) \quad \dots(14)$$

where

Q_R = radiated thermal power (kwt)

η_f = fin effectiveness

ϵ = surface emissivity

σ = Stephan-Boltzman constant = $5.02 \times 10^{-13} \text{ kw/ft}^2 \text{ } ^\circ\text{R}^4$

A_R = radiating surface area (ft^2)

T_R = radiating surface temperature ($^\circ\text{R}$)

T_S = sink temperature ($^\circ\text{R}$)

Equations 1 through 14 form the basis for the design and analysis of the power conversion system. The remainder of this section is concerned with material efficiency (η_m), transmission efficiency (η_T) and power output per unit area (P/A_R). These terms are often used in describing the performance of the power conversion system. Material efficiency is calculated from the equation

$$\eta_m = \frac{\sqrt{1 + Z\bar{T}} - 1}{\sqrt{1 + Z\bar{T} + T_{CJ}/T_{HJ}}} \quad \dots(15)$$

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where

$$Z = \text{figure of merit} = \left[\frac{S_N + S_p}{\sqrt{\rho_N k_N} + \sqrt{\rho_p k_p}} \right]^2 (\text{°R}^{-1})$$

$$\bar{T} = \frac{T_{HJ} + T_{CJ}}{2} (\text{°R})$$

ρ = electrical resistivity of TE material (ohm-in.)

k = thermal conductivity of TE material (watts/in. -°R)

Transmission efficiency (η_T) represents the degree of perfection in transmitting thermal and electrical power through the converter. It provides a measure of parasitic thermal and electrical losses due to electrical contact resistance, strap resistance, thermal impedances, and shunt heat. In equation form

$$\eta_T = \frac{\eta}{\eta_c \eta_m} \quad \dots(16)$$

where

η_T = transmission efficiency

$$\eta_c = \text{overall Carnot efficiency (NaK to radiator)} = \frac{T_{\text{NaK}} - T_R}{T_{\text{NaK}}}$$

An approximate equation for calculating transmission efficiency is

$$\eta_T \cong \eta_{Ct} \eta_{St} \eta_{tt} \eta_{Sh} \quad \dots(17)$$

where

η_{Ct} = contact transmission factor

$$= \frac{\text{element electrical resistance}}{\text{element} + \text{contact electrical resistance}}$$

η_{St} = strap transmission factor

$$= \frac{\text{element} + \text{contact electrical resistance}}{\text{element} + \text{contact} + \text{strap electrical resistance}}$$

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η_{tt} = thermal transmission factor

$$= \frac{\text{element thermal impedance}}{\text{NaK to radiator thermal impedance}} = \frac{T_{HJ} - T_{CJ}}{T_{NaK} - T_R}$$

η_{Sh} = shunt heat transmission factor

$$= \frac{\text{hot junction heat input}}{\text{hot junction heat input} + \text{shunt heat to radiator}}$$

The electrical power output per unit of radiator area when $T_R^4 \gg T_S^4$ is given by

$$\frac{P}{A_R} = \frac{\eta_T \eta_m \eta_f \epsilon \sigma \eta_c (1 - \eta_c)^4 (T_{NaK})^4}{1 - \eta_T \eta_m \eta_c} \quad \dots (18)$$

Typical transmission efficiencies for the SNAP 10A module are shown in Table 4.

TABLE 4
COMPONENT TRANSMISSION EFFICIENCIES

Converter Parameter	Efficiency
Contact Resistance (M Ω /couple)	0.126
Contact Transmission Efficiency	0.97
Strap Resistance (M Ω /couple)	0.326
Strap Transmission Efficiency	0.93
Thermal Impedance ($^{\circ}\text{C}/\text{watt}$)	1.9
Thermal Transmission Efficiency	0.889
Shunt Heat Loss (%)	8.0
Shunt Transmission Efficiency	0.92
Total Transmission Efficiency	0.735

E. DESIGN CONSIDERATIONS

1. Design Point Selection

The selection of the converter radiator design point was based on an overall system minimum weight criteria. Considerations of pump, structure, and piping

weights determined the effective diameter and number of NaK tubes (or legs). The determination of element length was the result of a parametric study of converter weight vs element length and Carnot efficiency. In the study the temperature of the NaK supplied to the converter was fixed by reactor design considerations and the radiator temperature was the parameter used to vary Carnot efficiency. To minimize fabrication problems, only equal N and P length elements with a fixed diameter of 0.444 in. were considered.

The results of the parametric weight studies are shown in Figure 4. The minimum weight point occurred at an element length of 0.323 in. and a Carnot efficiency of 23%. Subsequent detailed design efforts and refinements produced only minor modifications in the design point selection. An element length of 0.323 in. and a Carnot efficiency of 23.8% were used as the nominal design points.

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Figure 4. Radiator Converter Weight vs Overall Carnot Efficiency for Various Element Lengths

It was concluded from the parametric weight studies that, since significant deviations about the minimum weight point result in only minor weight penalties, there is considerable freedom in the design point selection and that minor dimensional changes to accommodate fabrication requirements will not affect performance.

2. Radiator Fin Thickness and Element Spacing

Initial radiator design and element spacing were based on the assumption that maximum power output would be obtained when the temperature differential across each element is constant. To achieve a constant temperature differential, it was necessary to continuously vary radiator fin thickness and element spacing with position from NaK inlet to outlet due to the NaK temperature gradient and the variable area of the conical surface. For practical reasons, only three different radiator fin thicknesses and three different element spacings were used in the initial design. Subsequent design studies determined that constant fin thickness and/or constant element spacing could be used with no loss of power output. Three designs were considered in the studies:

- 1) Variable element spacing and variable fin thickness (20, 30, and 60 mil),
- 2) Variable element spacing and constant 30-mil fin thickness.
- 3) Constant element spacing and constant 30-mil fin thickness.

Table 5 compares the three designs on the basis of normalized power output. The total power output was essentially constant for all three designs, although the power produced per module type varied widely. (The power output for each module in Design No. 1 was proportional to the number of elements per module.) On the basis of these results, the original design No. 1 was modified to one that employed a constant fin thickness with three different element spacings, depending on the module type. This design was selected, rather than one that employed both constant fin thickness and element spacing, because it yielded less variations in the temperature difference.

The final design used a constant 32-mil fin thickness and the element spacing was 1.274 in. in Module A, 1.18 in. in Module B and 1.05 in. in Module C.

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TABLE 5
RADIATOR MODULE POWER OUTPUT

Module Design- nation	Thermo- element Numbers	Normalized Power Output		
		Design Number		
		1	2	3
A	1-20	1.000	0.988	0.890
B	21-44	1.000	1.037	1.008
C	45-72	1.000	0.989	1.073
Total		1.000	1.005	1.001

3. Reliability

The inherent reliability of the converter was based on a design which minimized stresses, and on stringent process control which ensured a TE module with complete reproducibility of performance.

It was recognized early in the design of the converter that converter reliability could be increased by arranging the modules in parallel branches, rather than in a single series electrical circuit. However, it was expected that, because of variations in properties of the TE materials, circulating currents within the converter would cause excessive power loss. Consequently, extensive analytical studies utilizing digital computer techniques were performed to evaluate the effects of property variations and parallel circuitry on power output.

The following property variations were considered:

- 1) Fundamental property variations of N and P elements because of variations in the Seebeck coefficient (S) and material resistivity (ρ),
- 2) Random variation of the internal electrical resistance due to manufacturing tolerances,
- 3) Fundamental variation of voltage potential (V) with internal resistance (R) such that $V^2/R = \text{constant}$ or $S^2/\rho = \text{constant}$,
- 4) Random variation of voltage potential (V) superimposed on Item 3 due to slight variations in the value of S^2/ρ , variations in the extra-thermoelement thermal impedance, and variations in the material thermal conductivity,

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5) Variation in the voltage potential (V) as a function of position along a converter leg due to the variation in radiator area and NaK temperature along the leg.

A study of available experimental data determined that, for SiGe, the Seebeck coefficient varies with resistivity such that $S^2/\rho = \text{a constant}$. The results of the calculations for this case are shown in Figure 5. The analytical model for these calculations consisted of two converter legs, each containing 72 elements, with a variable number of interconnections between legs. It was concluded from the results that:

- 1) The power output of the SNAP 10A SiGe converter is independent of the number of parallel interconnections.
- 2) The loss in power output of the SNAP 10A converter due to the parallel arrangement of converter legs is negligible.

Figures 5B and 5C show that, for certain variations in S and ρ , power output is a function of the number of parallel interconnections.

The primary purpose of series-parallel circuitry is to avoid complete converter failure if open circuits occur in the TE circuit. The probability of obtaining some power output (i.e., $1 - \text{probability of complete failure}$) is

$$pc = \{ 1.0 - [1.0 - (1.0 - p)^m]^n \}^\ell$$

where

n = number of parallel series circuit

ℓ = number of interconnections between series circuits

m = number of TE elements between interconnections

p = open-circuit failure probability per element

pc = probability of producing some power output

The value of pc for the SNAP 10A converter is 0.997 and is based on the following values:

$n = 2.0$ parallel series circuits

$m = 2.0$ elements between interconnections

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Figure 5. Effect of Module Power Output Due to Parallel Interconnections

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l = 720 interconnections

p = 0.001 (1 part per thousand) element open-circuit failure rate.

The element open-circuit failure rate (p) of less than 1 part per thousand was demonstrated by qualification tests.

The probable power output of the SNAP 10A converter after open-circuit failures, if complete failure does not occur, is

$$\frac{P}{P_D} = \frac{2 - (1-p)^m}{4 - 3(1-p)^m}$$

where

P = probable post-failure power output

P_D = prefailure power output .

The ratio P/P_D is 0.996; thus, the probable power loss due to open-circuit failures is 0.4%.

There is a 50% probability that the loss in power output will be less than or greater than the calculated value. Therefore, there is a 50% confidence level associated with the power loss of 0.4%.

4. Materials Selection

For a direct radiating converter system with heat input via a liquid metal, the basic module assembly must contain five components:

- 1) A container for the liquid metal,
- 2) An insulator between the element and the structure to prevent current leakage,
- 3) A power producing thermoelectric element,
- 4) A radiator to reject heat to space, and
- 5) Electrical connections between elements.

To satisfy these requirements, materials were required whose physical and mechanical properties differed greatly. A cross section of the completed stack is presented in Figure 6 for ease in interpreting the following discussion.

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Figure 6. SNAP 10A Stack Configuration

a. NaK Tube

It was necessary for the material chosen for the NaK tube to be resistant to the hot sodium-potassium alloy. In addition, it was required that the material possess high thermal conductivity, high strength at design and fabrication temperatures, reasonable ductility, a low thermal expansion coefficient, a resistance to diffusion of the braze alloy over extended periods of time (1 year), and should also be easily weldable.

Four materials were considered: 304 SS, 405 SS, 446 SS, and Hastelloy-N. At the time of development, information concerning the behavior of Hastelloy-N was insufficient to compare this material to the better known stainless steels. Type 304 SS met all of the criteria except that its thermal expansion coefficient was high. Type 446 SS suffers from hot shortness (embrittlement) near the

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designed operating temperature. Type 405 SS has good weldability and a favorable expansion coefficient and does not appreciably suffer from the hot shortness problem generally found in ferritic stainless steels of higher chromium content. For these reasons it was chosen as the NaK tube material.

b. Electrical Insulator

The electrical insulator requirements included high electrical resistivity, high thermal conductivity, and good strength. The two materials which best met these requirements were beryllium oxide (BeO) and aluminum oxide (Al_2O_3). BeO was interesting because of its light weight and very high thermal conductivity. However, the state-of-the-art was not sufficiently advanced to compare this material favorably with Al_2O_3 . Due to its availability from a variety of sources, and the fact that extensive metal-to- Al_2O_3 bonding technology exists, Al_2O_3 was chosen as the reference design material for the electrical insulator.

c. TE Element

The primary factor in the selection of SiGe as the TE material was that consistently reproducible values for device resistance, voltage, and structural strength could be obtained with the material. The disadvantages of the moderate material efficiency of SiGe are offset by the fact that its good strength, high-temperature stability, and low vapor pressure allow it to be fabricated into a module recovering a high fraction of that efficiency. The physical, mechanical, and TE properties of P and N (67 at. % Si - 33 at. % Ge) material are shown in Figure 7 and listed in Table 6.

It was necessary to separate the SiGe element from the adjacent materials in the stack by inserting a shoe between it and the materials to prevent low melting point alloys from forming. The necessary requirements for a proper shoe material were:

- 1) An expansion coefficient similar to that of SiGe.
- 2) Ability to form a good bond with SiGe.
- 3) Sufficiently strong to help shield the SiGe from stress.

Tungsten satisfied these criteria and a test program showed that, with minor adjustments in the SiGe fabrication procedure, reliable, low-resistance bonds could be achieved.

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a. Variation of the Figure of Merit with Temperature of 67% Si -33% Ge

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b. Variation of Thermal Resistivity with Temperature of 67% Si -33% Ge

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c. Variation of Electrical Resistivity with Temperature of 67% Si -33% Ge

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d. Variation of Absolute Seebeck Coefficient with Temperature

Figure 7. Physical and Thermoelectric Properties of 67% Si -33% Ge

TABLE 6
MECHANICAL AND PHYSICAL PROPERTIES OF SiGe

	N-Type	P-Type
Young's Modulus (10^6 psi)	18	19
Shear Modulus (10^6 psi)	7	9
Ultimate Compressive Strength (psi)	>200,000	>200,000
Ultimate Tensile Strength (psi)	2100-2700	2900-4500
Poisson's Ratio	0.25	0.23
Density (lb/in. ³)	0.145	0.145
Specific Heat (Btu/lb-°F)	0.14	0.14
Thermal Expansion (10^{-6} in./in. °F)	2.8	2.8
Melting Point (°F)	2240	2240
Vapor Pressure at 800°C (torr)	$<10^8$	$<10^8$
Oxidation Resistance	Excellent	Excellent

d. Radiator

Aluminum was used for the radiator material because it has the highest thermal conductivity per unit weight and allows the achievement of a high fin effectiveness (0.90) in the temperature range of interest. The aluminum radiator was coated with a chrome-nickel spinel to obtain an emissivity of 0.90. A tungsten upper compensator pad was bonded to the radiator for stress compensation.

e. Electrical Connection

The electrical connection between elements was made with a copper strap at the hot end and the aluminum radiator platelet at the cold end. Copper was used for the hot strap because it forms a stable low-resistance bond when joined to the adjoining materials, and it has a high electrical conductivity per unit weight. Lighter weight aluminum was investigated as a material for the hot strap but proved unsatisfactory because of difficulties in achieving a stable high-temperature bond.

f. Stress Compensating Materials

In addition to the materials required from a performance standpoint, the mismatch of thermal expansion coefficients required additional materials to

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minimize the stresses in the stack and obtain a metallurgically bonded module with high integrity and minimum loss in performance.

At the hot end of the TE element it was necessary to bond SiGe with tungsten shoes (expansion coefficient, $\alpha = 4.3 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$) to a copper conductor ($\alpha = 19.0 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$) from a stainless steel tube ($\alpha = 13.5 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$).

The natural tendency of the system was to bow at the NaK tube and to dome at the tungsten. Both of these tendencies was detrimental to the performance of the system. The doming of the tungsten resulted in tensile stresses within the SiGe element, which in turn resulted in cracks in the element. The bowing of the NaK tube was detrimental to the mechanical integrity of the legs, particularly the welded joints.

To develop an acceptable assembly or stack, it was necessary to meet two engineering objectives: (1) Maintain a flat NaK tube by obtaining bimetallic bending movement neutralization at that point, and (2) Achieve a slightly dished surface at the tungsten to maintain compressive stress in the element.

According to rigid seal theory, it would be impossible to attain the desired engineering objectives. However, during the investigation of the problem a maximum shear stress theory was developed. The conclusions of the maximum shear stress computations for this application (the lower region of the stack) follow.

1) Experimental evidence strongly suggests that the bimetallic bending in seals of dissimilar metals is largely determined by shear stresses in the braze material.

2) By appropriate use of hard and soft brazes in a stack assembly, it should be possible to exert considerable control over curvature effects.

3) For maximum curvature effects, the thickness of members in a seal should be approximately in inverse ratio to their values of Young's modulus.

4) Because curvature effects are controlled by shear stresses at the bonds, the effect of remote elements will be relatively weak. Desired curvature effects must, therefore, be locally achieved.

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To meet the engineering requirements of the stack assembly, it was necessary to introduce negative curvature components into the stack. The theoretical concepts developed in maximum shear stress calculations indicate how this was done:

1) Since curvature is largely determined by the maximum shear stress at the joints, all joints with desired negative curvatures should employ hard brazes, while the joints contributing to undesired positive curvatures should have soft brazes.

2) Since curvature is largely determined by the maximum shear stress at the joints rather than the difference in expansion coefficients, net negative curvatures can be obtained by having more negative joints than positive joints. The negative joints can be slowly graded downward through several numbers while the necessary positive joints should drop through the largest possible expansion difference; in addition, one member of a positive joint should have a low Young's modulus.

3) Maximum shear stress theory indicates that, to obtain optimum curvature with minimum weight, the component members should have thicknesses approximately in inverse ratio to their modulus of elasticity. It will be noted that the number thicknesses in the present stack assembly (empirically determined) approximately satisfy this condition.

4) Maximum shear stress theory indicates that remote numbers will have a relatively small effect on local curvature. Because of the natural overall tendency of the insulator stack toward positive curvature, bimetallic bending moment neutralization to keep the NaK tube flat is most effectively accomplished by the nearest adjoining member. This member should be of higher expansion than the NaK tube to achieve negative compensation.

Figure 8 shows the basic design of the lower portion of the stack after incorporating the preceding ideas. The insulator stack assembly had three negative joints and two positive joints. A copper pad, a molybdenum equalizer, and tungsten lower compensator were added to the basic components of the insulator stack assembly.

The criteria for choosing the proper braze alloy were its melting temperature and strength characteristics. As shown in Figure 8 a hard braze and a

Figure 8. Exploded View of Insulator Stack Assembly

soft braze were required. It was necessary for the hard braze to be strong and unyielding to the shear stress encountered in the stack. The soft braze had to yield to these stresses, thereby preventing, to a certain extent, curvature of the stack.

Nioro (82 Au, 18 Ni, mp 950°C) was used as the hard braze material due to its exceptionally good strength characteristics and its ability to wet molybdenum.

A braze of lower yield strength was developed by alloying nickel with copper and germanium to attain a melting region similar to that of Nioro. The fabrication of the insulator assembly was thus simplified by allowing only one brazing cycle. The optimum composition of the alloy was determined to be 0.25 wt % Ni, 12 wt % Ge, and 87.75 wt % Cu. Tests were performed with the braze to determine its compatibility with the structural materials involved and no deleterious effects were observed. The braze was quite acceptable as the soft braze required by the maximum shear stress theory.

A transfer of stresses from the lower part of the stack could cause cracks to develop in the brittle SiGe element. This would lead to lower efficiency and could have resulted in structural failure. For this reason a ductile material with a low yield strength was desirable between the insulator assembly and the

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element to prevent the transfer of stress. Gold was found to be the most suitable material for this purpose.

Because of the ductile nature of aluminum, sufficient compensation for the bending moment caused by the difference in expansion between the aluminum and the upper tungsten was obtained by bonding a tungsten pad to the opposite side of the radiator.

A complete listing of materials used in the TE stack is presented in Table 7.

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TABLE 7
PARTS LIST FOR SNAP 10A TE STACK

Part Name	Composition	Dimensions	Platings
Upper Compensator	Tungsten	0.460 in. diameter by 0.020 in. thick	0.0001 in. Ni, 0.0025 Cu each side
Radiator	1100 - H14 Aluminum	0.032 in. thick	--
Upper Shoe	Tungsten	0.460 in. diameter by 0.020 in. thick	0.0001 in. Ni, 0.0025 Cu Radiator side only
N-Element	66.6 at. % Si, 33.1 at. % Ge, 0.3 at. % As	0.444 in. diameter by 0.323 in. length	--
P-Element	66.6 at. % Si, 33.1 at. % Ge, 0.3 at. % B	0.444 in. diameter by 0.323 in. length	--
Lower Shoe	Tungsten	0.460 in. diameter by 0.040 in. thick	0.0005 in. Ni - Au Ring side only
Bonding Ring (Split)	Gold	0.375 in. OD, 0.280 in. ID 0.030 in. thick, 0.020 in. split	--
Lower Compensator	Tungsten	0.470 in. diameter by 0.020 in. thick	0.0005 in. Ni - Au Ring side 0.0001 in. Ni, 0.001 in. to 0.002 in. Cu Hot Strap side
Gemco Braze Disc	88 w/o Cu, 12 w/o Ge	0.470 in. diameter by 0.001 in. thick	--
Hot Strap	OFHC Copper	0.025 in. thick	--
Nioro Braze Disc	82 w/o Au, 18 w/o Ni	0.470 in. diameter by 0.001 in. thick	--
Insulator Disc	94 w/o Al ₂ O ₃ , 4 w/o MnO ₂ 2 w/o SiO ₂	0.470 in. diameter by 0.0195 in. thick	Molybdenum 0.0005 in. to 0.0014 in. and Fe 0.00002 to 0.00005 in. both sides
Nioro Braze Disc	(See Above)	0.470 in. diameter by 0.0015 in. thick	--
Equalizer Disc	Molybdenum (99.99%)	0.470 in. diameter by 0.015 in. thick	0.0001 in. Fe - both sides
Gemco Braze Disc	(See Above)	(See Above)	--
Contact Disc	OFHC Copper	0.470 in. diameter by 0.025 in. thick	--
Gemco Braze Disc	(See Above)	(See Above)	--
NaK Tube	405 SS - ASTM A-268-61	D-Shaped, 0.516 in. flat surface, 0.302 in. OD radius	Ni Flash, 0.0001 in. Cu

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III. FABRICATION

The discussion of fabrication techniques in this section refers to the flight module design. An extensive development program preceded this design and many changes in structure and process were experienced. These changes and the process development required to arrive at the flight module are discussed in detail in earlier progress reports.⁽¹⁻⁷⁾

A brief summary of the major changes made during the program is given in Table 8.

A. MODULE FABRICATION

The primary fabrication processes were associated with bonding of the stack, the low emissivity coating, and the high emissivity coating.

1. Stack Bonding

Fabrication was complicated by the number and variety of materials comprising the stacks. Two basic bonding techniques were required: (1) the insulator assembly required a brazed joint in several locations to adjust the stress distribution encountered from the association of materials with such diverse expansion coefficients. (2) Brazing was not feasible in the upper portion of the stacks due to the relatively low softening point of the aluminum radiators and due to the possible contamination of the element and shorting of the insulator due to braze runover. A flow diagram of the module fabrication procedure is presented in Figure 9.

Three basic subcomponents were initially assembled. These were the insulator stack assembly, the hot strap subassembly, and the element subassembly. Components of the first two assemblies were joined by a lucite binder which kept the many component materials in proper position during the assembly for the brazing operation. The third subassembly, consisting of the element and tungsten shoes, was fired at 1472°F for 30 min to diffusion bond the components.

The insulator stack assembly and the hot strap subassembly were combined with the NaK tube to form the braze assembly, which was brazed at 1860°F for 3 min in dry hydrogen. The brazed assembly and the diffusion-bonded element were positioned with a gold ring between them in the final bonding assembly.

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TABLE 8

THERMOELECTRIC MODULE PRODUCTION CHANGES DURING DEVELOPMENT

Component	Module Type								
	I	II	III	III G. R.	IVP	IV	V DEV	V P	V F
Upper Compensator Plating (in.)	Ni Plate Au Plate Cu Plating 0.0005- 0.0015 thick	Ni Plate Cu Plating 0.0015 thick	Ni Plate Cu Plating 0.0015 thick	Ni Plate Cu Plating 0.0015 thick	Ni Plate Cu Plating 0.0025 thick	Ni Plate Cu Plating 0.0025 thick	Ni Plate Cu Plating 0.0025 +0.0008, -0.0003	Ni Plate Cu Plating 0.0025 +0.0008, -0.0003	Ni Plate Cu Plating 0.0025 +0.0008, -0.0003
Radiator Emissivity Coating Black $\epsilon = 0.85 \text{ Cr}_2\text{O}_3$ White $\epsilon = 0.91 \text{ SnO}_2$ on spinel	Black	Black	Black or White	White	White	White	White	White	White
Radiator Thickness (in.)	Variable	Variable	Constant	Constant	Constant	Constant	Constant	Constant	Constant
Upper Shoe Plating (in.)	Ni Plate Cu Plating 0.0005 to 0.0015 thick	Ni Plate Cu Plating 0.0015 thick	Ni Plate Cu Plating 0.0015 thick		Ni Plate Cu Plating 0.0015 thick		Ni Plate Cu Plating 0.0025 +0.0008 -0.0003	Ni Plate Cu Plating 0.0025 +0.0008, -0.0003	Ni Plate Cu Plating 0.0025 +0.0008, -0.0003
SI GE Ratio	70 - 63 30 - 37	63 37	63 37	63 37	63 37	63 37	63 37	63 37	63 37
Lower Shoe Plating (in.)	Ni Plate Cu Plating 0.0005 to 0.0015 thick	Ni Plate Cu Plating 0.0005 to 0.0015 thick	Ni Plate Cu Plating 0.0005 to 0.0015 thick	0.0007 Ni Plate	0.0007 Ni Plate 0.0025 Cu Plate	0.0007 Ni Plate	0.0007 Ni Plate	0.0007 Ni Plate	0.0007 Ni Plate
Bonding Ring or Disc Dimensions (in.)	Disc 0.444 dia 0.005 thick	Disc 0.375 dia 0.005 thick	Disc 0.375 dia 0.005 thick	Ring 0.375 OD Various ID Various Thicknesses	Ring 0.375 OD 0.280 ID 0.030 thick	Ring 0.375 OD 0.280 ID 0.030 thick	Ring 0.375 OD 0.280 ID 0.030 thick	Ring 0.375 OD 0.280 ID 0.030 thick	Ring 0.375 OD 0.280 ID 0.030 thick
Lower Compensator Plating (in.)	Ni Plate Cu Plating 0.0003 all	Ni Plate Cu Plating 0.0003 or 0.0015	0.0001 Ni Plate Cu Plating 0.0015 thick	0.0005 Ni Plate	0.0005 Ni Plate	0.0005 Ni Plate	Top± 0.0005 Ni Bottom 0.0001 Ni 0.0015 Cu	Top 0.0005 Ni Bottom 0.0001 Ni 0.0015 Cu	Top 0.0005 Ni Bottom 0.0001 Ni 0.0015 Cu
Gemco Braze Alloy Lot Group	--	--	--	--	--	--	--	--	--
Hot Strap Au Foil Attachment	Wrap Around	Holes in hot strap for Au foil	Temporary hot strap cap	Riveted Au foil to hot strap	--	--	--	--	--

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Figure 9. Fabrication Sequence for SNAP 10A TE Modules

The radiator components were positioned and held in place by a molybdenum spring which exerted the required pressure for diffusion bonding. To facilitate bonding, the tungsten shoes and compensators are plated as listed in Table 9. To accomplish a satisfactory diffusion bond, this assembly was heated at 986°F for 1 hr in 3×10^{-5} mm of Hg vacuum.

2. Low-Emissivity Coating

The function of a low-emittance coating on the NaK tube and the hot strap was to prevent heat loss from these areas, thereby increasing the overall module efficiency, resulting in a higher power output for a constant NaK temperature. Two methods of incorporating the low-emissivity concept in the module fabrication sequence were studied: (1) Direct application of a low-emittance coating onto the NaK tube, and (2) Application of a low-emittance coating to a foil, which is in turn mechanically attached to the NaK tube and hot strap.

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TABLE 9
PLATING THICKNESSES OF DIFFUSION
BONDED TUNGSTEN COMPONENTS

Tungsten Component	1st Plating (Nickel) Thickness (in.)	2nd Plating (Copper) Thickness (in.)
Upper Compensator	0.0001	0.00025
Upper Shoe	0.0001	0.00025
Lower Shoe	0.0005	None
Lower Compensator	0.0001	0.0015

The direct coating process, consisting of an application of an enamel, ceramic, or metal followed by a gold emissivity layer, was not satisfactory. Three major difficulties developed.

1) Oxidation of the NaK tube occurred when adequate barrier adherence was obtained.

2) The coatings, particularly the enamels, spalled from the NaK tube and the hot strap.

3) The gold emissivity layer had poor adherence properties to the coatings.

The process was discarded in favor of the gold-coated foils.

Thin foils of copper and molybdenum and a thin sheet of mica were coated with Hanovia liquid Bright Gold and tested at 550°C. The results of the test indicated that gold on molybdenum foil and gold on mica were satisfactory. Due to the superior fabricability properties of molybdenum over mica, the gold on molybdenum system was given further study.

Life-testing of the gold-coated molybdenum foils for 4000 hr at 1022°F showed no visible degradation of the gold surface. Due to the favorable life test results and the minimal fabrication problems associated with the foil concept, this method was adopted for use on the modules.

The low-emissivity shields were formed by bending lips on the edges of the molybdenum strips in a jig. The strips are then rolled, inserted into an oxidized

stainless steel tube and heat set at 1000°C for 5 min in a hydrogen atmosphere. These shields were then snapped into place on the NaK tube. They were locked into position by welding clamp shields around the NaK tube between the copper hot straps. Figure 10 shows the exploded arrangement of the components. Similar pieces were developed for the top of the copper hot straps.

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Figure 10. Low Emissivity Shield for NaK Tube

3. High-Emissivity Coating

Early in the developmental stage of the SNAP 10A system, a program was initiated to develop a radiator control surface for the modules. A surface was desired which would reject internal heat and reflect solar input and operate efficiently at 600°F for 1 yr in a nuclear-space environment. In addition, it had to withstand the rigors of launch.

The initial design requirement for the radiator tailored coating was: $\epsilon = 0.85$ and $\alpha_s = 0.30$. Paints or enamels were not investigated because of their instabilities in nuclear radiation fields.

Additionally, primary emphasis was to be placed on utilization of two common inorganic binding agents, aluminum phosphate and potassium silicate.

Included in the several hundred coating systems investigated during this work were many of the basic metal oxides, with particular interest devoted to the white oxides. Screening tests were begun with an evaluation of the spectral reflectance and total normal emittance of candidate metallic oxides including the oxides of barium, cerium, antimony, silicon, tin, titanium, zinc, and zirconium. The results of this study showed that:

- 1) The thermal emittance at 600°F for coatings with the aluminum phosphate binder was consistently 3 to 5% higher than coatings with the potassium silicate binder.

2) The solar absorptance for coatings with the aluminum phosphate binder was consistently 10 to 20% higher than coatings with the potassium silicate binder.

3) The white pigment which exhibited the highest thermal emittance at 600°F was stannic oxide.

In that the optimum thermal effectiveness of the radiator coating was determined primarily by the thermal emittance, further coating development effort emphasized use of the stannic oxide pigment and an aluminum phosphate binder. Total hemispherical emittance measurements of the stannic oxide coating system yielded a value of $\epsilon = 0.88$ at 600°F.

The thermal emittance of a coating system of finite thickness is not a surface phenomenon, as markedly as is the property of solar absorptance, but is a bulk effect encompassing such parameters as coating thickness, porosity, and surface texture. An effort was made to further increase the emittance of the SnO_2 coating system by analyzing its spectral emittance (emittance vs wavelength) properties. It was noted that in the near infrared region (1 to 4μ) the emittance of the SnO_2 coating was depressed below 0.90.

Many black coatings have a high thermal emittance in this short wave-length region. Thus, to further increase the bulk emittance, a composite coating system was devised in an effort to maximize the spectral emittance throughout the infrared region. A high thermal emittance, black subcoat was used with the stannic oxide as a topcoat. The black subcoat was a mixture of the oxides of chromium, cobalt, and nickel. Total hemispherical emittance measurements of the two-layer composite coating yielded a value of $\epsilon = 0.91$ at 600°F.

A tailored coating, designated AI93, was selected for qualification testing; this testing yielded the following results:

1) AI93 on aluminum substrates resulted in a measured total hemispherical emittance of from 0.90 to 0.92 after 4900 hr at 600°F in a vacuum of 10^{-5} torr. A similar test for 2000 hr in a vacuum of 10^{-9} torr yielded a hemispherical emittance of 0.89 to 0.90.

2) An environmental qualification test was performed to determine the adherence qualities of the AI93 coating. The environment simulated that

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which would be experienced by the coating during the ascent of the vehicle. The AI93 was applied to 2- by 3-ft panels of aluminum. The ascent heatup rate for the aluminum panel was ambient to 770°F in 141 sec. Each panel underwent 10 cycles using these heatup rates. No damage to the coating occurred during the test.

3) The emittance coating successfully withstood mechanical vibration strain levels of 2072μ in. (approximately 62,000 psi stress) without apparent damage. The 2-min test at the first resonant mode (22 cps) resulted in over 2600 cycles of reversed loading on the coating material. Lesser strain levels occurred during the tests conducted at the second and third resonant modes.

4) Four AI93 tailored coating samples were irradiated to a neutron flux level of 3×10^{18} nvt. The maximum gamma exposure was 1.9×10^{10} r. During the irradiation test, the samples were maintained at 600°F, 10^{-5} torr, for 288 hr. The change in total hemispherical emittance of three of the AI93 samples was ~1%. The fourth AI93 sample experienced a change in emittance of 2%.

These data indicated that the AI93 coating was quite stable in the nuclear irradiation environment of the SNAP 10A system. Vacuum-temperature stability in these environments was also demonstrated.

5) The initial high-energy-particles bombardment test of the AI93 tailored coating was performed in the AI Statitron. Prior to the electron irradiation, the total hemispherical emittance of the coated specimen was 0.90. During the Statitron test, the coated specimen was maintained at 600°F and received an integrated electron dosage of 3×10^{18} , 1.25 Mev energy. After irradiation, visual examination of the specimen showed no damage to, or discoloration of, the coating. Emittance measurements were repeated. The emittance of the coated specimen was 0.88.

6) Atmospheric testing indicated a decrease in solar absorptance after 30 days. It was therefore necessary to protect the radiative surface from prolonged exposure of the system to the atmosphere prior to launch.

Based on these results, the reference design coating for the SNAP system high temperature radiators was AI93 ($\epsilon = 0.91$, $\alpha_s = 0.30$). The composite

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AI93 coating system consisted of a subcoat of chromium-cobalt-nickel spinel-bonded with aluminum phosphate, and a topcoat of stannic oxide bonded with aluminum phosphate.

The application of the high emissivity coating was performed in two steps. The radiator surface was sandblasted and the subcoat of chromium-cobalt-nickel spinel was sprayed on the surface. The subcoat was dried for 1 hr in air. The module was then baked for 15 min in an argon atmosphere. The tin oxide coat was sprayed on the subcoat surface and dried and baked in the same manner as the subcoat.

Application of this coating was the final process in the module fabrication sequence.

B. LEG FABRICATION

Although the 405-CRES stainless steel selected for the NaK tube was susceptible to martensite formation during the braze cycle, particularly in the welded joints between modules, the properties were not critically impaired and were recovered within the first few hours of operation. The effect of welding 405 CRES to 405 CRES could have been detrimental, however, since the material was rapidly cooled from the molten state and the bond had a martensitic region which had very low ductility. To restore the properties would have required an annealing at 1450°F with subsequent slow cooling. This was undesirable due to the low melting point components in the stacks.

The literature advised that acceptable welds could be made with 304 or 310 stainless steel inserts between the pieces of 405 SS being joined. A heat treatment was still required but the time at temperature was much lower and, with appropriate use of chill blocks, the temperature reaching the stacks was not detrimental.

A consumable insert ring of 310 SS was inserted between the adjoining 405 SS NaK tubes. The welds were then made using the TIG process. The post-welding heat treatment fixture is presented in Figure 11. Chill blocks were mechanically attached to the 405 SS tubing to prevent excessive heat from reaching the thermoelectric stacks. The heaters were placed in position around the weld zone, as illustrated, and the weld zone heated for 15 min at 1300°F. This procedure

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Figure 11. Post-Welding Heat Treatment Fixture for Leg Welds

restored the properties of the weld zone. During subsequent qualification tensile testing, no tensile failures were recorded in the weld zone.

The completed leg was mounted to the converter shell structure mechanically utilizing studs brazed to the individual modules. These studs were illustrated in Figure 1. The studs passed through an elongated hole in the structure with a Mykroy 1100 insulator between the stud face and the bracket. The insulator decreased thermal losses to the structure. The mounting was completed by placing a spring between the nut and the structure as shown in Figure 12. A torque of 16 in.-ounces was applied to the nut which was then tack-welded to the stud. Thus, the leg was held firmly in place on the support channel. However, with the elongated hole in the channel, the leg was free to move under the stresses arising from thermal expansion of the NaK tube at operating temperature. The system is designed so that this stud assembly slippage will occur well before the stresses are large enough to buckle the NaK tube.

Element, module, and leg interconnection posts were then stud welded to the radiators. The stud welding apparatus is shown in Figure 13. The location of the three types of interconnections is illustrated in Figure 14, which shows a completed leg ready for assembly on the converter shell.

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Figure 12. Leg Attachment to Converter Shell Structure

Figure 13. Stud Welding Apparatus for Attaching Element, Module, and Leg Electrical Interconnections Posts

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Figure 14. Location of Element, Module, and Leg Interconnection Posts

After each leg was mounted on the structure, the NaK tubes were welded to inlet and return manifolds using the same technique described for the welding of the modules into a leg.

After attaching the individual legs to the shell the electrical connections between elements, modules, and legs were completed. The posts from the element interconnects were bent 90° and welded together. To accomplish the module and leg interconnects, an aluminum strip with an expansion loop was welded into the slots of the interconnect parts.

The power connects to the converter were accomplished by stud welding slotted posts to the radiator in the same manner as the module interconnects. A terminal post assembly was positioned between the appropriate legs and an aluminum strip was welded in slots in the power connects and the terminal post assembly.

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The design of the connection is shown in Figure 15. In this design, the connector was a strip of 1/4 by 1/32-in. aluminum, spot-welded to the aluminum radiator and arc-welded to an aluminum terminal post. The terminal post was located between a set of parallel TE legs so that a connector could be attached to both legs for better reliability. The connector spanned the entire radiator width so that vertical vibration movement and differential thermal expansion resulted in a very small bending angle on the connector. The connector also had a 90° bend for lateral flexibility to minimize lateral loading on the TE pellet.

The terminal post consisted of two identical machined Mykroy insulators housing an aluminum terminal post mounted to the inside of the SNAP unit structure.

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Figure 15. SNAP 10A TE
Converter Power Con-
nector and Terminal
Layout

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IV. TEST PROGRAM AND RESULTS

A. DESCRIPTION OF MODULE TESTS

The basic objectives of the test program were to provide the performance information required for system design, qualify the modules for use in the expected system environment and provide sufficient test data to allow a high degree of confidence in the reliability of the converter and determine the operational limits of the module.

Three general test categories — acceptance, qualification, and developmental — were performed during the program.

1. Acceptance Test

The purpose of this testing was to ensure product uniformity and eliminate any modules which might include manufacturing defects. The initial acceptance test procedure consisted of, (1) physical, dimensional and electrical inspection; (2) shock and vibration to two-thirds of the qualification specification; (3) repeat of Item (1); (4) "warm" electrical and thermal test; and (5) repeat Item (1).

This test procedure depended on physical inspection and electrical resistance measurements to determine the integrity of the module; it was based on the theory that any cracks in the material or separation of the bonds during acceptance test would result in significant changes in the resistance of the module.

The warm performance test, during which the module was heated to 600°F in a vacuum and voltage output was measured, was used to evaluate the thermal resistance of the stack. As the program progressed, it became apparent that, because of the low electrical and thermal resistance of the metallurgical bonds, unbonded areas of less than about 90% could not be detected by this method and a static load test was therefore added to the procedure and the warm performance test was eliminated.

The static load test consisted of applying a 40-lb tensile load (about 80 times the maximum expected load during launch) between the tube and the radiator at every element in the module. This technique proved extremely effective in determining the integrity of the element bonds. The fact that no failures occurred

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during the 3 SNAP 10A system tests which utilize flight qualified modules indicates that the acceptance test successfully accomplished its purpose. The final acceptance test sequence used for all flight type modules is shown in Figure 16. Figures 17 to 20 show the acceptance test area and portions of the tests being conducted. During the acceptance testing of over 610 (14,640 elements) flight-type modules, the dimensional tolerances proved to be the only cause for rejection. This record is a tribute to the stringent process and quality control procedures developed by the module manufacturer.

2. Qualification Test

The qualification test was intended to demonstrate that the module would perform as required under the expected system operating and environmental conditions. Since the system conditions could not be firmly established, the qualification testing was accomplished at test levels at least 10% above the expected system conditions. The qualification test sequence for flight type modules shown in Figure 16 simulated the SNAP 10A acceptance test, launch, startup in space, and steady-state space operation. No failures occurred during the testing of over 45 flight type modules, resulting in an estimated converter reliability of greater than 0.996 at 50% confidence.

Two additional test sequences were added to the test program to rapidly provide useful information to the process and fabrication development effort. These sequences were designated the thermal mechanical acceptance test (TMA) and the accelerated qualification test. As shown in Figure 16, these tests utilized severe thermal cycle conditions and high temperatures to force failures and point out areas of weakness in the module. The accelerated test was primarily used to yield information on the electrical performance of the module and the thermomechanical acceptance test was used to evaluate the integrity of the module.

3. Developmental Tests

These tests were designed to obtain performance information at off-design conditions, determine the operating limits of the module, and qualify the module for expected environmental conditions not included in the standard qualification test. Table 10 summarizes the maximum test conditions to which the modules have been subjected.

Figure 16. Type V Module Test Sequences

Figure 17. Acceptance Test Area

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Figure 18. Measuring Resistivity During Module Acceptance Tests

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Figure 19. Microscopic Examination of Incoming Modules

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Figure 20. Static Load Test of TE Module

TABLE 10

MAXIMUM TEST CONDITIONS FOR SNAP 10A SiGe MODULES

Hot junction temperature	1300°F (1000 hr)
Thermal cycling	100 cycles at 15°/min
Static load	250 lb
Vibration	50 g at 4000 cps — 100 min
Nuclear radiation	1.2×10^{16} nvt
Vacuum	4.8×10^{-9} torr (at 1000°F)
Internal pressure	50 psi
Maximum module time at test temperature	31,000 hr

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An important phase of the test program was the extensive post-operative examination and failure analysis of the modules. The examination utilized metallurgical chemical microprobe and tensile testing techniques to determine not only the cause of failures but to characterize the bond systems and predict long life characteristics from relatively short time tests.

B. TEST EQUIPMENT AND INSTRUMENTATION

Thermal vacuum testing of modules was conducted in oil diffusion pumped vacuum systems in the pressure range of 1×10^{-3} to 1×10^{-6} mm Hg. Figure 21 shows the vacuum test stations and Figure 22 shows a typical thermal vacuum test setup. Vibration and shock testing was performed in the SNAP Dynamic Test Laboratory in Building 027 at Santa Susana. Figure 23 shows the basic instrumentation used to monitor module performance during the thermal vacuum tests.

The module load circuit consisted of a relay, a calibrated 1-mohm shunt and a variable resistance, all in series with the module. Voltage output was read directly from the ends of the module, thus eliminating voltage drop across the lead resistance. Voltage across the calibrated 1-mohm shunt was measured to determine current under load. The relay was opened by the automatic data logging system 0.62 sec before the emf open circuit voltage was sampled, then it was closed again after the reading was recorded. A mercury relay was used because it has low contact resistance and rapid response resulting in minimal temperature and emf changes from Peltier effects. Temperatures were sensed with 0.005-in. -diameter chromel-alumel thermocouples spot-welded to the NaK tube, lower tungsten shoe and upper tungsten shoe on selected elements (see Figure 24). Heat was supplied to each module by a radiant heater fabricated of Thermo-Coax (nichrome wire with compressed MgO insulation in an Inconel sheath) wire to fit inside the NaK tube (see Figure 25).

All voltage readings (module voltage, shunt voltage, thermocouple signals) were read and automatically printed on tape by a digital data system with a 2500-channel capacity. The data on the printed tapes were transcribed into Fortran language and reduced to engineering units by an IBM 7090 computer. This included least squares fit of the data into graphical form showing module resistance, emf and power vs time, respectively, for each module in test. The

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Figure 21. Thermal Vacuum Test Stations

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Figure 22. TE Modules Installed in Thermal-Vacuum Test Chamber

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Figure 23. Module Test Instrumentation

Figure 24. Module Assembly with Thermocouple Location

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Figure 25. Module Heater

The data were normalized to a fixed ΔT to eliminate fluctuations in module temperature.

Figure 26 shows the module data acquisition and reduction sequence. Figure 27 shows the typical curves obtained by this procedure.

C. MODULE TEST SUMMARY

During the SNAP 10A program over 1300 modules were fabricated, 720 modules were used in systems, and 389 were used in the module test program. The modules used in the test program represented stages in development of the final flight module. The intended use of the modules is shown below:

- 1) Types I and II modules were used for ground system tests and continuation of the original basic research and development.

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Figure 26. TE Performance
Data Reduction

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Figure 27. Typical Module Performance Curve

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2) The Type III modules were transitional from Type I and II to the Type IV modules and were used to provide information required to finalize the fabrication process.

3) Type IV and V modules were divided into three categories:

a) D modules were developmental with process changes incorporated during fabrication; they were to be used for individual (not in a system) module test.

b) P modules were preliminary, fabricated in accordance with the then-current flight module manufacturing process, and unchanged from module to module; they were to be used for test purposes to qualify the process and design of the flight module (again not tested in flight systems).

c) F modules were flight-qualified modules; they were to be used in either ground system tests or final flight systems.

Type of test and number of modules tested is shown in Figure 28 with the failure rates for each module type based on qualification test results shown in Figure 29, and the accumulated module test time is shown in Figure 20. A summary of the testing for each module type is discussed in the following section.

D. TYPES I, II, AND III MODULE DESCRIPTIONS AND TEST RESULTS

The thermoelectric stack assembly for these modules consisted of the components listed in Table 11 with their respective dimensions. The tests described below were performed on these modules.

1. Acceptance Test (All Modules)

The acceptance test consisted of:

1) Cold resistance measurements taken upon removal from the shipping container, after dimensional check, after shock and vibration testing, and after hot performance testing.

2) A dimensional check for conformance to specifications was made.

3) Shock and vibration tests were made to the following levels:

a) Shock Loads

Two 6-msec shocks in each direction along each axis of magnitudes: Normal ± 20 g, Lateral ± 20 g, and Longitudinal ± 20 g.

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Figure 28. Module Test Summary

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Figure 29. SNAP 10A Thermoelectric Element Failure Rate Experience

TABLE 11
COMPONENTS OF TE STACK ASSEMBLY FOR
TYPES I, II, AND III MODULES

Components	Material	Dimensions (Dia. and thickness)
Upper compensator	W	0.460 in. / 0.020 in.
Radiator	Al	0.020 in. + 0.060 in. (variable)
Upper shoe	W	0.460 in. / 0.020 in.
Element	SiGe	70/30 (%)
Lower shoe	W	0.046 in. / 0.020 in.
Diffusion disc	Au	0.444 in. / 0.005 in.
Lower compensator	W	0.470 in. / 0.020 in.
Hot strap	Cu	0.025 in.
Insulator	Al ₂ O ₃	0.470 in. / 0.020 in.
Equalizer	M _O	0.470 in. / 0.015 in.
Lower compensator disc	Cu	0.470 in. / 0.025 in.
NaK tube	405 SS	0.020 in.
Plating on element shoes	Cu	1.5 mils
Plating on upper compensator	Cu or Au	Au-0.5 mils - Cu 0.5
Radiator coating	Cr ₂ O	~0.5 mil

b) Vibration Loads

Vibration loads were applied along each of three mutually perpendicular axes. The loads along each axis consisted of a single sweep at a constant octave sweep rate proceeding from low to high frequency in 5 min. The level of loading was measured as close to the module mounting points as possible. The vibration levels used are shown below for all axes.

Peak Magnitude (g)	Frequency (cps)
1/8 in., 0 to peak	5 to 20
5	20 to 40
7.5	400 to 1500
15	1500 to 3000

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Figure 30. Qualification and System Testing of S10A Module

2. Qualification Test

The qualification test consisted of:

- 1) 100 hours at steady-state design temperature in a vacuum.
- 2) 10 thermal cycles between 200°F and design temperature in a vacuum.
- 3) 100 hours at steady-state design temperature in a vacuum.
- 4) Repeat of shock and vibration tests described above under acceptance test.
- 5) 650 hours at steady-state design temperature in a vacuum.

Several process changes were introduced during the fabrication of the Type II modules. The designations and their most significant differences are listed in Table 12.

The Type III modules were the same as the Type II except that the radiators had a constant thickness of 0.032 in., and the radiator emissivity coating was either Cr_2O_3 or Spinel-tin oxide.

The change in SiGe ratio was made to more closely match the thermal expansion of the SiGe alloy and the tungsten shoes. The gold bonding disc diameter

TABLE 12
PROCESS CHANGES INTRODUCED DURING
FABRICATION OF TYPE II MODULES

	Change	
	From	To
Si/Ge ratio (%)	70/30	67/33
Gold bonding disc diameter (in.)	0.444	0.375
Copper plating thickness on element shoes (mil)	0.5	1.5
Copper plating thickness on upper compensator (mil)	0.5	1.5

was reduced to lower the transmission of stresses from the NaK assembly to the SiGe element. Platings were thickened to increase the strength and life of the diffusion bonds at temperature.

3. Conclusions

Metallurgical analysis of the failed bonds on Types I, II, and III revealed the following:

- 1) The failure, in most instances, occurred between the gold disc and the tungsten shoe.
- 2) Heated elements all showed at least a partial separation or void formation starting at the outside edge of the gold disc and progressing inward through the bonded area.
- 3) Unheated elements did not show a void formation.
- 4) The failures occurred, specifically, in the copper electroplate or at the nickel-copper interface.
- 5) The void formation and separation was less severe in the bond between the gold and the diffused Cu-Ni alloy on the lower tungsten compensating pad.
- 6) In general, bonding was restricted to a peripheral band.
- 7) The strength of heated, but unfailed, elements was still high in most instances.

Table 13 is a summary of the failures of these modules during qualification testing. The failures occurred because of the net flow of copper atoms into the gold, which left vacancies that condensed to form voids in the copper. The voids may or may not have been interconnected, but they weakened the material, leaving the area susceptible to shear due to differential expansion.

TABLE 13
FAILURES DURING QUALIFICATION TESTING OF
TYPE I, II, AND III MODULES

Module Type	Number of Failures	Time to Failure (hr)	Portion of Qualification Test Causing Failure (Number of failures and location of failures)*	
			Vibration and Shock	Thermal Cycling
I	63	200-3000	12 W - Au 6 SiGe 19 W - Al 1 W - SiGe	16 W - Au 14 W - Al 1 SiGe 4 W upper compensator
II	41	200-3000	2 W - Au	20 W - Au 11 W upper compensator 2 W - Al 6 SiGe
III	11	200	5 W - Au	5 W - Au 1 W - Al

*See Figure 31 for key to location of failures.

E. TYPES IV AND V MODULE DESCRIPTIONS AND TEST RESULTS

1. Type IV

Failure analysis resulted in processing changes on Type IV and IVP (production) modules, and the changes in the specifications were made as shown in Table 14.

Figure 31. TE Module Cross-Section Showing Failure Location

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TABLE 14
PROCESS CHANGES INTRODUCED DURING FABRICATION
OF TYPES IV AND IVP MODULES

	Changed	
	From	To
Upper Compensator		
Cu plating thickness (in.)	0.0015	0.0025
Ni plating thickness (in.)	Flash	0.0001
Element Assembly		
Upper shoe		
Ni plating thickness (in.)	Flash	0.0001
Cu plating thickness (in.)	0.0015	0.0025
Gold Bonding Ring		
Shape	Disc	Ring
Inside diameter (in.)	None	0.280
Outside diameter (in.)	0.375	0.375
Thickness (in.)	0.005	0.030
Slot width (in.)	None	0.020
NaK Tube Assembly		
Lower Compensator		
Ni plating thickness (in.)	0.0001	0.0005
Cu plating thickness (in.)	0.0002	None
Final Bonding Schedule		
Time at temperature	15 min	1 hour
Temperature (°C)	550	530 to 540
Pressure	-	Equivalent to 0.008 to 0.010 in. deformation in Au ring

The gold ring was chosen to replace the gold disc to increase the force per unit area, which, together with the thicker material, results in increased deformation of the gold during bonding. The increased deformation produces more intimate contact between the gold and nickel.

At this time a number of modifications were made for acceptance and qualification testing of the Type IV and IVP modules. The revised test sequences are described below.

a. Acceptance Tests

The acceptance tests included:

- 1) Dimensional and visual inspection including microscopic examination for element cracks.
- 2) Module resistance check consisting of
 - a) Individual element resistance
 - b) Overall module resistance
 - c) Resistance between NaK tube and radiator.
- 3) Warm electrical test (to 600°F in vacuum)
- 4) Overall module resistance check. If overall module resistance varied by more than $\pm 1\%$ of the value recorded in (2) above, individual element resistances were taken.
- 5) Vibration at 2/3 qualification level for 5 minutes
- 6) Repeat of (4) above
- 7) Visual inspection including microscopic inspection for element cracks
- 8) Static load test (40-lb load)
- 9) Repeat (4) above plus measurement of resistance between radiator and NaK tube
- 10) Repeat of (7) above.

b. Qualification Tests

The qualification tests included:

- 1) Steady-state performance at a pressure of less than 1×10^{-3} torr at design temperatures for 100 hr
- 2) Ten thermal cycles between design temperature and 200°F (2.4 hr/cycle) at same pressure as step (1)
- 3) Steady-state performance test at same conditions as step (1)
- 4) Shock and vibration at ambient temperature and pressure to the following levels:

a) Application of vibration loads along each of three mutually perpendicular axes. The loads along each axis consisted of a single sweep rate proceeding from low to high frequency in 25 minutes. The level of loading was measured as an input to the fixture as close to the module mounting points as practical.

<u>Peak Magnitude</u>	<u>Frequency</u>
1/8 in. 0 to peak	5 to 20
5	20 to 400
7.5	400 to 3000

b) The modules were subjected to two 6-msec shocks in each direction along each axis of the following magnitudes:

Normal	±20 g
Lateral	±20 g
Longitudinal	±20 g

5) Steady-state performance for a minimum of 1000 hr and a maximum of 3000 hr as specified in (1) above.

6) Tensile tests and metallographic examination of selected elements.

Module voltage, current, resistance, and temperatures are measured periodically at design temperatures during steps 1, 2, 3, and 5.

In addition to the qualification tests described above, 12 Type IVP modules were subjected to tests designed to evaluate performance characteristics and force failures, and to more quickly determine the ultimate strength of the braze joint, as well as the integrity. The tests consisted primarily of thermal cycling the module followed by the application of some tensile load, applied either with the acceptance test static load device or a tensile test machine. Although there was some variation in the heating and cooling rates used, the cycle was in all cases more severe than that encountered in the qualification tests. These tests formed the basis for the thermal-mechanical acceptance test (TMA) and accelerated test sequences used on the flight modules.

The results of the test program indicated that the only weakness was at the braze joint between the tungsten compensator and copper hot strap and that

this joint was subject to deterioration during thermal cycling but not sensitive to time at steady-state temperature.

2. Type V

a. Fabrication changes

To ensure the thermal cycling capability of the modules, the process shown in Table 15 was used in the fabrication of the bond for use in Type V Dev. (developmental), Type VP (production), and Type VF (flight) modules.

TABLE 15
PROCESS CHANGES INTRODUCED IN FABRICATION
OF TYPES V DEV. VP, AND VF MODULES

1. Plating — Lower Tungsten Compensator	
Nickel plate on diffusion bond side (mil)	0.5
Nickel plate on braze side (mil)	0.1
Copper plate on braze side (mil)	1.5
2. Braze Conditions	
Braze temperature (°F)	1875 to 1895
Rise time	
Room temperature to braze temperature (min)	5 to 9
960°C to braze temperature (min)	3.5
Time at braze temperature (min)	5.0
3. Gemco Composition	
Germanium (%)	11.8 to 12.0
Nickel (%)	0.2 to 0.3
Phosphorous (%)	0.04 to 0.08
Silicon (%)	0.005 to 0.10
Copper	balance

The test sequence which evolved during testing of earlier modules is shown in Figure 16. This is the sequence used for the Type V modules which were used in the SNAP 10A flight system. The TMA test was also performed on the Type V modules.

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b. TMA Tests

The TMA test was a destructive test designed to give an early indication of weakness in braze joints or diffusion bonds.

Twenty Type V Dev. modules, 14 Type VP modules, and 31 Type VF modules were designated for the TMA tests. The modules were cut in half, and the first and last elements from each half were removed and used in metallography. The remainder of these two sections were tested, 1/2 section for each sequence of the TMA test. The two sequences were as follows:

1) Long Sequence

- a) 100 hours steady state at a hot shoe temperature of 1100°F
- b) 50 thermal shocks at a cooling rate of 900°F/30 min and a heating rate of 900°F/10 min from 1100 to 200 to 1100°F
- c) 50 hours steady state at a hot shoe temperature of 1100°F
- d) Static loading of each element from 0 to 100 lb
- e) Tensile testing to failure.

2) Short Sequence

When the hot shoe temperature of 1100°F was reached, steps b, d, and e of the long sequence were repeated.

A test program to determine the effect on the strength of the module as a result of variations in gold ring depression showed that satisfactory strength could be achieved with a depression of 0.006 in. instead of the previously specified 0.008 in. As a result, the specification for the gap between the lower shoe and the compensator was changed from 0.022 to 0.024 in.

On the Type V Dev modules there were seven tungsten to gold diffusion bond separations on three modules during the thermal cycling of the short sequence.

Investigation revealed a large backlog of P elements which led to a longer than normal storage period between nickel plating of the element shoe and the final bonding. These failures were attributed to oxidation of the nickel plate before final bonding. A cleaning process was added to the fabrication procedure to eliminate this possibility in flight modules.

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Types VP and VF went through all of the TMA test phases up to static load without any failures.

Results of the TMA tests, Table 16, demonstrate the reliability of the braze joints.

TABLE 16
SUMMARY OF THERMAL ACCEPTANCE TEST,
TYPES V DEV., VP, AND VF MODULES

Test Sequence	Module Type	Steady State Operation (100 hr at 1100°F)		50 Thermal Cycles		Steady State Operation (50 hr at 1100°F)		Static Load (100 lb)		Tensile Test Load Range (lb)
		MF/MT	EF/ET	MF/MT	EF/ET	MF/MT	EF/ET	EF/ET	MT/ET	
Long Sequence	VD	0/20	0/194	0/20	0/194	0/20	0/194	14/191	20/154	11-340
	VP	0/14	0/150	0/14	0/150	0/14	0/150	16/150	14/107	45-350
	VF	0/31	0/314	0/31	0/314	0/31	0/314	18/60	31/245	125-575
Short Sequence	VD	No test		3/20	7/193	No test		25/186	20/135	60-323
	VP	No test		0/14	0/150	No test		17/150	14/111	75-450
	VF	No test		0/31	0/314	No test		20/60	31/243	40-575

MF - Modules failed
MT - Modules tested
EF - Elements failed
ET - Elements tested

c. Static Load Testing of Type VF Modules

After 18 Type VF modules were static-loaded, it was decided to delete this phase of the testing because of the uneven loading of the static loading device.

d. Accelerated Tests

This test was designed to more quickly evaluate performance characteristics of modules and module integrity than possible with qualification tests.

Eighteen Type VP modules were subjected to the sequence listed below.

- 1) Steady-state operation for 100 hr at a hot shoe temperature 110% above design temperature.
- 2) Fifty thermal cycles from zero to full power then returned to zero power at the rate of 30°F per minute.
- 3) Steady-state operation for 8 hr as specified in (1) above.
- 4) Static load test to 100 lb.

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- 5) Tensile test.
- 6) Metallography.

No failures occurred during the thermal-vacuum tests. Test results are shown in Table 17.

TABLE 17
VP MODULE ACCELERATED TEST RESULTS

Steady State 100 hours (1060-1120°F)		50 Thermal Cycles (30°F/min)		Steady State 118 hr (1060-1120°F)		Static Load (100 lb)		Tensile Test	
MF/MT	EF/ET	MF/MT	EF/ET	MF/MT	EF/ET	MF/MT	EF/ET	MT/ET	Load Range (lb)
0/18	0/416	0/16	0/376	0/16	0/376	11/18	22/416	15/157	60-360

MF - Modules failed
MT - Modules tested
EF - Elements failed
ET - Elements tested

The accelerated tests subjected the modules to thermal cycling conditions, temperatures, and static loads in excess of those expected during the flight test. The ability of the modules to withstand this test sequence without failure confirmed the integrity of the bonds and indicated that the Type V modules would meet the requirements of the flight system. Table 18 is a summary of the failures during qualification testing of Type IVP and VP modules.

F. POST OPERATIVE TESTING

1. Metallographic Examinations

The characteristics of the individual bonds which are most susceptible to failure during life testing were discussed in detail elsewhere.⁽⁸⁾ Since that report, life data up to 20,000 hours has been accumulated on similar test modules. The present report updates the knowledge of the character of those bonds. To better visualize the location of the bond areas, a panoramic view of the lower portion of a stack is presented in Figure 32. This stack is from Module X1314-5 which accumulated 15,897 hours at an average hot strap temperature of 970°F with 11 thermal cycles. Figure 33 is a panoramic view of the upper portion of the same stack. Both views are at 200X.

TABLE 18
 FAILURES DURING QUALIFICATION TESTING OF TYPE IVP AND VP
 MODULES

Module Type	Number of Failures	Time to Failure (hours)	Portion of Qualification Test Causing Failure (Number of failures and location of failures)*	
			Vibration and Shock	Thermal Cycling
IVP	16	4700 → 20,280	9 W-W	4 W-Cu 1 SiGe 1 W upper comp. 1 W-SiGe
	9	8670 → 18,820	None	2 W-SiGe 7 W-Al
VF	22	2250	None	1 W-Al
		10,593	None	2 W-Al
		10,606	None	3 SiGe
		10,606	None	2 W-Al
		10,845	None	3 SiGe
		10,845	None	4 W-Al
		10,845	None	5 W-Al
		6223	None	1 SiGe
		6700	None	1 W-Al

*See Figure 31 for key to location of failures.

a. Alumina Bond

Penetration into the molybdenum equalizer by the braze material (Nioro) is evident in all modules with more than 15,000 hours (Types B and C). The penetration increases with time and with temperature of operation. The appearance of the microstructure in the penetrated areas is similar to the visual effects observed in higher temperature (1100 and 1200°F average hot strap) testing of similar modules. The penetration has not affected the strength of the bond significantly. Tensile data presented in Section IV-F-2 (below) illustrates this point. The visual character of the bond has not changed other than in the manner just described.

Figure 32. Panoramic View of
Lower Stack After 15,897 hr at
an Average Hot-Strap
Temperature of 970°F

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SiGe

TUNGSTEN COLD SHOE

AI-Cu BOND

ALUMINUM

TUNGSTEN

200X

Figure 33. Panoramic View of Radiator Bond Area After 15,897 hr at an Average Hot-Strap Temperature of 970°F (Average radiator temperature - 644°F)

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b. Gold Ring Bond

Past investigations^(8,9) have shown the bond to be subject to temporary embrittlement when the phase WNi_4 forms in the 0.005-in. nickel plate. The formation of the phase is time-dependent due to the rate of diffusion of tungsten into nickel. The formation of the phase is also dependent on the mass of nickel present since, for thinner platings of nickel (<0.003-in. thick), it was shown that the interdiffusion of nickel and gold was fast enough to lower the amount of nickel to the level where the available nickel was insufficient to alloy with tungsten to form WNi_4 . The embrittlement was found to be temporary since, even after the phase forms, continued diffusion of nickel and tungsten into gold lowers the amounts of each of these elements in the bond until the phase disappears and the strength of the bond improves to former levels.

There are visual and mechanical indications that this embrittlement area has started in the qualification modules. Three tensile test failures were observed at this bond for the first time on modules with extended times at temperature (see Figure 38). The strength of the bond has not as yet become as detrimental to the life of the stack as the radiator bond, however, since the average failure load is still better than the radiator bond and as good as N-type SiGe. As long as 0.005-in. -thick nickel platings are used, significant deterioration in strength can be expected at times greater than 20,000 hours for a bond of this type at qualification temperatures.

c. Tungsten-SiGe Shoe Bond

The tungsten shoes are diffusion-bonded to the SiGe elements at 1472°F for 30 minutes. The bond formed is between tungsten and silicon. This leaves a silicon-depleted region in the element near the shoe, as shown in Figure 34.

During the metallographic examination of the 16,000- to 20,000-hour specimens, a phase, Figure 35, was discovered at the WSi_2 -SiGe element interface. This phase was examined with the electron microprobe. It is primarily a germanium and arsenic alloy. A study of N elements showed that this phase is present in lesser amounts in as-fabricated stacks. It is associated with thick WSi_2 layers. The assumption is made that the phase is a result of the bonding process. The amount of phase present evidently increases with time at operating temperature.

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Figure 34. Module X1012-6 As-Fabricated N-Type Specimen Shoe Bond

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Figure 35. Module X1499-3. 15,869 hr at 1000°F
Average Hot-Strap Temperature.
Note Phase at W etc.

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In general, the bond appears in very good condition with the exception of some longitudinal cracking across the interface of the bond. This cracking extends into the SiGe and probably enhances failure in the SiGe in the proximity of the shoe. Void formation in the bond area was not significantly dangerous.

d. Radiator Bond

The depletion rate of copper is critical at this bond region. As the copper is consumed, aluminum joins with the nickel plate and copper to form a Cu-Ni-Al alloy which is very brittle. However, even with the formation of the phase, the strength of the bond is not significantly lowered to endanger the life of the stack as long as the phase is embedded in copper.

Figure 36 shows the depletion rates of copper for the Types A, B, and C modules. It shows that all of the module types should have no copper remaining after 15,000 hours.

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Figure 36. Depletion of Copper as a Function of Time for the Type A, B, and C Module Radiator Temperature

Examination of Types B and C modules with 15,000 to 19,000 hours of life showed that, in practically every case examined, the copper had not been completely consumed. In some cases as much as 0.001 in. of copper remained. However, in all cases sufficient aluminum had penetrated the copper to allow formation of the brittle phase.

The reason for the inhibited copper depletion rate is not known; however it is undoubtedly responsible for the higher-than-expected strength of the bonds observed on the long-life specimens.

2. Tensile Testing

A comprehensive tensile testing program during the qualification testing of the VP and VF modules yielded significant results.

The tensile test was accomplished by bonding a threaded stud to the upper compensator with Eastman 910 cement and restraining the NaK tube in a special fixture. The load was applied at a uniform rate in an Instron test machine. Due to the crude fixtures involved and the uniqueness of the specimen, the data was interpreted in a relative manner. At the outset, an applied load of 200 lb was considered as a minimum strength goal. The significance of this goal varied depending on the failure location. For instance, the W-Au bond has a higher stress rating at 200 lb than the W-Cu bond due to its lower bond area.

As mentioned previously, the prime purpose of the tensile test was to provide relative strength information within the stack by pointing out the weakest bonds and/or materials. These then could be improved to upgrade the overall strength of the stack. Figure 37 presents these results in graphical form. Each module type A (1030°F, B (1000°C), or C (970°F) has been separated into three time categories: 0 to 5000 hr, 5001 to 11,000 hr, and >11,000 hr. The frequency of failures has been plotted at 25-lb load intervals. The bar graph representation (Figure 38) of the failures at particular joints shows the number of failures experienced, and the high, low, and average load obtained for each category.

For all operating temperatures, average strength of the Mo-alumina bond increased with time at temperature up to 15,000 hours. This increase in strength reflected the loss of the laminated structure of the molybdenum. However, there was some strength and bond structural deterioration of the molybdenum at very

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Figure 37. Results of Tensile Testing Type VP and VF Qualification Test Modules

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Figure 38. Location of Tensile Test Failures of Type VP VF Qualification Test Modules

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long times (16,000 to 20,000 hours) at 1000°F. The observed microstructure was similar to that observed at higher temperature testing⁽⁹⁾ where the braze penetrated into the molybdenum. The deterioration was observed in the tensile data by the decrease in the value of the average strength at >11,000 hours (1000°F) and by the increased spread between the low value of strength for this group and the average value. The deterioration of this bond was not observable in the 1030°F data since these very long times (15,000 hours) were not achieved.

Over the life of a module, the N-type SiGe elements remained one of the weaker areas of the system. These elements generally deteriorated with time at temperature. They did not deteriorate catastrophically, as did the radiator bond, but rather declined from a peak average strength of 320 lb (0 to 5000 hr at 1000°F) to the 200 lb at long times at all temperatures of operation.

The P element remained as one of the strongest areas during life testing of the areas where failure was observed.

The radiator bond was a source of occasional failure during qualification testing of the modules. The first appearance of failures was noticed at times >11,000 hours at 1000°F (669°F radiator temperature) or in the range of 5000 to 11,000 hours at 1030°F (696°F radiator temperature).

The mechanism of failure at this bond region was associated with the formation of a brittle copper-aluminum-nickel phase which formed near the tungsten interface after depletion of the copper plate.⁽⁸⁾ Stress application was a critical factor in the failure. Since the failures occurred only during a thermalcycle or thermal shock, it was believed that application of stress to the brittle phase was necessary for failure. Thus, formation of the phase at operating temperature was not in itself detrimental to the life of the stack under steady-state temperature operation.

Another factor, as yet little understood and not thoroughly documented, appeared to extend the life of this bond. There were instances when the depletion of the copper plate is in some manner inhibited, and formation of the critical phase was delayed beyond the calculated time. This delay was probably the primary reason for the higher-than-expected strength of this bond, occasionally observed during extended life testing.

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The three failures at the W-Au interface were probably associated with the formation of WNi_4 .⁽⁸⁾ This was an interim phase in that it was stable only as long as there was sufficient nickel present. It disappeared as the nickel was dissolved by the gold. The formation of the phase was time- and temperature-dependent in that tungsten must diffuse into the nickel. Thus, during life testing, the bond experiences a brittle period that is "self-healing." For a more complete explanation of this phenomena, see Reference 8.

3. Resistance Change

The percent change in resistance of N elements for extended life-testing at temperature is presented in Figures 39 through 41. The data for P elements are not presented since the change was minor (<3%) over similar periods of time. The change was computed from 200-hr operation data and final life-testing data. The 200-hr period was chosen since repeatability of measurements occurs at that point. There was significant resistance degradation prior to this time, but individual elements did not behave in a comparable fashion until this early degradation had occurred. The temperature of operation in this range (970 to 1030°F average hot strap) had little effect on the degradation curve. The degradation for all three types of modules seemed to reach the 20% level at or near 2000 hr of test. The degradation peaked out at 45% at all temperatures. It should be remembered that this was 45% relative to the resistance value after 200 hr of steady-state operation at temperature.

The prime cause of resistance degradation in the N elements was the precipitation of dopant (arsenic) from the lattice of the SiGe element. Other degradation, such as increased resistance due to cracks and void precipitation at bond areas, was small compared to the dopant precipitation, as illustrated by the low degradation observed in the P elements.

4. Summary of Post Testing Analyses

The results of the post testing investigation and analyses have shown that the SNAP 10A converter system can attain the objective of one-year operation at design temperature, 937°F average NaK, in a space environment without a stack failure. The accelerated qualification test demonstrated that the modules will successfully operate at hot-strap temperatures up to 1000°F for more than 10,000 hours with occasional thermal cycles without failure. At temperatures

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Figure 39. Resistance Change with Time at Temperature of N-Type SiGe (970°F)

Figure 40. Resistance Change with Time at Temperature of N-Type SiGe (1000°F)

Figure 41. Resistance Change with Time at Temperature of N-Type SiGe (1030°F)

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in excess of 1000°F, failures at the radiator bond and in the thermoelectric element occurred at or near 1-year life and generally during a thermal cycle. Test information, furthermore, leads to the prediction that the expected life of the 500-watt module can be extended to 2 yr at 937°F average hot strap temperature.

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module and system tests. For comparison with system data performance properties of the SiGe couple from the module tests were arithmetically averaged at points of equal operating time and a line was drawn through the resulting data points. Although an analytical method of fitting the data points for best accuracy was not applied, the scatter in data points was small so that a line could be drawn through the points with good accuracy. The only significant scatter occurred in module data taken in the first 800 hr of operation.

An appreciable reduction in converter power output during the FSM-4 system test was caused by a decrease in the isolation resistance between the converter and system ground. During this test an increase in resistance to ground was effected by admitting air into the vacuum test chamber. Periodic injections of air into the test chamber raised the isolation resistance to satisfactory levels, but frequent drops in resistance below 30 ohms caused many fluctuations in electrical performance. Consequently, plots of FSM-4 converter data show considerable scatter.

Performance data for the Type VF modules and for three system tests are shown in Figure 42. Seebeck coefficient, electrical resistance (R) and matched load power output normalized to unit thermoelectric ΔT squared ($P_m/\Delta T^2$) on a per couple basis are shown as a function of operating time. The parameter $P_m/\Delta T^2$ was calculated using the Seebeck coefficient and electrical resistance. The relationship is:

$$\frac{P_m}{\Delta T^2} = \frac{s^2}{4R} \cdot$$

The parameter $P_m/\Delta T^2$ is important because it determines the degradation in power output caused by changes in Seebeck coefficient and electrical resistance of the thermoelectric couple. A power degradation of approximately 9.5% during 1 yr of operation is obtained from the module data in Figure 42.

A difference in operating temperature between module and system tests was largely responsible for the higher Seebeck coefficient and resistance obtained from module tests. In the FS-3 test, converter average NaK temperature continuously decreased with operating time. Property curves for SiGe showed a

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Figure 42. Module and Converter Performance Data

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reduction in Seebeck coefficient and electrical resistance with lowering temperature. The temperature effect is evident in Figure 42 as it is seen that the rate of increase in Seebeck and resistance with time for FS-3 was not as great as for the module. The parameter $P_m/\Delta T^2$ was unaffected because it had very little temperature dependence.

In the FSM-4 data, the noticeable drop in Seebeck coefficient and resistance points near 250 and 1100 hr of operation was attributed to the low resistance-to-ground problem. The resistance-to-ground degraded to approximately 6 ohms near the 250 hr point and to approximately 20 ohms near the 1100 hr point. As the resistance-to-ground decreased below 30 ohms, converter open and closed circuit voltages also decreased.

Figures 43 and 44 show the average ΔT across the SiGe couple and matched load power output, both normalized to a constant 920°F average NaK temperature for the three systems. This normalization eliminated the effect of changes in NaK temperature on the ΔT and power output. Normalized power output provides a measure of power degradation resulting from a combination of property changes in the SiGe couple and changes in the ΔT across the element with time. In all systems, there is an initial decay in the normalized ΔT across the SiGe couple which produces a high initial degradation in power output. The initial reduction in normalized ΔT is a result of increased shunt heat losses to the backside of the radiator as system components approach their equilibrium temperatures. Once the system attains equilibrium or near equilibrium temperatures, the normalized ΔT is stable.

The space heat sink effect was responsible for the higher normalized power output and ΔT in the FS-4 system.

Figures 43 and 44 show overall, Carnot, and device efficiency for the converter assembly in the three systems. Overall converter efficiency is the ratio of converter power output to converter heat input. Heat input to the converter is defined as reactor thermal power less heat input to the NaK pump and less losses from supply lines, reactor support legs and the upper torque box. The Carnot efficiency in Figures 43 and 44 is based on converter average NaK temperature and average radiator temperature. Converter device efficiency is defined as the product of material conversion efficiency and converter transmission efficiency. It is found by dividing overall efficiency by Carnot efficiency.

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Figure 43. SNAP 10A Thermoelectric Converter Data
(Average TE ΔT and matched load power normalized
to 920 $^{\circ}$ F average NaK)

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Figure 44. SNAP 10A Thermoelectric Converter Data
(Carnot, device, and overall efficiency)

The space heat sink effect accounted for the higher overall converter efficiency indicated. Device efficiency and overall efficiency of the FSM-4 converter were noticeably low. The very low points in the efficiency were found to correspond to a low resistance-to-ground. Also, changes in the efficiency with operating time were found to follow changes in the resistance-to-ground. Also noted in the FSM-4 test data, near the end of the test, was a gradual increase in the temperature on some components while the converter average temperature remained constant, indicating an increase in converter heat losses and hence, a decrease in converter efficiency. Higher heat losses resulting from changes in the emissivity of radiating surfaces due to the presence of air in the FSM-4 test chamber is very likely.

Calculated shunt heat and leakage heat loss efficiency components of the transmission efficiency are shown in Figures 45 and 46 for systems FSM-4 and FS-3. Converter heat losses could not be determined for the FS-4 system because instrumentation was limited in the flight test. Shunt and leakage heat losses were obtained from heat balance calculations in which constant surface emissivities were assumed. This assumption was necessary since surface emissivities were not monitored. Figures 45 and 46 show very little change in heat loss efficiencies with operating time, once the system components attained equilibrium or near equilibrium temperature.

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Figure 45. SNAP 10A TE Data
(Shunt heat loss efficiency)

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Figure 46. SNAP 10A TE Data
(Leakage heat loss efficiency)

The shunt heat loss efficiency is the ratio of heat absorbed at the SiGe hot junction to the sum of the heat absorbed at the hot junction and the heat absorbed at the back side of the radiator. The leakage heat loss efficiency is the ratio of heat absorbed at the SiGe hot junction and radiator backside to the total heat input to the converter. Thus, the product of shunt heat and leakage heat loss efficiencies is the fraction of the total heat input to the converter that is available to the thermoelectric material for power production.

To allow comparison of the ground test data with the data obtained from the flight test an analysis was conducted to adjust the power from FS-3 to the test conditions of the FS-4. The results of this analysis are shown in the upper curves of Figure 47. The adjustments which were made in FS-3 power included:

- 1) Adjustment to FS-4 matched load power output for power output at 29.4 v
- 2) Adjustment for FS-3 chamber wall emittance
- 3) Adjustment for 125°F FS-3 chamber temperature to 0°F space temperature
- 4) Adjustment for FS-4 reactor average temperature.

As shown in Figure 48, when these adjustments were made excellent agreement between the FS-3 and FS-4 data was attained.

The space heat sink effect accounts for the higher normalized power output and ΔT in the FS-4 system.

The FS-3 system was operated for a period of over 1 yr in a simulated space (low pressure) environment. From the time the reactor controller was turned off (3 days) until 1 yr, converter power output (normalized to constant reactor outlet temperature) degraded 9.5%. Based on data obtained from FS-4 the same type of degradation could be expected from other flight systems.

The observed power degradation was due almost entirely to the increase in resistance of the N type element. Table 19 shows the change in the FS-3 converter resistance after 1 yr, as well as the change in resistance and thermal conductivity of the N and P element for the same period of time obtained from modules operated under similar temperature conditions.

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Figure 47. FS-3 Power Adjustments to FS-4 Test Conditions

Figure 48. Comparison of FS-3 and FS-4 Power Output During Passive Control Period

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TABLE 19
FS-3 THERMOELECTRIC CONVERTER PERFORMANCE

FS-3			Based on Module Data			
Time (yr)	Relative Power Out	Resistance (ohms)	Resistance (ohms)		Thermal Conductivity (watts/cm-°C)	
			N-Type	P-Type	N-Type	P-Type
0	1.0	1.575	1.065	0.51	0.0415	0.0487
1	0.905	1.940	1.43	0.51	0.0415	0.0487

The increase in the resistance of the arsenic doped N element occurred because, to obtain the carrier concentration necessary for optimum thermoelectric properties, the arsenic in the SiGe alloy must be in a supersaturated condition. Under the SNAP 10A temperature conditions this is an unstable situation and results in the loss of carriers in the lattice structure and increase in both the Seebeck coefficient and resistivity of the N element. Since the power output of the converter is proportional to S^2/ρ the fact that the Seebeck coefficient is increasing compensates for the resistivity increase.

It can be shown analytically that the power output is proportional to the figure of merit, i. e.,

$$P_o \sim \frac{(|S_N| + |S_P|)^2}{\left(\rho_N \frac{\ell_N}{A_N} + \rho_P \frac{\ell_P}{A_P}\right) \left(k_N \frac{A_N}{\ell_N} + k_P \frac{A_P}{\ell_P}\right)},$$

and that for equal length elements an optimum ratio of N to P cross sectional areas which maximizes the power exists. As shown in Figure 49, for SNAP 10A conditions an area ratio of 1.51 results in maximum initial power. The figure also shows that the SNAP 10A design with equal size elements results in a 5% loss in initial power.

Increases in the resistance of the N element cause a further departure from the optimum ratio and contribute to the observed degradation. Figure 50 shows the effect on FS-3 degradation as a function of the area ratio: with the optimum design the FS-3 degradation would be less than 6% in 1 yr.

Figure 49. Effect of Element Area Ratio on
Converter Performance
(Converter power relative to initial FS-3)

Figure 50. Effect of Element Area Ratio on
Converter Performance
(% converter degradation)

H. FS-4 ISOLATION RESISTANCE

During the flight test the resistance to ground was determined by measurement of the leakage current from the converter to ground with the use of a differential current transducer. The telemetry data indicated a continuous linear increase in leakage current beginning about 25 days after reaching full power. The leakage was interrupted as a decrease in resistance to ground and a resultant power loss as shown in Figure 51.

The observed increase in leakage current was probably due to degradation of the exposed converter insulators. The converter was isolated electrically from the NaK tube by means of a 0.020-in.-thick alumina insulator at each of the 2880 TE elements. The converter isolation resistance was therefore dependent on the parallel resistance of 2880 alumina insulators, all of which are exposed to the system environment. The behavior of the flight system isolation resistance was very similar to that observed during ground testing of individual modules and test systems. During ground testing of FSM-4 and FS-4 it was noted that the isolation resistance at operating temperature decreased to values below 100 ohms in a few hours. Measurements made on these systems established that the reduction in isolation resistance was due to the degradation of the individual alumina insulators which had changed from an initial average resistance of approximately 10^8 ohms to less than 3×10^5 ohms during operation.

During ground testing of the FS-4 system the converter was exposed to oxygen so as to restore the isolation resistance. This treatment increased the isolation resistance from about 150 to 6000 ohms. The data obtained from the flight test were not meaningful for values above 200 to 300 ohms. However, if it is assumed that the initial resistance of the FS-4 in space was 6000 ohms, it appears that a delay of about 400 hr occurred prior to the start of the degradation as shown in Figure 52. As shown in Figure 53 this behavior is consistent with observations made in module tests where the modules had been exposed to oxygen.

From the results of ground testing and the fact that the resistance degradation curve for the flight system was similar to that obtained on module tests it must be concluded that the degradation of the FS-4 isolation resistance during the flight was due to degradation of the individual alumina insulators and not to a single point type short elsewhere in the system.

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Figure 51. FS-4 Flight Converter Performance

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Figure 52. Fit of Carbon Film Theory to FS-4 Data

Figure 53. Comparison of Module Test Data with FS-4 Isolation Resistance Behavior

1. Insulator Degradation Mechanism

a. Metallic Deposit

The possibility that degradation observed on ground tests was due to the deposit of metallic materials or to the growth metallic whiskers has been eliminated by a series of tests in which degraded insulators were treated with chemicals which are known to attack metals. The results of this test are summarized in Table 20. It can be seen that none of the insulators degraded under normal test conditions was affected by the chemical treatment, but that exposure to air resulted in an increase in resistance. This behavior is what might be expected if the deposit were carbonaceous. It is also interesting to note that the insulator which was deliberately coated with a metal, iron, was restored to its initial value by chemical treatment.

TABLE 20
EFFECT OF CHEMICAL TREATMENT ON INSULATOR RESISTANCE

Treatment Sequence	Sample 1 Resistance (ohms) (As received ins)	Sample 2 Resistance (ohms) (Degraded ins)	Sample 3 Resistance (ohms) (100 Å Fe)
None	2×10^{11} (Initial Res)	1.4×10^3 (Initial Res)	
H ₂ (1 atm)	2×10^{10}	0.94×10^3	
HCl	$>2 \times 10^{11}$	2.0×10^3	
H ₂ SO ₄	$>2 \times 10^{11}$	2.0×10^3	
NaOH	$>2 \times 10^{11}$	2.0×10^3	
HF	$>2 \times 10^{11}$	1.5×10^3	
Air	$>2 \times 10^{11}$	3.5×10^6	
None	-	-	18×10^3
HCl	-	-	1×10^{10}

b. Carbonaceous Deposit

Although it has been impossible to identify carbon on the alumina insulators by direct analytical methods, sufficient experimental work has been done to allow the conclusion that the degradation was due to the deposition of outgassed hydrocarbons on the exposed surfaces of the insulators. At the operating temperature the hydrocarbons pyrolyze to form a carbonaceous conducting but initially discontinuous film. As this process of deposition and pyrolysis goes on the film it becomes thicker and more continuous resulting in a reduction of the insulator resistance. This conclusion is supported by experiments which show that, (1) degradation does not occur in the absence of hydrocarbons, (2) degradation can be produced by deliberately introducing hydrocarbon contaminants (Table 20), and (3) identification of carbon atoms on an alumina substrate heated in a hydrocarbon contaminated system (see Figure 54).

These conclusions are based on ground tests and it is conceivable that space environmental conditions are sufficiently different to invalidate them.

An evaluation of the known space environment raises the possibility that metal was deposited on the insulators by action of micrometeorites; however the available data indicate that the micrometeorite density and energies at 700 miles is insufficient to cause erosion or sputtering.

2. Source of Carbonaceous Deposits During Flight Test

Extensive analysis of deposits found in the vacuum chambers used for system ground tests revealed that many of the insulating materials used in the instrument compartment and the high temperature wire inside the APU structure contained hydrocarbons which tend to outgas at the operating temperature. Prior to flight the slots providing a path between the inside of the structure and the converter insulators were covered in an attempt to prevent the hydrocarbons from the instrument compartment and the high temperature wire from depositing on the insulators. Subsequent tests have shown that the slot covers were ineffective. The experimental results indicate that the slot covers left an opening equivalent to an 0.125-in.-diameter capillary tube. Assuming the outgassing rate predicted from tests performed prior to the flight (20 to 40 mg/hr) the 1% power loss point would be 800 to 1600 hours, compared to 820 hr calculated from

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Figure 54. Hydrocarbon Nucleation Site on Alumina
Subsurface (95,000X)

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the flight data. The relative agreement between the observed and experimental values leads to the conclusion that the source of contamination during the flight test was the material inside the APU structure.

3. Resistance-to-Ground Tests

A large number of tests have been performed on individual insulators in severely degrading low pressure environments containing hydrocarbon contamination. It has been shown that the resistance degradation rate can be lowered by decreasing the hydrocarbon pressure and by increasing the leakage resistance path across the insulators which isolate the converter from ground. Figure 55 shows the results of a long term (>2000 hr) endurance test performed on insulators in a low pressure environment containing Convoil-20 heated to 105°F (equivalent vapor pressure $\sim 3 \times 10^{-6}$ torr). This plot of isolation resistance vs time shows the 0.600-in.-diameter insulator to be about a factor of 100 better in isolation resistance after 500 hr at 950°F, and a factor of about 30 better in isolation resistance after 2000 hr at 950°F, than the 0.470-in.-diameter insulator. The improvement in isolation resistance is considerably greater than the ratio (~ 8 to 1) between insulator resistance leakage paths. The hydrocarbon pressure during this test was several decades higher than would be encountered during a typical converter test in a space application. Had these larger diameter insulators been used on the FS-4 system it is unlikely that the resistance would have dropped low enough to have been detected.

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Figure 55. Typical Isolation Resistances Measured on 0.600 in. and 0.470 in. Diameter Insulators in Severely Degrading Hydrocarbon Vacuum Environment

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V. CONCLUSIONS

The SNAP 10A thermoelectric converter program has resulted in the development and qualification of a power conversion system capable of meeting the requirements for a long life space NPU. The performance of the SNAP 10A system during ground and flight system testing has demonstrated that the reliability inherent in thermoelectric devices can be achieved in an operational system. The converter developed under this program has a specific power of 3.75 w/lb, a reliability of 0.996 at 50% confidence and a power degradation of less than 6% in the first year. Accelerated module tests have shown that a minimum of two years life can be achieved at the design temperatures.

The modular design of the converter allows direct extrapolation to higher power systems with a high degree of confidence. Modules presently under development utilizing SiGe in the SNAP 10A configuration with improved bonding technology have been operated for over 14,000 hours at 1300°F and at 1500°F for shorter times. Completion of the development of this technology will result in the ability to fabricate thermoelectric nuclear power units in the 15 to 20 kwe range with the same reliability as demonstrated by SNAP 10A.

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REFERENCES

1. "Development of Thermoelectric Modules for SNAP 10A," RCA Progress Report No. 1, January 1, 1962 to February 28, 1962
2. "Development of Thermoelectric Modules for SNAP 10A," RCA Progress Report No. 2, March 1, 1962 to April 30, 1962
3. "Development of Thermoelectric Modules for SNAP 10A," RCA Progress Report No. 3, April 30, 1962 to July 31, 1962
4. "Phase III, Development and Fabrication of Thermoelectric Modules for SNAP 10A," RCA Quarterly Report No. 1, July-August-September 1962
5. "Phase III, Development and Fabrication of Thermoelectric Modules for SNAP 10A," RCA Quarterly Report No. 2, October-November-December 1962
6. "Phase III, Development and Fabrication of Thermoelectric Modules for SNAP 10A," RCA Quarterly Report No. 3, January-February-March 1963
7. "Phase III, Development and Fabrication of Thermoelectric Modules for SNAP 10A," RCA Quarterly Report No. 4, April-May-June 1963
8. R. M. Willard, "SNAP 10A Thermoelectric Module Post-Mortem Examinations and Material Bond Characteristics," NAA-SR-11205, December 15, 1965 (CRD)
9. S. J. Block and R. M. Willard, "High Temperature Performance Testing and Evaluation of Type VF Modules," NAA-SR-MEMO-10126, June 17, 1964 (CDI)
10. P. L. Soske, "SNAP 10A FSM-4 System Test," NAA-SR-11814 (Unclassified)
11. S. Miner, "FS-3 System Test," (Addendum), NAA-SR-11206
12. G. Berg, "Final SNAPSHOT I Performance Summary," NAA-SR-11934 (to be issued)

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