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AEC RESEARCH AND
DEVELOPMENT REPORT

GA-5317

(Title unclassified)

SNAP-15A THERMOELECTRIC GENERATOR

FINAL REPORT

May 6, 1963, through September 30, 1964

Prepared under
Contract AT(04-3)-167
Project Agreement No. 21
for the
San Francisco Operations Office
U. S. Atomic Energy Commission

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May 6, 1963, through September 30, 1964

by

F. S. Baker, R. J. Campana, W. S. Sargent

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I. INTRODUCTION

This report summarizes a program conducted by General Atomic Division of General Dynamics Corporation for the U.S. Atomic Energy Commission under Contract AT(04-3)-167, Project Agreement 21. The purpose of the program was to develop the SNAP-15A generator, a Pu-238 fueled, metal thermocouple generator capable of producing about 1 milli-watt of output power at greater than 4.5 volts for 5 years with very high reliability even under extreme environmental conditions.

Twenty-one generators of the prototype SNAP-15A design (Fig. 1) were built and submitted to an extensive environmental test program. Test results indicate the generators are highly reliable. An approach to reliability was used wherein the components and generators were "over-tested," and the failure mechanisms were evaluated together with the margin between design and failure point to indicate the reliability of the device. Test results show that the SNAP-15A generator will exceed the specifications prepared by the AEC at the beginning of the program as shown in Table 1.

The aspects of the development program summarized here are presented in more detail in complementary reports on design, test evaluation, and safety. The summary information is to be presented herein in functional sequence, i. e., design, materials and process development, fabrication and quality control, performance tests, environmental tests, reliability, and safety.

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Table 1

AEC DESIGN SPECIFICATIONS FOR SNAP-15

Life	40,000 hr
Load voltage	4.5 v minimum during life and all environment conditions
Electric current	200 μ a
Heat source	Pu-238
Ambient temperature range . .	-65 ^o to +165 ^o F
Geometry	Right cylinder
Volume	25 in. ³ maximum
Diameter	3.0 in. maximum
Weight	1.0 lb maximum
Environment	
Radiation	1000 r total over life, 100 r in single short burst, 20 mr/hr at generator surface, maximum
Mechanical shock	100 g
Vibration	0-3000 cps at 10-g acceleration
Thermal cycling of	
ambient temperature	-65 ^o to +165 ^o to -65 ^o F, 5-min transient
Acceleration	60 g constant
Relative humidity	93% at 149 ^o F
Reliability	90% confidence of < 1 failure in 1000 units

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Fig. 1--SNAP-15A generator model

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II. DESIGN SUMMARY

2.1 GENERATOR DESCRIPTION

The SNAP-15A generator as developed is shown in Fig. 1; its present performance is given in Table 2 and its I-V curve in Fig. 2. Heat is supplied by the decay of radioactive Pu-238 contained in a fuel capsule which in turn is held in place by a capsule holder. The capsule holder is recessed at one end into which the hot junctions of the thermocouples are potted with a silicone rubber to form one end of the thermopile. The thermopile consists of 1300 thermocouples made from Tophel Special and Cupron Special wire of 2 mils diameter. Twenty-five couples are wound in series and are bundled together to form a thermobundle. Bundles are subsequently connected as parallel pairs, and then 26 pairs are connected in series to complete the circuitry. The result is a series-parallel grid of thermocouples that enhances the reliability of the generator.

The cold junctions of the thermobundles are potted to a stainless steel ring in a manner similar to that used at the hot junctions. The hole in the ring is somewhat larger than the hot well of the capsule holder because two 10-mil-diameter lead wires have been potted onto the thermobundles to facilitate their interconnection. After interconnection is accomplished, the wires are potted and covered by a stainless steel disk held together by a set of four studs.

The comparatively large mass of the stainless steel ring and disk incorporates thermal capacitance which, in conjunction with the resistance of the thermal insulation surrounding the thermopile, provides a means of dampening transient changes in load voltage that occur when the ambient temperature is suddenly changed. The four mounting studs form thermal shunt through the thermal insulation, but such shunting is minimized by the length-to-area ratio chosen and the low thermal conductivity of stainless steel.

The thermopile is imbedded in Min-K-503, the best available thermal insulation which does not depend on vacuum to achieve its low conductivity value. It minimizes the heat lost by flow paths other than through the thermopile and mechanically supports the thermopile and canister envelope. A cylindrical plug of thermal insulation permits insertion and withdrawal of fuel capsules through the port in the canister.

Table 2

PERFORMANCE OF SNAP-15A GENERATORS*

Power output	1.75 mw
Open-circuit voltage	8.70 v
Load voltage	6.28 v
ΔV_L during ambient transient . . .	0.68 v
Load resistance	22.5 k Ω
Generator resistance	8.66 k Ω
Thermal input	1.65 w
Over-all efficiency	0.116%
Bypass heat loss	58%
Geometry	Cylinder
Diameter	2.5 in.
Length	5.0 in.
Weight	0.85 lb
Thermopile	
p-leg wire	Tophel Special
n-leg wire	Cupron Special
Wire diameter	2.0 mils
Couple length	1.5 in.
Hot-junction temperature	400 $^{\circ}$ F
Cold-junction temperature	100 $^{\circ}$ F
Number of couples	1300
Number of circuits	2
Materials	
Radioisotope	Pu-238
Thermal insulation	Min-K-503
Electrical insulation	Pyre-ML + RTV-60
Canister	Al-epoxy sealed
Capacitor	316 stainless steel

* Start-of-life conditions.

The thermal insulation and the aluminum canister are filled with argon to exclude oxygen and water vapor. The canister is sealed with epoxy resin to a leak rate of $< 10^{-8}$ cc/sec. In addition, the canister provides mechanical protection for the thermal insulation.

2.2 THERMOELECTRIC EFFICIENCY

In the design of radioisotope-powered generators, experience has shown that the major cost and weight factors are likely to be those associated with the radioisotope. The first objective of the design was to establish

Fig. 2--I-V curve of SNAP-15A generator

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the thermal efficiency so as to minimize the cost and achieve a weight within the specified limit. An upper limit to the over-all efficiency is the thermoelectric conversion efficiency. This may be written as

$$\eta_e = P_o / q_h, \quad (1)$$

where η_e = thermoelectric conversion efficiency,

P_o = output power (1×10^{-3} w(e)),

q_h = rate of heat absorbed at the hot junction of the thermocouple.

The terms in Eq. (1) may be written in terms of the thermoelectric properties of materials and the number and geometry of the thermocouples. This is done below in simplified form where the length and area of the legs were taken to be equal and the electrical resistivities and conductivities are arithmetic averages of the values representing those of the individual couple materials. In any detailed computation, of course, the optimum length and area ratios should be used along with the individual materials properties.

P_o may be expressed in terms of basic thermoelectric factors as

$$P_o = \frac{[\alpha(\Delta T)]^2 2mnA}{(1+m)^2 \rho L}, \quad (2)$$

where α = the difference of the Seebeck coefficients of the two legs,

ΔT = difference of hot- and cold-junction temperatures,

m = ratio of load resistance to generator resistance,

n = number of series-connected couples,

A = cross-sectional area of each thermocouple leg,

ρ = average resistivity of two leg materials,

L = length of thermocouple legs.

The heat input q_h is the sum of four terms: (1) conduction, (2) Peltier heat, (3) Thomson heat, and (4) Joule heat.

$$q_h = 2nk(\Delta T)\frac{A}{L} + n\pi I + nT \frac{\Delta\alpha}{\Delta T} \frac{I}{2} - \frac{I^2 R_i}{2}, \quad (3)$$

where k = average thermal conductivity of the two legs,

π = combined Peltier coefficient,

R_i = generator resistance.

The last three terms may be shown to be negligible for generator materials with low z values or for generators where the load resistance

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and internal generator resistance are badly matched. That one or the other of these two conditions prevails is shown later in this discussion. Thus, simplification of Eq. (3) to

$$q_h = \text{Ank}(\Delta T) \frac{A}{L} \quad (4)$$

is justified. The thermoelectric efficiency may be then rewritten as

$$\eta_e = \left(\frac{\alpha^2}{\rho k} \right) (\Delta T) \frac{m}{(1 + m)^2}$$

or simply

$$\eta_e = z(\Delta T) \frac{m}{(1 + m)^2}, \quad (5)$$

since the thermoelectric figure of merit $z = \alpha^2 / \rho k$. Therefore, the thermoelectric conversion efficiency depends only on (1) the figure of merit which is a function of material properties alone, (2) the ΔT , and (3) a load matching factor. The maximum efficiency with respect to electrical matching occurs when $m \sim 1$; thus

$$\eta_{e \max} = \frac{z(\Delta T)}{4} = \frac{P_o}{q_{h \min}}, \quad (6)$$

and

$$q_{h \min} = \frac{4P_o}{z(\Delta T)}. \quad (7)$$

2.3 OVER-ALL EFFICIENCY

In any thermoelectric generator there is a bypass heat loss. The bypass heat is all that heat which is transferred from the heat source to the heat sink without passing through the thermocouples, i.e., the heat that bypasses the thermocouples. This bypass heat is always important in determining the over-all efficiency of the generator, but in the SNAP-15A generator it is a major effect and, therefore, warrants particular consideration.

To obtain the over-all conversion efficiency, it is necessary to add the bypass heat to that absorbed at the hot junctions of the couples to obtain the total heat input, i.e.,

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$$q_t = q_h + q_b .$$

The bypass heat may be estimated by assuming a concentric spherical geometry for simplification of the computations. Consider a radioisotope heat source imbedded in a sphere of thermal insulation through which the thermocouple wires pass from inner radius to outer radius. The heat conducted through the insulation, ignoring the area occupied by the couples in the flow path, is

$$q_b = \frac{4\pi K(\Delta T)}{\frac{1}{R_1} - \frac{1}{R_2}} , \quad (8)$$

where K = thermal conductivity of insulation,
 R_1 = inner radius of insulation or radius of the heat source,
 R_2 = outer radius of insulation.

When q_b is added to $q_{h_{min}}$, the result is

$$q_t = \frac{4P_o}{z(\Delta T)} + \frac{4\pi K(\Delta T)}{\frac{1}{R_1} - \frac{1}{R_2}}$$

or

$$q_t = \frac{C_1}{(\Delta T)} + C_2(\Delta T) , \quad (9)$$

where

$$C_1 = \frac{4P_o}{z} \text{ and } C_2 = \frac{4\pi K}{\frac{1}{R_1} - \frac{1}{R_2}} .$$

For any chosen set of thermoelectric and insulation materials and sphere sizes, there will be a value of ΔT which will minimize q_t and, therefore, maximize the over-all efficiency. The ΔT which will optimize the efficiency may be found by setting the differential of Eq. (9) with respect to ΔT equal to zero and solving for $(\Delta T)_{opt}$. The result is

$$(\Delta T)_{opt} = (C_1/C_2)^{1/2} \quad (10)$$

or

$$C_2 = C_1/(\Delta T)_{opt}^2 . \quad (11)$$

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Substituting $(\Delta T)_{\text{opt}}$ and the equivalent of C_2 from Eq. (11) into the equation for the total heat input (Eq. (9)),

$$q_{t \min} = \frac{2C_1}{(\Delta T)_{\text{opt}}} = 2C_2 \Delta T \quad (12)$$

An important result drawn from Eq. (12) is that the minimum heat input occurs when the heat through the thermocouples is equal to the bypass heat. Thus, when both electrical and heat loads are matched, a very significant result is found:

$$q_{t \min} = 2q_{h \min}$$

and

$$\eta_{\max} = \frac{z(\Delta T)_{\text{opt}}}{8} = z^{1/2} \left(\frac{P_o}{16C_2} \right)^{1/2} \quad (13)$$

Returning to Eq. (10), it may be observed that the $(\Delta T)_{\text{opt}}$ depends on (1) thermoelectric materials properties, (2) thermal conductivity of the insulation, and (3) a geometric form factor. To achieve the best $\eta_{\max}$ possible, one would make $(\Delta T)_{\text{opt}}$ as large as possible. Presumably having selected the best materials possible, the form factor alone remains to be adjusted. The value of R_1 , the radius of the fuel element, is relatively fixed; thus the efficiency will increase as R_2 is increased as much as possible within the weight limitations specified and provided no limit on the size is imposed.

2.4 COMPARATIVE FIGURES-OF-MERIT

In the foregoing section it was shown that the maximum over-all efficiency of the generator depends on the square root of the figure-of-merit (z) of the thermoelectric materials chosen. For this reason a study of the figure-of-merit of metals, alloys, semiconductors, and insulators was made to aid in the choice of materials to be incorporated into a generator. But the value z is not a sufficient criterion for choosing the material. The need for design and construction of an adequate generator in a short time period required that state-of-art devices be built and that a minimum of development consistent with maximum reliability be emphasized. Because of this, many interesting materials have been discarded from the list of possible candidates because major development programs would have been required to fabricate and use them with skill comparable to that already achieved with better known materials.

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The figures-of-merit of some of the more attractive materials considered are presented in Table 3. Most of these data are taken from measurements made at General Atomic.

Table 3

CHARACTERISTIC THERMOELECTRIC FIGURES-OF-MERIT
OF SOME CLASSES OF MATERIALS

	Temperature Range (°C)	Figure of Merit (°C ⁻¹)
<u>Semiconductors^a</u>		
[PbTe-ZnSb	100-300	1.2×10^{-3}
[PbTe-PbSnTe	100-300	1.0×10^{-3}
[GeSi alloy	100-300	4.0×10^{-4}
Bi ₂ Te	100-300	1.7×10^{-3}
<u>Alloys and Metals^a</u>		
[Cu-Constantan	100-300	4.6×10^{-5}
[Fe-Constantan	100-300	5.8×10^{-5}
[Chromel-P/Constantan	100-300	1.02×10^{-4}
Constantan	0-900	1.6×10^{-4}
40 Pd-60 Au	0-900	$2.4-3.3 \times 10^{-4}$
Chromel-P	0-1200	0.7×10^{-4}
82 Ni-18 Mo	0-1200	2.1×10^{-4}
79 Ni-20 Mo-1 Mn	25-1000	2.7×10^{-4}
<u>Carbides, Oxides, and Silicides</u>		
Cr ₂ O ₃		1.6×10^{-4}
Graphite - B ₄ C		2.6×10^{-7}
Co ₃ O ₄		1.9×10^{-6}
Cu ₂ O		$\sim 10^{-5}$
TiO ₂		8.1×10^{-8}
MnSi ₂		7.0×10^{-4}

^aNote: [indicates couples.

Table 3 shows that the better semiconductor materials have about a factor of 10 superior figure-of-merit over the better metals, alloys, carbides, oxides, and silicides. But, since the over-all efficiency is proportional to $(z)^{1/2}$, the semiconductor's advantage is reduced to about 3. The obvious choice would seem to be a semiconductor, until consideration is given to the problem of matching the generator resistance to that of the load ($R_L = 22.5 \text{ k}\Omega$).

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2.5 GENERATOR-LOAD RESISTANCE MATCHING AND AREA-TO-LENGTH RATIO

In a practical and reliable generator the high z values of semiconductors may be compromised by mismatching of the generator and load. A value of the matching factor $m = 10$ would erase the z advantage of semiconductors completely, provided the competing materials are capable of matching the generator and load resistances. Whether the materials have this capability depends on the area-to-length ratio that can be achieved with each in the fabrication of a reliable generator. This fact may be shown by examination of the matching factor

$$m = \frac{R_L}{R_i} = \frac{R_L}{n\rho} \frac{A}{L}, \quad (16)$$

but

$$n = \frac{V_t (1 + m)}{\alpha (\Delta T) m}, \quad (17)$$

where V_t is the terminal or output voltage of the generator at load conditions.

For the matched electrical conditions, $m = 1$; thus,

$$\frac{A}{L} = \frac{2V_t\rho}{R_L\alpha(\Delta T)}, \quad (18)$$

and for matched heat loads $\Delta T = (\Delta T)_{\text{opt}}$. The Eq. (18) shows that A/L is a constant under these conditions. The $(\Delta T)_{\text{opt}}$ is proportional to $(1/z)^{1/2}$ (see Eq. (10)). Thus, the A/L ratio of the thermoelectric materials may be compared by normalizing to $(\Delta T)_{\text{opt}} = 100^\circ\text{C}$ and the z value of PbTe-ZnSb couples. The results of using Eq. (18) with this normalization are presented in Table 4.

Table 4 shows that the A/L (area-to-length ratio) values needed are in the range of 10^{-5} cm. It is possible to attain the needed A/L ratios with Si by such techniques as vapor deposits on substrates. However, if the substrate is not removed, then it becomes a thermal bypass path which will reduce its performance. Also, the $(\Delta T)_{\text{opt}}$ is excessive as a result of the small z -value. MnSi₂, Cr₂O₃, and other materials of the same class are relatively unknown materials and would undoubtedly require substantial development before their properties and fabricability, including their A/L , could be used to design a reliable generator.

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Table 4

AREA-TO-LENGTH RATIO FOR MATCHED LOAD CONDITIONS
(Normalized to $(\Delta T)_{\text{opt}} = 100^{\circ}\text{C}$ for PbTe-ZnSb)

Material	$(\Delta T)_{\text{opt}}$ ($^{\circ}\text{C}$)	A/L Required (cm)
PbTe-ZnSb	100	6.95×10^{-5}
Ce-Si alloy	173	1.93×10^{-5}
Bi_2Te_3 (p and n)	80	3.88×10^{-5}
Chromel-P/Constantan	333	2.47×10^{-5}
Si (p and n)	3050	8.4×10^{-5}
MnSi_2	131	1.38×10^{-5}
Cr_2O_3	274	6.2×10^{-6}

2.6 SEMICONDUCTOR VERSUS METAL

From a practical standpoint, A/L ratios of 10^{-2} to 10^{-3} cm are about the best achievable using PbTe, ZnSb, and Bi_2Te_3 semiconductors, while metal thermocouples easily achieve 10^{-6} cm. The mismatch of the generator resistance to load resistance when the optimum A/L ratios are not attainable make the metal thermocouple superior to the semiconductor thermocouple in the low power output range. This is shown in Fig. 3 where the over-all efficiencies of p-PbSnTe and PbTe thermocouple generators are compared to that of a generator using Tophel Special, a modified chromel, and Cupron Special, a modified constantan, as a function of power output at 4.5 volts across a 22.5-k Ω load. Optimum hot-to-cold-junction temperature differences were used when the ΔT fell below the maximum permissible value, which was assumed to be 400° and 500°C for the semiconductors and metals, respectively. At power outputs greater than ~ 10 mw the optimum ΔT would have been too great; thus, the maximum ΔT for metals was substituted for the optimum ΔT while ΔT was limited to the maximum for semiconductors even at 1 mw. The load voltage affects the efficiency only when the desired value of A/L cannot be achieved. Since the metal thermocouples can attain the necessary A/L values, the efficiencies of generators made from them are independent of load voltage. This is not the case for the semiconductors.

The cross-over from metal to semiconductor superiority as a function of power output and load voltage is interesting. Fig. 4 is a curve of the cross-over power output versus load voltage drawn from the intersection points of the curves shown in the previous figure. Above a load current of 15 ma semiconductor thermocouples are superior, while below this value the metal thermocouples prevail. When voltage matching devices

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Fig. 3--Comparison of metal and semiconductor thermocouple generators from 1 to 10,000 milliwatts

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Fig. 4--Effect of load voltage on choice of metal and semiconductor thermocouples

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are used, the current requirement of the matching device may be used as the load current taking into account the additional power required by inefficiency of the matching device itself.

Matching the SNAP-15A generator to the load with some kind of an electronic matching device was considered to make the use of semiconductors more attractive. It would be necessary, then, to take into account the power consumption, weight, and efficiency of the matching device. Since a reduction of two to three orders of magnitude in the A/L ratios is required to reach the range where semiconductors would be useful, the load voltage would have to be reduced to the range of a few to 100 mv. These voltages are well below the normal operating voltages of transistorized matching devices. Also, it was considered that the use of such a device together with semiconductors to obtain a matched generator load might severely compromise the reliability of the generator.

Even more important than the efficiency considerations in selection of metal thermocouples in preference to semiconductor thermocouples is their relative state-of-art and its effect on the generator reliability. Fabrication of metal thermocouple wire has reached a very high degree of sophistication by long term development of the thermocouples for use as precise temperature sensors. Metal may be alloyed, drawn, insulated, and joined by techniques that are well developed and have been accepted by industry for many years. The thermoelectric properties of the alloys are inherent and, therefore, are not readily affected by minor impurities. Mechanically, the properties of metal thermocouple wire are well known, and are excellent for thermopile construction, especially at small A/L ratios.

On the other hand, semiconductors are in a comparatively earlier stage of development. Many of the semiconductors are brittle, difficult to fabricate, and are very sensitive to impurities which make their properties less reproducible and their compatibility with other materials more critical. Diffusion of impurities and dopant with time and temperature results in property changes which affect performance greatly. Mechanical properties of semiconductors are not well known as a result of their brittle nature. This makes them much more difficult to build into thermopiles of structural soundness required for high reliability. In fact, it is because of the their mechanical properties that they cannot achieve A/L ratios comparable with metals. Not only are very small A/L ratios not attainable but the absolute cross-sectional dimensions needed would result in thermopiles of considerably more bulk than those made from metal thermocouples.

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2.7 SIZE AND WEIGHT

The weight of the device was specified to be less than 1 lb. Of this total, the weight of the thermocouples is trivial even if large numbers are required. An upper weight limit of the radioisotopic fuel element may be obtained by assuming the smallest $(\Delta T)_{\text{opt}}$ that one would estimate, say 100°C . The over-all efficiency for Chromel-P/Constantan thermocouples will be, for this ΔT ,

$$\eta = \frac{z(\Delta T)_{\text{opt}}}{8} = 0.127\%$$

The power-to-weight ratio of Pu-238 is 0.55 w/g and the power density is 8.73 w/cm³. Thus, the fuel will weigh

$$W_{\text{fuel}} = \frac{P_o}{\eta(0.54)} = \frac{1 \times 10^{-3}}{0.00127(0.54)} \approx 1.45 \text{ g of Pu-238},$$

allowing a factor of five in weight to account for the fuel encapsulation; the fuel capsule is a trivial weight component.

It was shown previously that the size of the generator should be made as large as possible in order to maximize the over-all efficiency within the 25-in.³ and 1-lb weight limit. The thermal conductivity and density of thermal insulation will determine the weight, cost, and efficiency of the generator. Eq. (13) may be employed to make this clear when it is rewritten in the form

$$\eta = \frac{z}{8} \left[\frac{P_o \left(\frac{1}{R_i} - \frac{1}{R_o} \right)}{\pi K} \right]^{1/2} \quad (19)$$

The over-all efficiency will peak with respect to K when K is minimum. The generator weight will be approximately

$$W = \frac{4}{3} \pi R_o^3 d \quad (20)$$

where W is the total weight specified as 1 lb and d is the density of the insulation. Rearranging,

$$R_o = \left(\frac{3W}{4\pi d} \right)^{1/3} \quad (21)$$

To achieve the largest value of R_o and, thereby, η with respect to R_o , the density of the insulation must also be minimized. In Table 5, the effective

thermal conductivity and average density of the best known thermal insulators and their temperature limitations, when available, are compiled. From this list, the plastic foams are found to be superior in their usable temperature range, having a combined thermal conductivity times density value (kd) of 9.7×10^{-6} . Min-K-503 in vacuum is next with a kd value of 2.2×10^{-5} and operates at higher temperatures followed by Min-K-1301 in vacuum having a kd value of 7.4×10^{-5} and ranging to still higher temperatures. Min-K-503 has a thermal conductivity when operated in a vacuum approximately 2.3 times lower than that when operated in air. Similarly, a factor of 1.47 exists for Min-K-1301 thermal conductivities between operation in vacuum and air. The weight penalty associated with vacuum containment is not apparent. The size of the container and the wall thickness depends on the specific design of the generator. Concentric spheres of insulation may be employed where each is the best material (lowest kd value) that can operate in the temperature range at that point. Using Min-K-503, a 25-in.³ spherical generator was estimated to weigh 0.2 lb.

Eq. (10) for the optimum ΔT , i. e., one that will minimize the heat required to generate a given amount of power, may be written in the form

$$(\Delta T)_{\text{opt}} = \left(\frac{C_1}{C_2} \right)^{1/2} = \left(\frac{C_1}{GK} \right)^{1/2}, \quad (22)$$

where G is the geometry factor and K the thermal conductivity of the thermal insulation. From this it can be seen that the temperature of operation for constant parameters otherwise depends on the thermal conductivity of the insulation. Selection may be made from a list such as that of Table 5, which permits, therefore, a choice of operating temperature of the generator. If some of the lowest conductivity insulators are chosen, $(\Delta T)_{\text{opt}}$ may exceed the capability of the materials from which the generator will be built including the insulation itself. Nevertheless, it is desirable, if K is small enough, to design at less than $(\Delta T)_{\text{opt}}$ in that the heat input may still be less than that required with insulation of larger K and optimum ΔT .

A second and related aspect to the selection of operating temperature is concerned with the number of thermocouples required to provide the specified voltage. The number of series-connected thermocouples varies inversely with the ΔT from hot-to-cold junction when the load voltage and materials properties are fixed (see Eq. (17)).

Thus, it can be seen that there was a choice to be made of the thermal insulation to be used which would determine the operating temperature and minimum number of thermocouples of the generator. At one end of the range a high operating temperature associated with a small number of thermocouples will result, while at the other end of the range the converse

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Table 5

EFFECTIVE THERMAL CONDUCTIVITY OF INSULATION MATERIALS

Material	Density (g/cm ³)	Thermal Conductivity (10 ⁻⁴ w/cm-°C)	Measured at Mean Temperature (°C)	Maximum Operating Temperature (°C)
Still air	1.29×10 ⁻³	2.3	0	
		3.0	100	
Charcoal	0.18	5.5	20	
Cork	0.05	3.2	0	
Felk hair	0.27	3.6	30	
Glass wool	0.22	4.2	50	
Mica	-----	50.0	50	
Mineral wool	0.15	4.2	30	
Sponge rubber	0.09	3.7	25	
Steel wool	0.15	8.0	55	
Argon	1.78×10 ⁻³	2.13	100	
SiO ₂	2.3	35.3	180	
Thermobestos	0.176	5.48	100	650
Magnesia 85%	0.176	5.56	109	3.5
Suprex	0.385	9.95	210	1040
Suprex M	0.336	8.95	210	870
Banroc blanket		4.90	150	540
Min-K-503	0.22	2.31	150	250
Min-K-503 in vacuo	0.22	1.00	150	250
Min-K-1301	0.32	3.4	325	700
Min-K-1301 in vacuo	0.32	2.31	325	700
Linde Superinsulation	0.11	0.05	270	540
Linde Superinsulation	0.11	0.008	20	540
Polystyrene Freon foam	0.0321	3.6	5	150
Polyurethane CO ₂ foam	0.0321	3.03	24	210
Stafoam, flexible	0.0321	4.04	24	----
Stafoam, Freon	0.0337	2.27	24	----
Tipersul	0.445	4.19	290	1200
Tipersul	0.445	5.05	540	1200

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will occur. Any combination between the end points is also acceptable with respect to performance. The design point with respect to the operating temperature and number of couples was chosen with regard to the need for high reliability, but the considerations were necessarily subjective.

The choice of thermal insulation material ultimately reduced to a choice between two basically different types of insulation: (1) those dependent on vacuum for their low effective conductivities; and (2) those not dependent on evacuation.

The "vacuum" insulation results in generators of high operating temperature and relatively small numbers of couples, while the converse results from "non-vacuum" insulation. But the combination of high-temperature and vacuum conditions is very demanding on the basic properties of materials. Failure of materials and insulation properties are exponential with temperature, since the mechanisms of diffusion, outgassing, and vaporization are exponentially related to temperature. Thus, a generator operating at a high-temperature design point was believed to be substantially less reliable than one at low temperature.

The loss of reliability resulting from the large number of thermocouples needed in a low-temperature generator might overwhelm the gain resulting from lower temperatures. However, the failure mechanisms of thermocouples result from the same mechanisms noted above. At operating temperatures $< 500^{\circ}\text{F}$, these processes are proceeding so slowly that thermocouple failure can be reduced to a very low level by quality control procedures prior to generator assembly. Thus, the non-vacuum insulation Min-K-503 was chosen, resulting in low operating temperatures ($< 500^{\circ}\text{F}$) and large numbers of thermocouples (1300). In this temperature range, it was believed high-temperature varnishes could be used as thermocouple wire insulation.

2.8 SERIES-PARALLEL CONNECTIONS

The reliability of the generator was greatly increased by incorporating a parallel circuit of series-connected thermocouples with multiple cross-connections. This was possible because of the small A/L ratios attainable with metal couples. In fact, because of volume limitations and the desire to reduce the number of couples, the thermopile is not matched to the load. The generator resistance is $8600\ \Omega$, while that of the load is $22,500\ \Omega$. The mismatch was deliberately chosen based on judgment as to the smallest diameter wire that could readily be handled to assure early production of generators and reliability of junctions versus number of junctions and temperature of operation. With the load-to-generator resistance ratio of 2.65, the number of thermocouples was reduced from 1886 to 1300. The

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circuit employed is shown in Fig. 5 where 25 couples are series-connected and comprise a thermobundle. Two thermobundles are connected in a parallel pair and 26 pairs are series-connected. Thus, a complete failure by short circuiting of one thermobundle will result in a voltage and power loss of 1/26 of the initial value, while a failure by open circuiting of one bundle will result in no change of open-circuit voltage and a small gain in load voltage (generator resistance approaches load resistance).

2.9 TRANSIENT RESPONSE

The requirement that the load voltage of the generator be maintained over its design life above a minimum of 4.5 volts during a 5-min transient in the ambient temperature between -65° and $+165^{\circ}$ F in either direction could be satisfied by establishing the steady load voltage to compensate for the transient loss when: (1) the transient response is dampened, and (2) when it is not. In either case the number of couples or the hot-to-cold ΔT or both must be raised to increase the load voltage. But, as discussed above, increasing the number of couples or the ΔT each reduce reliability, and in addition more power is generated than needed which has to be paid for by added radioisotope. By dampening the transient response, those factors were minimized. To achieve dampening, a large thermal capacitor was attached to the cold end of the thermopile.

When considering the transient response, the generator may be considered as two independent parts, the cold end and the hot end, with the objective of stabilizing the hot-to-cold-junction ΔT even though the temperature level may increase or decrease. To achieve this, the time constant for each end must be equal, i.e.,

$$R_c C_c = R_h C_h$$

where R = thermal resistance,
 C = thermal capacitance,
 c = cold,
 h = hot.

When this condition holds, the rates of temperature change of the cold junction and the hot junction due to a change in the ambient temperature are the same; but, in order to establish the desired ΔT between the hot and cold junctions,

$$R_h \gg R_c$$

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Fig. 5--Thermobundle electrical circuit network

Thus, C_c was designed to be as large as possible within the volume and weight limits specified to make $R_c C_c$ as nearly equal to $R_h C_h$ as possible. The final configuration was arrived at as a result of analog and digital computer transient studies and transient experiments by modification of an early model SNAP-15A generator.

2.10 ANALOG COMPUTER TRANSIENT STUDY

The analog computer circuit used to represent the generator for transient studies of the hot-to-cold-junction temperature difference and load voltage is shown in Fig. 6. The values of resistance and capacitance were computed from an approximation of the desired generator geometry and materials of construction. The thermal resistance of the thermopile was probably subject to the most error because of the difficulty of estimating the packing of thermocouples and the amount and properties of potting material. The axial temperature profile of the generator derived by the analog computer for the range of resistance values of R_4 shown in Table 6 is presented in Fig. 7. This may be compared with a similar profile resulting from the digital computer results (Table 7) and measurements of an actual generator (Fig. 8).

Table 6
AXIAL TEMPERATURE PROFILE PREDICTED BY
ANALOG COMPUTATION
(Power Input = 1.0 Watt)

Temperature Point	Temperature ($R_4 = 12^\circ\text{F/w}$)		Temperature ($R_4 = 60^\circ\text{F/w}$)	
	T($^\circ\text{F}$)	$\Delta T(^{\circ}\text{F})$	T($^\circ\text{F}$)	$\Delta T(^{\circ}\text{F})$
Capsule and holder	446	---	446	---
Hot junction	443	13	433	13
Mid thermopile	264	169	269	164
Cold junction	170	94	184	85
Ambient air	166	4	166	18

The results of the analog study are summarized in Fig. 9. To suppress the transient response of the generator to ambient step function, thermal capacitance of about 1.0 watt-min/ $^\circ\text{F}$ was needed with resistance of greater than 50 $^\circ\text{F/watt}$.

- R = thermal resistance in $^{\circ}\text{F}/\text{watt}$
 R_1 = 25.3 - capsule to hot junctions
 R_2 = 328 - half of thermopile
 R_3 = 328 - half of thermopile
 R_4 = 12.2-180 - Min-K and studs, cold junctions to ambient
 R_5 = 216 - Min-K mid thermopile to ambient mid thickness
 R_6 = 216 - Min-K thermopile ambient mid thickness to ambient
 R_7 = 216 - Min-K capsule to ambient mid thickness
 R_8 = 216 - Min-K capsule to ambient mid thickness to ambient
 C = thermal capacitance in watt-min/ $^{\circ}\text{F}$
 C_3 = 0.0712 - thermopile
 C_4 = 0.640, 1.28, 1.92 - thermal capacitor
 C_6 = 0.290 - Min-K thermopile to ambient
 C_7 = 0.0487 - capsule and holder
 C_8 = 0.290 - Min-K capsule to ambient
 $\Delta T = T_h - T_c = V_2 - V_4$

Fig. 6--Analog computer circuit representation of SNAP-15A generator

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Fig. 7--Temperature distribution determined by analog computation

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The SNAP-15A generator, as built, has 1.05 watt-min/ $^{\circ}$ F of capacitance and 23 $^{\circ}$ F/watt resistance. Selection of the values was limited by the size and volume restrictions. Further evidence for the design of the transient dampening network was obtained from the digital computer study.

Table 7

CENTERLINE, AXIAL TEMPERATURE PROFILE
OF SNAP-15A GENERATOR TAKEN FROM
RAT CODE ANALYSIS OF CASE A-1
(Heat Input = 2.0 Watts)

Axial Point	Temp. ($^{\circ}$ F)	ΔT ($^{\circ}$ F)	Thermal Resistor
Ambient	165	---	
2	199	34	Air film
6	217	18	Cold-junction insul.
9	221	4	Stainless steel
10	229	8	Across potting
12	297	68	Across cold junction
21	597	300	Couples
22	696	99	Across hot junction
26	759	63	Capsule

2.11 DIGITAL COMPUTER TRANSIENT STUDY

Transient load voltage response was studied with the aid of the RAT (Radial-Axial-Temperature) code on the IBM-7090 computer. The general configuration of the generator was established, and the mathematical model was determined from it. In some regions it was necessary to homogenize the materials properties, e.g., the thermopile properties. Different radial and axial thermal conductivities were estimated for the junction regions where the potting compound is pierced longitudinally by the metal wires.

The D/L ratio of the generator was adjusted while maintaining the generator volume constant. The thickness of insulation around the capacitor was limited by the volume available at the cold end. The volume, therefore, was proportioned between the thermal resistor and capacitor. The insulation was distributed with approximately uniform thickness in the axial and radial directions about the surfaces of the thermal capacitor. The total heat input and the change in load voltage were taken as the independent variables. The mounting studs attached to the capacitor are thermal shunts around the insulation. Variation of the shunt properties was also investigated.

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Fig. 8--Measured temperature profile of SNAP-15A generator

Fig. 9--Parametric analog results of RC dampening of transient load voltage

Some of the materials considered for the capacitor are shown in Table 8. Beryllium is the best material but is costly and toxic. Water in the liquid phase is also desirable, but as ice its heat capacitance per unit volume is not comparable with stainless steel and tests showed the minimum voltage occurred during the ice state. Thus, Type 316 stainless steel was selected where volume was limited and aluminum was added because of its superior heat capacitance per unit mass whenever the maximum weight limit was approached. Computation showed that volume was more critical than weight. A total of 10 cases were run, as shown in Table 9, to change from case to case. The reference case shown in the table is the present SNAP-15A generator configuration.

Table 8

SPECIFIC HEAT AND HEAT CAPACITANCE OF SOME METALS

Metal	C_p (cal/mole-°C)	m (g/mole)	ρ (g/cm ³)	C_p /mass	C_p /vol.	K (w/cm ² -°C)
Al	5.82	27	2.7	0.216	0.583	2.3
Be	4.26	9	1.85	0.573	1.06	1.7
Graphite	2.04	12	2.25	0.170	0.383	0.013
Cr	5.55	52	7.14	0.107	0.763	0.855
Cu	5.86	63.5	8.95	0.092	0.824	3.82
Fe	5.97	55.9	7.86	0.107	0.841	0.69
Pb	6.32	207	11.48	0.0306	0.351	0.335
Mo	5.87	96	9.01	0.061	0.550	1.0
Sn	6.3	119	5.75	0.053	0.305	0.6
U	6.57	238	18.7	0.0276	0.516	0.26
Zr	6.01	91	6.44	0.066	0.425	0.2
316 SS	----	---	7.92	0.12	0.95	0.146

The results of the analysis are shown in Table 10. Since the ΔV_L is independent of the thermal input of the isotope source, several of the cases indicate constant values. In these cases, the heat input was varied in order to determine the heat input and hot-to-cold-junction ΔT required to maintain the minimum load voltage specified (4.5 volts). The results indicate that the ΔV may be reduced to zero or even reversed in direction but that larger total heat is required because the hot end thermal resistance is reduced to accomplish it. Case B, while appearing very desirable, was rejected on a judgment of uncertainty about the reliability of the bakelite inserts in dynamic mechanical environment. Cases A and C were quite close; but, since the Case C result depended on the homogenization of aluminum and stainless steel properties, there was more uncertainty about its validity. The results obtained are substantially correct.

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Table 9

INDEX OF CHANGES MADE IN REFERENCE GENERATOR
FOR RAT CODE ANALYSIS

Case	P _{in} (w)	Bundles	Stud Insulator	Thermal Capacitor	Thickness of Thermal Resistance Around Capacitor	Diameter and Length
A-1.1	1.35					
A-1.2	1.48					
A-1.3	The reference generator is described by design drawing 354-06-100 (SNAP-15A Prototype Design)					
A-2		46				
A-3		34				
B-1	1.35		1/8-in. bakelite			
B-2	1.48		1/8-in. bakelite			
C-1	1.48			SS + Al	0.2 in.	
D-1	1.25					2.25-in. Dia. × 6.3 in.
D-2	2.0					2.25-in. Dia. × 6.3 in.

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Table 10

RESULTS OF TRANSIENT ANALYSIS OF SNAP-15A GENERATOR USING RAT. CODE FOR IBM-7090

Case	Heat In (w)	No. of Bundles	$\Delta T_{(-65^{\circ}\text{F})}$ amb. ($^{\circ}\text{F}$)	$V_L_{(-65^{\circ}\text{F})}$ amb. (v)	ΔT_m ($^{\circ}\text{F}$)	t_m (min)	V_{Lm} (v)	ΔV (v)	Pu-238 at Design Point (g)	Required Heat In (w)
A-1.1	2.0	52	306	6.27	279	81	5.72	0.55	2.93	1.612
A-2	2.0	46	324	6.12	295	81	5.60	0.52	2.98	1.642
A-5	2.0	34	391	5.85	338	86	5.04	0.81	3.68	2.022
A-1.2	1.35	52	198	4.06	170	84	3.48	0.58	3.07	1.688
A-1.3	1.48	52	217	4.45	189	81	3.88	0.57	3.07	1.688
B-1	1.35	52	194	3.98	183	35	3.75	0.23	2.92	1.603
B-2	1.48	52	212	4.35	201	35	4.12	0.23	2.93	1.610
C-1	1.48	52	216	4.43	195	43	4.00	0.43	3.00	1.648
D-1	1.25	52	118	2.42	118	0	2.42	0	4.22	2.32
D-2	2.0	52	199	4.08	198	12	4.06	0.02	4.03	2.22

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A temperature profile of the generator obtained from the digital output is shown in Table 10. It is obvious that the properties estimated for the radial thermal conductivity of the composite material about the hot and cold junctions were pessimistic. Similarly the air film ΔT and capsule-to-hot-junction ΔT are too great. Verification was obtained when measured temperatures based on the same design were obtained and may be compared by reference to Fig. 8 and Table 11.

Table 11

TEMPERATURE PROFILE OF SNAP-15A GENERATORS
(Heat Input = 1.52 Watt, $V_L = 4.88$ Volts)

Component	Temp. ($^{\circ}$ F)	ΔT ($^{\circ}$ F)
Capsule holder	367	
Hot junction	358.5	8.5
Cold junction	104.5	254
Thermal capacitor	99.5	5.0
Canister (cold end)	83.0	16.5
Canister (side)	83.0	-----
Ambient air	76.0	7.0

2.12 TRANSIENT EXPERIMENTS

The effects of step changes in the ambient temperature on the load voltage were found experimentally by modification of Generator No. 5, one of the early experimental models. The basic generator configuration is shown in Fig. 10. In Table 12, the effects of the modifications during the transient are given. Modification 4 closely resembles case A-1 of the RAT code analysis, and the two results are similar in ΔV values but differ in the time at which the minimum is reached. By the modifications made to the generator, the ΔV was reduced by a factor of four which is equivalent to about 0.38 watt (0.7 g of Pu-238) or 13% in the input heat required.

In modification 5, the effect of the delay of the heat absorbed by melting water at constant temperature was studied. Since the specific heat of ice is only one-half that of water, minimum voltage was reached before the melting point was attained. Separate experiments with mixtures of water with ethylene glycol, ethyl alcohol, etc., indicated they would not be satisfactory because their heat capacities were low and melting does not occur at constant temperature.

Fig. 10--Experimental Generator No. 5 basic configuration

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Table 12

RESULTS OF TRANSIENT EXPERIMENTS WITH GENERATOR NO. 5

Generator Identification	Description of Change	ΔV (v)	$t_{\min.}$ (min)
Basic Model No. 5	None	2.02	18
Modification 1	488 g of Cu attached by mounting studs and covered with 1/4-in. foam rubber insulation up to 1 in. of generator length.	1.32	27
Modification 2	Same as modification 1, but foam rubber insulation extended over whole generator	0.90	32
Modification 3	Bottom of can cut-off, 225 g of Cu potted on and covered with 1/2 in. of Min-K insulation.	0.71	19
Modification 4	Same as modification 3, but with foam rubber insulation covering can where cold junctions come near surface of Al cylinder	0.50	20
Modification 5	Cu thermal capacitor replaced by one of 69.7 g of SS can containing 9 g of H ₂ O.	0.59	21

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Upon reviewing the results of the analog, digital, and experimental studies, the final configuration was chosen in which the experimental results were weighed more heavily than the analytical results. While the diameter-to-length ratio of 5.0/2.5 is not optimum, it is in the region of the optimum. The transient response of the first generator built with the thermal RC dampener is shown in Fig. 11.

Some of the dampening initially attained in the prototype design was subsequently lost when the Min-K insulation conductivity values were reduced by the introduction of baking and filling with argon gas. Programmatic requirements have prevented further design modification, but there is no reason why the ΔV cannot be reduced to a value close to zero. Consideration was given to the addition of helium gas to argon gas, filling the generator to reduce the ΔV and simultaneously the ΔT . Adding helium increases the thermal conductivity of the Min-K, thereby permitting greater heat leakage. Thus, for constant power input, the ΔT , ΔV , and V_L would all be reduced. The same effects result simply by decreasing the power input. The maximum ΔT reduction attained by adding helium beyond that achieved by input heat reduction was found to be 10°F while the average value was about 3°F . Thus, it is concluded that the addition of the helium to the argon has little or no advantage.

2.13 ISOTOPE REQUIREMENT

While the primary objective of the design was to provide extremely high reliability, it was desired, insofar as possible without compromising reliability, to minimize the quantity of fuel material. The amount of Pu-238 or the thermal input was estimated for the SNAP-15A generator as shown in Table 13. From this table it is clear that the bypass loss is the predominant loss mechanism. Bypass heat losses are sensitive to the size of the fuel capsule and its holder. Thus, there arises a compounding effect on the isotope requirement; i. e., if some change requires the input heat requirement to rise, more radioisotope must be added to the fuel capsule, which would increase the size of the fuel capsule and holder. The increased size of the capsule holder permits greater bypass heat losses so that still more input heat is needed. The compounding continues until a new balance is reached. The same compounding process works in the reverse direction also. For example, if the fuel capsule holder were eliminated leaving the fuel capsule supported by insulation alone, the bypass heat loss would drop by 0.25 watt. This reduction in bypass heat losses results in a greater reduction in isotope requirements.

The table shows the heat associated with maintenance of minimum voltage swing to be almost as great as that due to through heat losses. This represents the heat required to maintain a minimum output voltage rather

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Fig. 11--Transient response of SNAP-15A generator load voltage with thermal RC dampener

than develop needed power. By proper tuning of the thermal circuits, the voltage change ΔV can be virtually eliminated and this heat saved. As the generator was developed, detuning of the thermal circuits occurred. This was particularly true when the baking and sealing processes were introduced to stabilize the thermal insulation. Reduction of the ΔV can be accomplished by geometric changes in the generator design, e. g., diameter and insulation thickness around the thermal capacitor or changing the composition of the gas filling the insulation thereby changing its conductivity. It was necessary to fix the generator design early in the program, so retuning by variation of geometry was left to future developments. When this method of tuning is used, both savings in isotope requirement and reduced ΔT will result.

Table 13
ESTIMATED HEAT DISTRIBUTION

Heat Component	Heat Input		
	Watts	Equivalent g of Pu-238	%
Heat through thermocouples	0.310	0.565	22.2
Heat bypassing thermocouples	0.810	1.472	58.0
Heat to sustain voltage during transient ambient temperature conditions	0.275	0.500	19.8
Total heat requirement	1.395	2.537	100.0

Finally, reduction of the fuel required has a compounding effect on the tuning, since the fuel capsule and holder constitute the major thermal capacitances delaying the change of the hot junctions with ambient temperature changes.

2.14 GENERATOR MOUNTING

With the concentration of the mass of the generator in the thermal capacitor, it was desirable to provide support directly to that mass. The weight distribution of the generator shown in Table 14 indicates that the thermal mass is 40% of the mass of the generator, with 44% being well distributed in the Min-K insulation and canister and the remaining 15% associated with the thermopile, capsule and holder, and miscellaneous. Therefore, the mounting studs are attached to the thermal capacitor (in fact, are part of it) and to the canister. It was desirable for the studs to be of small diameter to minimize their thermal shunting across the

Min-K insulation and to be of large diameter to support the generator during dynamic mechanical loading. Thermal analysis has been discussed above. Failure of the studs was expected in shear rather than bending because of their short length. The studs have been computed to have a safety factor of five during 100-g mechanical shock, the most severe loading when the generator is mounted to produce the worst shear situation. Consideration was given to the use of Ti-6Al-4V alloy for stud material because of its lower (1/2) thermal conductivity. It was not used because its impact strength is only 1/10 that of stainless steel.

Table 14
WEIGHT DISTRIBUTION IN SNAP-15A GENERATORS

Component	Weight		
	(g)	(lb)	(%)
Fuel capsule	13.2	0.03	3.5
Fuel capsule holder and cap	9.0	0.02	2.4
Thermal capacitor	151.9	0.33	40.0
Thermopile and potting	15.5	0.03	3.5
Mounting studs	15.4	0.03	4.0
Min-K	85.1	0.19	22.4
Canister	81.0	0.18	21.4
Miscellaneous (terminal, wire, connector, epoxy, etc.)	10.5	0.02	2.8
Total	379.6	0.83	100.0

Min-K was found, according to manufacturer's data, to possess adequate compressive strength to be capable of supporting the parts of the generator with respect to one another, but its properties in a dynamic mechanical environment were not known. The same situation prevailed with respect to the thermopile. Extensive measurements were performed on Min-K, and it proved to be strong enough that, even though dynamic calculations were not very accurate, it was a safe assumption that Min-K could withstand the forces induced in testing.

III. MATERIALS AND PROCESS DEVELOPMENT

The reliability of the SNAP-15A generator is dependent on the materials from which it is constructed and the materials and processes used in its assembly. In order to achieve the reliability desired, materials were selected wherever possible whose capabilities exceeded the temperature capabilities required. For this reason, inorganic materials are preferred but organic materials were used where necessary. Materials found to be critical were (1) the braze alloy used to join the Tophel Special and Cupron Special thermocouple wires, (2) the Pyre-ML polyamide electrical insulation, (3) Min-K-503 thermal insulation, (4) RTV-60 silicone rubber electrical insulation and thermopile potting material, and (5) epoxy resin canister sealant.

In general, the criteria for the final selection of a material and its processing were (1) the specific required properties of the material to fulfill its special role in the generator and (2) the stability of the material after processing under anticipated service conditions of time, temperature, and atmosphere. The following paragraphs summarize the results of the materials and process development work and illustrate the bases on which these materials were selected for inclusion in the SNAP-15A generator.

3.1 BRAZING OF THERMOCOUPLE JUNCTIONS

For the brazing of the junctions between the Tophel Special and Cupron Special wires, the alloy 45 Ag-15 Cu-16 Zn-24 Cd was initially selected. This alloy was unsatisfactory with respect to its high vapor pressure (namely, the elements zinc and cadmium) at the operating temperature. The alloy 60 Ag-30 Cu-10 Sn was then investigated and it proved satisfactory with respect to wetting, flow, compatibility with the base material, and vapor loss.

3.2 MIN-K-503 INSULATION

This is one member of a series of high-grade insulations produced by the Johns-Manville Corporation. The material as received from Johns-Manville is a low thermo-conductive inorganic fibrous insulation with the elemental composition (wt-%) as shown in Table 15.

Table 15
CHEMICAL COMPOSITION OF MIN-K-503
(in wt-%)

Silicon	37.7	Calcium	0.3	Potassium	0.02
Carbon	11.6	Magnesium	0.2	Sulfur	0.4
Titanium	0.01	Oxygen	45.5	Phosphorous	0.01
Iron	1.3	Manganese	0.03	Chloride	0.01
Aluminum	0.2	Sodium	0.5	Hydrogen	0.2

Spectrographic traces of barium, boron, chromium, cobalt, nickel, molybdenum, and zirconium; plus 1.1 wt-% bound moisture and 2.0 wt-% phenolic binder.

The testing program undertaken on this material was designed toward the goals of:

1. Removing the moisture without damaging physico-chemical properties.
2. Improving (i. e., lowering) the thermal conductivity.
3. Retaining dimensional integrity--a requirement imposed by generator fabrication procedures.

The three goals are really inseparable and therefore any pretreatment established had to achieve them concurrently. Through numerous preliminary tests, it was established that any pretreatment process must incorporate:

1. A baking process.
2. Total exclusion of oxygen during treatment.
3. A time-temperature schedule, rigidly adhered to in order to achieve uniform results.
4. Total inertness of the final product to preclude chemical cross contamination with the organic materials in the generator, e. g., RTV-60.

By temperature-pressure tests, it was determined that a bake temperature of 930° to 950°F best accommodated the total requirements of achieving the goals mentioned while keeping the process within reasonable time limits. The pressure-temperature tests indicated a pressure peak at about 650° F. This temperature, however, was too low to allow a timely removal of moisture and binder residue. The higher temperature (950°F)

permits rapid evolution of these and allows the pretreatment process to be carried out within a 24-hr period. The process is as follows: The insulation is machined and made ready for installation into the generator. The machined parts are then placed in a furnace evacuated to about 20μ Hg pressure and heated to 950°F . When 950°F oven temperature and 20 to 25μ Hg pressure is achieved, the insulation is back-filled with high-purity dry argon gas. When the temperature again drops to 70°F , the insulation is removed and stored in tightly sealed, argon-filled polyethylene bags until used.

Numerous tests were conducted to determine the acceptability of the foregoing treatment. The test results are shown in Table 16.

Table 16
MECHANICAL PROPERTIES OF MIN-K-503 BEFORE AND
AFTER BAKING

Property	Treated	J-M ^a	Control
Total weight loss (%)	4.0	4.0	--
Modulus of rupture (psi)	41	30	51
Compression (psi/%)	120/4.8	45/5	93/4.4
Linear shrinkage ($\Delta L/L$)	0.005/1	(b)	--
Compression fracture (%)	5.0 ^c		5.0 ^c
Compression recovery (%)	4.0 ^d		4.0 ^d

^aJohns-Manville published data, private communication.

^bNegligible.

^cMinimum % compression for fracture detection in all samples.

^dMaximum % compression for total dimensional recovery.

3.3 RTV-60

This material is employed as an electrical insulation and to lend structural strength to components within the interior of the generator. Being a silicon-elastomer, RTV-60 inherently possesses high reliability in high-temperature ambient environment. Its electrical resistivity is greater than $10^{14} \Omega\text{-cm}$. No diluents are added and only minimal catalyst is used for curing. The curing process and potting techniques have been developed through a testing and evaluation program. This provided a

temperature-time curing schedule compatible with the chemistry of the elastomer and the geometry of the potting. The bake-cure schedule is designed to relieve the RTV-60 pot of all molecular weight compounds which are volatile within the operating temperature range of the generator. The elimination of these prevents structural reversion of the elastomer and ensures long-term chemical stability. Therefore, the processes developed guarantee retention of the best mechanical and chemical properties with negligible weight loss at high temperature. Other properties of RTV-60 are shown in Table 17.

Table 17

PROPERTIES OF RTV-60 ELECTRICAL INSULATION
AND POTTING MATERIAL

Tensile strength	600 psi
Elongation	110%
Shore (A) hardness	60
Chemical resistance	Excellent
Electrical strength	600 v/mil

Elastomeric properties are retained under continuous exposure at 500°F.

A special application of RTV-60 is an insulation in the fabrication of the individual thermocouple bundles. For this use it is reduced in viscosity with an aromatic solvent. The viscosity reduction, application techniques, and curing process again have been developed to provide retention of the adhesion, thermal, mechanical, and electrical properties of the elastomer. ⁽¹⁾

3.4 PYRE-ML INSULATING VARNISH

This material is a polyamide-type varnish used to electrically insulate the individual thermocouple wires in the generator thermopile. Laboratory evaluation of the varnish showed that it has excellent thermal, radiation, and solvent resistance along with outstanding electrical properties. It exhibits excellent bond strength to wire and retains its bond strength at elevated temperature. Laboratory thermal life is established to be in excess of 38,000 hr at 430°F⁽²⁾ when coated on copper wire.

A single disadvantage of this material is its ultimate deterioration when coated on iron-bearing alloys. In this case, the iron behaves as a catalyst in the curing process of the varnish, causing subsequent embrittlement and reduced breakdown voltage resistance. Extensive accelerated life testing of varnish-coated wires tends to substantiate this finding (see Section V).

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Tests⁽³⁾ indicated that a service life of 40,000 hr or more should be expected of this material when used as an insulating coating on nonferrous alloys.

3.5 GENERATOR SEAL

It is required that the generators be hermetically sealed. The course adopted was to develop binding techniques which exhibited high tensile lap shear strength, good flexural strength, low weight loss, and chemical stability over the range of ambient conditions to which the final generator assembly would be subjected. Subsequent to investigation into numerous bonding candidates, Epon 828/Versamid 125 was selected as the bonding system for the final sealing of the generators. It is a Bisphenol-A epichlorohydrin resin structure which, when properly used, possesses outstanding strength, adhesion, chemical resistance, and thermal stability.

There exists a wide variety of epoxy-based adhesives which could perform as well as the one selected. Choices of a specific resin, curing mechanism, and curing agent are always based on the end use, curing conditions, cost, and specific properties required in the application. Therefore, little data exist on specific uses and specific properties of the many possible modified epoxy systems.⁽⁴⁾ General purpose epoxy resin characteristics are published and available.⁽⁵⁾

Epon 828/Versamid 125 is an air-dry, room-temperature curing adhesive which possesses outstanding humidity resistance. Under conditions of proper surface preparation and mixing, its service life should be at least 5 years. This type epoxy is used in place of rivets in air-frame construction where service life requirements are rigidly imposed and bonds must remain stable under the most adverse atmospheric conditions.

Typically, this class of epoxy resins exhibits excellent thermal stress properties with negligible shrinkage. Tensile shear strengths are in excess of 2000 psi after 24 months immersion in distilled water. Aluminum is a preferred material for epoxy bonding and therefore offers joints of excellent over-all properties. Over the specified ambient temperature range of -65° to +165°F the generator seals exhibit no loss of tensile strength.^(5, 6)

Surface preparation procedures were carried out to guarantee the realization of the full cured strength of the 828/125 bonds. All the surfaces were sand blasted and solvent cleaned. The parts to be bonded were handled so as to avoid contamination of the bonding areas with grease.

In laboratory tests 0.005-in. aluminum bond coupons were immersed in a constant-temperature water bath and samples withdrawn at 100-hr

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intervals. In the lap-shear strength test, the epoxy bond strength exceeded the aluminum strength in all cases but two, in which both the aluminum and the bond experienced damage. The coupon bonds were prepared to test the worst possible bonding conditions. The aluminum coupons had highly polished surfaces and no special precautions were used to avoid grease contamination. Yet the bonds withstood loadings in excess of 300 psi, at which point the aluminum was torn.

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IV. FABRICATION AND QUALITY CONTROL

Fabrication techniques established to manufacture the SNAP-15A generator are heavily influenced by the reliability requirements of the unit. Since many of the process problems are unique to the design, conservative manufacturing techniques provide the greatest probability of success within the contractual time limits.

Based on the above premise, thermocouple fabrication has been established using a modular concept. Twenty-five thermocouples are wound in a series connection and fabricated into a small bundle to become a basic module (Fig. 12). This provides an excellent basis for unit process planning and control as well as flexibility to accommodate design changes. This procedure also permits reasonable rejection losses without incurring major scrap cost.

Since the basic module or bundle is a series connection, the parallel wiring is accomplished prior to final assembly by mating two bundles into a "dual unit" subassembly. These dual units are subsequently molded into a thermopile configuration of twenty-six "duals," then interconnected in series and tested prior to assembling the thermopile into the generator.

The fabrication plan can be considered as three major steps with intermediate processes. The following outlines these steps and briefly describes these processes:

4.1 FABRICATE THERMOBUNDLE (25 THERMOCOUPLES)

10 - Lace and twist ladder of 25 thermocouples (Fig. 13)

Both "P" and "N" wires are continuously laced in a fixture around a processing mandrel. After lacing, connecting wires are clipped and thermocouple junctions twisted. The mandrel holding the 25-couple "ladder" is removed from the fixture and numbered for quality control records.

20 - Remove insulation from twisted junctions

The thermocouple ladder and mandrel assembly is mounted in a fixture which masks the mandrel section and clamps the twisted

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Fig. 12--Thermobundle

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Fig. 13--Thermocouple ladder in winding jig

junctions while exposing the junction section which must have insulation removed for subsequent brazing. The Pyre-ML insulation is removed using a low pressure and blast technique applied to a selective area using a small hand nozzle.

30 - Trim twisted leads and braise

Excess junction material is sheared, the junctions fluxed, then dip brazed using No. 603 silver solder (1325°F).

35 - 100% Inspect

All brazed junctions are 100% inspected using a 40 power binocular microscope. Junctions are required to be brazed to at least 80% of their length, to be smooth, free of nodules, and without voids at the cross-over points of the wire twists. Total ladder resistance is measured and recorded for future comparison. Acceptable ladders are stamped and forwarded to the next operation.

40 - Spray coat twisted leads with RTV-60

All junctions are primed and spray coated with RTV-60 after masking the wire at the mandrel area.

45 - 100% inspect junctions

All junctions are inspected to assure 100% tip insulation using a 40 power binocular microscope.

50 - Collapse ladder and mold junctions

The processing mandrel was designed to permit collapsing in order to draw all thermocouple wires into one small bundle. This operation is performed manually using silicone primer as an adhesive to hold the bundle in the small configuration. The thermocouple junctions are now coated with RTV-60 and inserted into the tapered opening of a teflon mold. After closing the mold, the bundle is manually drawn into a 0.055-in.-diameter section of the mold, then cured.

60 - Attach nickel lead wires and braise

Two 0.010-in.-diameter nickel lead wires are attached to the cold end of the thermocouple bundle using RTV-60 as an adhesive and insulator. The 0.002-in.-diameter thermocouple wires are then sand blasted to remove ML insulation, wrapped to the base of the nickel lead wire, and brazed by dipping into No. 603 silver solder.

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65 - Inspect continuity and braze

All bundles are 100% inspected for continuity and braze quality, as well as general workmanship.

70 - Coat bundle with RTV-60

The bundle is now completely coated with a finish coat of RTV-60 and air cured.

80 - Bake completed bundle at 480^oF

Groups of bundles are placed in a baking fixture and oven-baked in air for 4 hr at 480^oF.

90 - 100% inspect and polarize

All bundles are 100% inspected for continuity, workmanship defects, latent short circuits, and the P connecting leg is flagged to indicate polarity. The polarity check involves application of low temperature to the hot end of the bundle and observing deflection of an electrical meter. The resistance of the finished bundle is compared to the initial resistance as processed during wiring. Any excessive change in resistance is cause for rejection.

4.2 ASSEMBLE THERMOPILE (52 BUNDLES)

10 - Join two bundles to form dual

Two single bundles are joined together using RTV as an adhesive to form a dual bundle. During this process the two P lead wires are joined by twisting. The two N lead wires are then joined to provide the first stage parallel wiring.

15 - Inspect

All dual bundles are inspected for workmanship, polarity, and latent short circuits.

20 - Construct duals into oriented thermopile

The dual bundles are fabricated into an oriented thermopile. This orientation provides a circular pattern to facilitate final wiring.

30 - Mold thermopile to thermal capacitor

The completed thermopile is solidly molded to the thermal capacitor using RTV-60.

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40 - Interconnect dual leads to provide series circuit

Starting at the outer circle of the oriented thermopile, the dual leads are individually fanned outward, interconnected in series, and spot welded. The leads are carefully dressed to within 1/32 of an inch of the thermal capacitor, then clipped except for the three leads used for final tap-off. All dressed leads are primed, the upper thermal capacitor placed into position, and the entire void space potted with RTV-60.

During the interconnect operation, a log sheet is maintained and the resistance of the device checked and posted to the log as connections are made.

50 - Mold junctions and apply capsule holder

The hot junctions of the thermobundles are coated with RTV-60 and molded to the capsule holder configuration. The hot-junction well of the capsule holder is coated with RTV-60 and assembled to the hot end of the thermopile. This completes the thermopile assembly (Fig. 14)

60 - Bake assembly at 480°F

The entire thermopile assembly is placed into a circulating oven and baked for 16 hr using a progressively increasing heat cycle, finally reaching 480°F.

4.3 ASSEMBLE THERMOPILE ASSEMBLY TO CONTAINER

10 - Fit pile assembly into Min-K details

The Min-K details have been machined, evacuated, and baked at 950°F. The core assembly is mated with the Min-K details and slipped into the outer container.

20 - Wire connector and cap assembly to pile

The connector wires are soldered to the tap-off leads of the pile assembly.

30 - Seal container with epoxy

The end details are coated with epoxy and pressed into position. The entire assembly is evacuated to eliminate air bubbles at the seal interfaces, then dried in air for 12 hr.

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Fig. 14--Thermopile assembly

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35 - Inspect

The completed assembly is inspected for workmanship and continuity, and internal resistances are compared to the log sheets written during core buildup. These resistances are then compared to the total resistance of the individual bundles used to fabricate the device.

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V. TEST EVALUATION5.1. COMPONENT TESTING

Component testing was initiated to qualify components for incorporation into the generator and to delineate, at the earliest possible time, long-time effects that might compromise the reliability of the generator. Components selected for testing were (1) thermocouple wire, (2) electrical insulation, (3) thermal insulation, (4) power feedthrough, (5) canister seal, and (6) thermobundles. The results of these tests are summarized below.

5.1.1. Thermocouple Wire

The thermoelectric and mechanical properties of several manufacturers' wire were measured and compared with published data. Tophel Special and Cupron Special were selected for more comprehensive testing and were found to be within 1% of published data. Curves of thermoelectric power and resistivity as measured at General Atomic are given in Figs. 15, 16, and 17.

5.1.2. Electrical Insulation

Insulations were evaluated as part of the material selection program (see Section III). Pyre-ML polyamide was applied to the wires by the manufacturer. To evaluate the effective life of this material, a voltage breakdown test was used. Specimens of the wire were wound on 1/8-in. - diameter metal mandrels which were inserted into a furnace and maintained at various temperatures ranging from 400° to 650°F. At first destructive tests were used, but the number of samples was small and the data so scattered that little information could be obtained without an extensive sample fabrication effort. A nondestructive tester was introduced instead which yielded more information with much less effort, since variations from sample to sample were reduced.

The results of the Pyre-ML insulation tests are shown in Figs. 18 and 19. These curves are based on average values determined in most cases from three or four specimens. The loss of breakdown voltage is rapid and extensive with both time and temperature. The effect of temperature is quite clear. Above 500°F there is little resistance to breakdown after 3000 hr. There is considerable scatter in the data, and the breakdown voltage loss appears to go in steps; thus it is not possible to extrapolate in time to the maximum voltage of 8.5 volts to which the insulation will be subjected in

Fig. 15--Tophel-Cupron thermocouple voltage output versus temperature

Fig. 16--Cupron Special resistivity versus temperature

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Fig. 17--Tophel Special resistivity versus temperature

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Fig. 18--Breakdown voltage of Pyre-ML insulation on Tophel Special versus time and temperature

Fig. 19--Breakdown voltage of Pyre-ML insulation on Cupron Special versus time and temperature

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the generator. While the insulation applied to Tophel Special wire is initially of superior breakdown resistance, after 6000 hr of exposure it is roughly equivalent to that applied to the Cupron Special wire. Over 6000 hr even at room temperature there has been a 30% to 40% loss.

The loss of breakdown voltage is more severe than would be expected from the insulation manufacturer's data (see Section III). Failure of the insulation resulted in failure of 12 thermobundles (see Table 18), which substantiates the breakdown voltage tests. Therefore, this component must be considered to be the component most likely to compromise the reliability of the generator and should be replaced early.

5.1.3. Thermal Insulation

Measurements of the thermal conductivity of Min-K-503 insulation were made to confirm vendor's data and to establish the effectiveness of the baking and gas filling processes devised (see Section III). Conductivity measurements were made on the Min-K-503 in the "as received condition" and after baking (1) in vacuum, (2) in argon gas, (3) in helium gas, and (4) in 50-50% mixture of argon and helium. The data are presented in Table 19 and Fig. 20. The differences in the vendor's data have not been explained. The measurements made at General Atomic were made on pieces of insulation of the size and shape quite close to those used in generators. Since Min-K-503 is quite heterogeneous, the size of samples measured may partially explain the difference in the results.

5.1.4. Electrical Feedthrough

The principal requirement on the electrical power feedthrough is its ability to maintain gas tightness under stringent environmental conditions. For that reason a connector qualified to military standards was selected and subjected to leak-rate tests using a helium mass spectrometer leak detector. A leak rate of $<10^{-8}$ std cc/sec was required. All feedthroughs tested were found to leak less than 10^{-9} std cc/sec.

5.1.5. Thermobundle Life Tests

Twenty-five series-connected thermocouples are used as the basic module from which the thermopile is assembled. Therefore, life testing of these components over a range of hot-junction temperatures was initiated early in the program. Bundles were added throughout the testing period so that changes in processing have occurred. Early thermobundles were made using a low-temperature braze (see Section III) and the RTV-60 was cured at room temperature. Later a high-temperature braze was introduced and RTV-60 was cured first at 600°F and later at 480°F. One very significant change was elimination of a 90-degree bend in early bundles which undoubtedly was a mechanical strain on the electrical insulation.

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Table 18

THERMOBUNDLE LIFE TEST RESULTS

Hot Junction Temp. Range (°F)	Total No. of Bundles	No. of Failures	Time Range to Failure (hr)	Number of Bundles Continuing on Test						
				3000- 4000 hr	4000- 5000 hr	5000- 6000 hr	6000- 7000 hr	7000- 8000 hr	8000- 9000 hr	9000- 10000 hr
400-450	4	1	2184-2328		1	1	1			
450-500	21	2	3836-3985	3	3	4	2	2	5	
500-550	9	3	1171-2328	4	1	1				
550-600	15	2	2117-2375	1	1	2	1	6		2
600-650	25	4	1340-2684	4	6	4		7		
Total	74	12		12	12	12	4	15	5	2

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Table 19
THERMAL CONDUCTIVITY TEST RESULTS OF MIN-K-503

Min-K-503	Av. Temperature Of Measurement (°F)	K $\left(\frac{\text{Btu-in.}}{\text{hr-ft}^2-\text{°F}}\right)$	K $\left(\frac{10^{-4} \text{ w}}{\text{in. - °F}}\right)$
Johns-Manville published data	200	0.16	3.26
Measured in air	300	0.17	3.46
As received (in air)	250	0.226	4.60
After baking (in helium)	250	0.320	6.52
After baking (in 50% He-50% Ar)	250	0.251	5.10
After baking (in argon)	250	0.189	3.85
After baking (in vacuum 5-10 μ Hg)	250	0.111	2.26

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Fig. 20--Measured thermal conductivity of Min-K-503 versus composition of back-filling gas

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The results of the tests to date are summarized in Table 18. Seventy-four bundles have been tested of which 12 failed. Failure is spread over the test temperature intervals. All of the failures occurred in bundles as first processed. In fact, 10 of the 12 failures occurred in the first 12 bundles (with 90° bends) placed on test. Even though placed on test at a later date, many bundles exceeded the time of the failures by factors of three and more. It appears that the fabricator's learning process may be influencing the results. All failures were found to be short circuiting in the region of the thermocouples protected by the Pyre-ML insulation. No failures occurred by open circuiting.

5.2. INITIAL GENERATOR PERFORMANCE

After completion of fabrication, each generator was leak tested, starting with Generator No. 9, and was subjected to an acceptance performance test before it was accepted for environmental and life testing. The purpose of the performance test was to determine the generator characteristics and to demonstrate that initially the generator was capable of performance according to specifications.

In the performance test, the generators were electrically heated and operated at constant-room-temperature ambient conditions. Steady operation was again established at -65°F ambient temperature. The ambient temperature was then raised to +165°F in less than 5 min, usually in about 1 min. The load voltage was monitored during the transient from steady operation at the low ambient temperature to steady operation at the high ambient temperature conditions.

The results of the performance tests are tabulated in Table 20. It is noted that the reproducibility of the measurements increases as one proceeds down the columns from the earliest prototype generator (Generator No.9) to the later ones. Increased reproducibility is the result of increased control of the fabrication processes and skill of the fabricators.

To be acceptable for life and environmental testing, the internal resistance of the generator must measure to within 660 Ω of the value determined by measurement of its individual thermobundles before they are assembled into a thermopile. In addition, the load voltage at end of life during the low-to-high ambient temperature transient must be equal at least to 4.5 volts when the heat input is initially 1.65 thermal watts. That is

$$(V_L - \Delta V_L) 0.95 \geq 4.5 \text{ volts,}$$

where the loss of voltage resulting from decay of the Pu²³⁸ source over a 5-year life is ~5%. Generators fulfilling the requirements were accepted

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Table 20

INITIAL PERFORMANCE OF SNAP-15A GENERATORS

Generator Serial No.	V _O (v)	V _L (v)	ΔV_L (v)	R _i (k Ω)	P _O (mw)	P _i (w)	ΔT_{hc} (°F)	W (lb)
1	0.17	0.165	----	0.726	----	----	---	-----
2	1.60	1.33	----	4.52	----	----	---	-----
3	7.10	4.93	0.96	10.0	1.08	1.81	266	-----
4	11.99	5.99	1.78	22.4	1.60	1.62	353	0.654
5	12.90	6.82	0.61	19.0	2.07	1.14	370	-----
6	7.98	5.74	0.53	8.77	1.47	1.48	263	0.834
7	8.69	6.28	0.57	8.66	1.75	1.34	287	0.830
8	8.80	6.31	0.73	8.87	1.77	1.37	288	0.807
9	8.73	6.23	0.70	9.04	1.72	1.38	283	0.807
10	3.12	2.59	----	4.60	0.30	----	---	-----
11	8.26	5.90	0.68	9.00	1.55	1.45	274	0.807
12	7.84	5.46	----	9.78	1.33	----	---	-----
13	7.45	5.32	0.54	8.85	1.26	1.56	252	0.825
14	8.33	5.90	0.66	9.24	1.56	1.44	276	0.824
15	8.22	5.97	0.64	8.49	1.59	1.41	271	0.832
16	8.46	6.00	0.68	9.23	1.60	1.42	273	0.828
17	8.54	6.15	0.78	8.74	1.68	1.42	271	0.825
18	7.64	5.48	0.70	8.88	1.33	1.57	269	0.828
19	8.26	5.93	0.65	8.85	1.56	1.43	276	0.839
20	8.45	6.10	0.69	8.64	1.65	1.43	278	0.811
21	5.91	4.29	0.54	8.52	0.82	1.94	---	0.817
22	8.41	6.05	0.69	8.76	1.63	1.41	269	0.825
23	8.41	6.05	0.75	8.77	1.63	1.43	276	0.830
24	8.16	5.90	0.68	8.65	1.55	1.45	272	0.822
25	8.46	6.14	0.74	8.51	1.68	1.41	281	0.825
26	8.55	6.15	0.68	8.80	1.68	1.39	283	0.832
27	8.42	6.02	0.60	8.98	1.61	1.40	266	0.83
28	8.45	6.11	0.56	8.64	1.66	1.37	279	0.83
29	8.43	5.96	0.65	9.35	1.58	1.43	277	0.83
30	8.23	5.95	0.72	8.62	1.57	1.45	275	0.83
31	8.41	6.06	0.67	8.68	1.63	1.41	281	0.83
32	8.29	6.01	0.64	8.48	1.61	1.41	299	0.83

V_O = open circuit voltage measured with 1.65 w(t) input power.V_L = voltage across 22.5 k Ω load with 1.65 w(t) input power. ΔV_L = voltage drop during -65° to +165°F, 5 min transient ambient temperature, electrically heated.R_i = internal resistance.P_O = power output with 1.65 w input power.P_i = end-of-life power input required to maintain a minimum voltage of 4.5 v. ΔT_{hc} = average temperature difference between hot and cold junction calculated from V_O measurements at +165°F ambient condition.

W = weight of generator when loaded with fuel capsules.

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for life and environmental testing. All of the prototype model generators built were acceptable except for Generator Nos. 10, 12, and 21. The thermopiles in Generator Nos. 10 and 12 were damaged in baking the thermopile in the final curing process of the RTV-60 potting to the capsule holder and thermal capacitor. Generator No. 21 had a thermobundle connection with reversed polarity.

Performance of Pu^{238} heated SNAP-15A generators was compared with the same generators when electrically heated. The performances are comparable within 5% except with respect to the ΔV_L (voltage drop during ambient transient). The Pu^{238} fuel capsule has a mass of about four times that of the electric heater. Thus, the thermal capacitance of the hot-junction region is increased, delaying its response to the ambient temperature change and resulting in increased ΔV . Comparative values are shown in Table 21.

5. 3. GENERATOR ENVIRONMENTAL TESTS

A spectrum of environmental tests was conducted to determine the versatility of the generator design, materials, and fabrication techniques and are shown in Table 22. In addition, through accelerated tests, confidence could be obtained in an indirect manner in the reliability of the generators as integrated structures. During any particular test, a generator was either electrically heated or loaded with a simulated fuel capsule. When electrically heated, the voltage output across a standard 1%, 22.5-k Ω resistor was monitored, otherwise the internal resistance was monitored. The basis for this duplicate test method was simulation of the thermal aspects of the generator in one case and mass distribution in the other. Heat loading would be preferable from thermoelectric and voltage data acquisition standpoints, while the dummy-mass loading is preferable from a structural integrity aspect (see Table 21). Therefore, testing under both conditions permitted a better characterization of the generators.

5. 3. 1. Irradiation

Two generators were subjected to 35 bursts of 3- to 4-r gamma radiation in less than 160 μsec at the General Atomic Linear Accelerator Facility. Total gamma irradiation was therefore in excess of 100 r. The radiation field dose was calibrated with cobalt glass. No detectable component or structural damage resulted. Since thresholds for radiation damage to the organic component materials are in excess of a megarad, further irradiation would offer no further useful information. (7)

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Table 21

COMPARATIVE PERFORMANCE OF ELECTRICAL AND Pu^{238} HEATED
SNAP-15A GENERATORS

Gen. No.	Proto- type No.	Electrical							Pu^{238}					
		Power Input (w)	V_o (v)	V_L (v)	ΔV_L (v)	R_i (k Ω)	P_o (mw)	ΔT_{hc} ($^{\circ}\text{F}$)	V_o (v)	V_L (v)	ΔV_L (v)	R_i (k Ω)	P_o (mw)	ΔT_{hc} ($^{\circ}\text{F}$)
9	P1	1.51	7.87	5.56	----	9.31	1.37	295	7.53	5.34	----	9.24	1.27	282
11	P2	1.54	7.46	5.24	----	9.52	1.22	280	7.53	5.18	----	9.48	1.19	282
13	P3	1.56	6.70	4.79	----	8.95	1.02	251	6.98	4.98	----	9.01	1.10	262
17	P7	1.51	7.81	5.63	0.78	8.74	1.41	273	7.87	5.67	0.86	8.73	1.43	280

 V_o - Open-circuit voltage. V_L - Voltage across 22.5-k Ω load. ΔV_L - Voltage drop during -65 $^{\circ}$ to +165 $^{\circ}\text{F}$ transient of ambient temperature in < 5 min. R_i - Internal resistance. P_o - Power output. ΔT_{hc} - Temperature difference between hot and cold junctions calculated from V_o measurements at room-temperature ambient.

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Table 22
SNAP-15A ENVIRONMENTAL TESTS COMPLETED

Generator No.	Performance Test	Vibration Test	Shock Test	Thermal-cycling Test	Acceleration Test	Humidity Test	Irradiation Test	Pu ²³⁸ Fueled Generators	No. Fueled Generators on Test
6	X	X	X	X			X		
7	X	X	X	X			X		
8	X	X	X	X					
9 ^a	X	X	X	X	X			X	X
10		X	X						
11 ^a	X	X	X	X	X			X	X
12									
13 ^a	X	X	X	X	X	X		X	X
14	X	X	X	X	X	X			
15	X	X	X	X	X	X		X	X
16	X	X	X			X			
17	X	X	X					X	X
18	X	X	X					X	X
19	X	X	X						
20	X	X	X						
21	X								
22	X	X	X						
23	X	X	X						
24	X	X	X						
25	X	X	X						
26	X	X	X						
27	X								
28	X								
29	X								
30	X								
31	X								
32	X								

^aVibration, shock, and acceleration tested with Pu fuel capsule.

5.3.2. Thermal Cycling

This is an environmental test designed to evaluate generator performance under accelerated extreme swings in ambient temperature. It is identical to the performance test described earlier but consists of six temperature cycles within a period of 24 hr. The test is conducted in a specially constructed high-low temperature chamber which automatically performs the temperature cycling and which achieves a temperature excursion between -65° and $+165^{\circ}\text{F}$ within a 5-min period. The test is done in an uncontrolled humidity atmosphere. The generator is held at each temperature extreme for 4 hr to permit thermal stabilization to occur.

Five generators were exposed with no thermopile degradation. The generators developed leaks in their epoxy seals. Examination under stereoscopic magnification determined that the substrate aluminum in the leak area had been improperly prepared. After repair of the seals, evacuation, and inert gas back-fill, the generators returned to their original performance. Performance under this test is illustrated in Fig. 21.

5.3.3. Shock Test

The shock test is in some aspects the most severe of the dynamic tests. Eighteen shocks are administered, three in each direction along the three mutually orthogonal axes (see Fig. 22). All shocks were performed on an oscilloscope-calibrated free-fall machine at 100 g at a pulse duration of 11 msec. The pulses have essentially a half-sine-wave form.

Sixteen generators were subjected to this test. Typically, the generators exhibit small fluctuations in internal resistance of approximately 1% or less and of several seconds lifetime. Load voltage measurements also indicate small fluctuations on the order of less than 10 mv, which is typical. Representative load voltage data are shown in Table 23.

5.3.4. Vibration

As in the shock test, sixteen generators were subjected to vibration testing along each of the three major axes. The test consists of essentially uniaxial sinusoidal vibration over the frequency range 0 to 2000 cps and return within a 60-min sweep period. Above 32 cps the vibration is constant at 10 g.

During the test all generators exhibited voltage and internal resistance changes. When vibration ceased, these quantities stabilized to their original values within about a 1-hr period. These changes are shown in representative curves in Figs. 23 and 24. Three generators suffered damage under vibration during the testing program. In two cases the damage was investigated in

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Fig. 21--Typical curve of load voltage variation during thermal cycling tests

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Fig. 22--Illustration defining generator axes

Table 23

MECHANICAL SHOCK TEST OF GENERATOR NO. 11

Axis	Drop	V_o^a (v)	V_o (v)	V_L^a (v)	V_L (v)
X-1	1	7.292	7.307	5.143	5.101
	2		7.308		5.101
	3		7.313		5.158
X-2	1	7.312	7.307	5.157	5.099
	2		7.304		5.098
	3		7.304		5.098
Y-1	1	7.299	7.299	5.107	5.107
	2		7.299		5.105
	3		7.299		5.106
Y-2	1	7.303	7.304	5.109	5.110
	2		7.302		5.108
	3		7.302		5.108
Z-1	1	7.297	7.298	5.105	5.105
	2		7.302		5.109
	3		7.302		5.109
Z-2	1	7.299	7.300	5.107	5.107
	2		7.306		5.134
	3		7.300		5.106

^a Prior to shock.

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Fig. 23--Typical curve of load voltage variation during vibration tests

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Fig. 24--Typical curve of internal resistance change during vibration tests

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detail and was found to have resulted directly from pre-existing structural defects. In one of the two cases a stud improperly fastened in the generator caused extreme oscillation during vibration testing, which resulted in damage to the thermopile and the stripping and shearing of several studs. In the other case, the fuel capsule was loosened and escaped from its holder during the vibration test, as a result of a loose-fitting cap whose threads had been reworked to correct a galling problem. The capsule hammered a cavity in the Min-K around the open end of the capsule holder. There was no other damage and the generator was completely repairable. In the third case, the center tap lead circuit opened, but the end taps were not affected.

5.3.5. Acceleration

High-level steady-state acceleration is performed for 5 min with rise and decay times of 2 min each for a total acceleration period of 9 min. The generators are subjected to this vibration in each direction along each of the major orthogonal axes. Five generators were tested during the program, with none of them suffering any structural damage or performance degradation.

During the 9-min period, changes occur in voltage and resistance similar to those experienced under vibration. Although to some extent the magnitude and form of the changes are peculiar to the axis of acceleration, typical curves were developed as shown in Figs. 25 and 26.

5.3.6. Humidity

Thermal cycling coupled with exposure to 93% humidity for a period of 20 days represents the most severe environmental test in the program. The test profile is illustrated in Fig. 27. During this test the epoxy seals are subjected to high tensile stress and flexure under severe ambient conditions. Four generators were subjected to this test during the program, with no failures.

5.3.7. Dynamic Testing of Plutonium-fueled Generators

Three generators, fueled with plutonium, were subjected to the shock, vibration, and acceleration tests described above. Typical results of voltage and resistance measurements indicate no significant departure from the results of testing under electrically simulated fuel heat and dummy-mass fuel load.

Life testing of the generators were performed concurrently with environmental testing. The life testing of each generator was interrupted periodically to perform environmental tests. The time in the life of each generator during which environmental tests were performed is shown in Section 5.4, Figs. 29 through 45.

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Fig. 25--Typical curve of load voltage variation during acceleration tests

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Fig. 26--Typical curve of internal resistance variation during acceleration tests

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Fig. 27--Humidity test-cycle definition curve

5. 4. GENERATOR LIFE TESTS

Life testing of the generators was performed concurrently with environmental testing; the test stands are shown in Fig. 28. The purpose of interrupting the life tests for environmental tests was to induce any aging or degradation of generator components that would help in appraising their long-life performance and reliability.

Generators were life tested at three ambient temperatures, -65°F , room temperature, and $+165^{\circ}\text{F}$. Life testing was performed with plutonium-heated capsules to the extent they were available. When plutonium capsules were not available, electrically heated capsules were used.

Accumulated generator-hours of testing, as of the end of August 1964 for each of three generator classes, are given in Table 24. Detailed life data at the end of August 1964 are presented in Table 25, including annotations regarding degradation, changes of internal resistance, accuracy of measurement, etc. Performance of the generators over their test life is presented

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Fig. 28--Life test stands

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as open-circuit voltage and load voltage to a 22.5 k Ω load as a function of time in Figs. 29 through 45.

Table 24
SUMMARY OF GENERATOR LIFE TEST
(As of 8/31/64)

Generator Type	Accumulated Generator- hours	Max. Test Time on Single Generator (hr)
Experimental	28,991	8,694
Demonstration	19,662	6,940
Prototype	<u>51,073</u>	5,163
	99,726	
Prototype		
Plutonium heated	18,168	3,720
High ambient temperature	13,346	2,848
Room ambient temperature	26,648	4,707
Low ambient temperature	11,099	3,500

Degradation in the generator load voltage of 11.5% may occur from replacement of the argon fill gas with air and water vapor through leaks in the generator canister seals. Such leaks have occurred in several generators and are shown by degradation of load voltage without changes in the internal resistance of the generator. By evacuating and refilling the generator with argon gas, it has been demonstrated that complete recovery of lost performance can be achieved in these cases.

In four generators (9, 11, 18, and 25) significant changes in generator resistance have occurred which indicate that either open circuit, short circuit, or a combination of open and short circuit conditions have developed in the thermopiles. Open-circuit failure increases resistance and short-circuit failure decreases resistance. However, because of the inherent reliability of the redundant circuit design, all of the generators continued to perform to specifications in spite of individual couple or bundle failures. Except for Generator No. 25, degradation has been less than 10%, most of which is attributable to leaks resulting in argon-air exchange. Thus, one of the three major conclusions of the test program is the need for an improved seal. The second conclusion is the need to replace the Pyre-ML insulation. The third conclusion is that other than these two items the generator fulfills and exceeds the performance specifications.

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Table 25

LIFE PERFORMANCE TEST ON SNAP-15A GENERATORS
(In hours as of 8/31/64)

Generator No.	Isotopic Heated	Electrically Heated	Low Temp. Ambient	Room Temp. Ambient	High Temp. Ambient	Total Test Time	Degradation ^a
1		2498			2498	Term. 12/29/63	100%
2		1296			1296	Term. 9/27/63	None
3		8694		8694		8694	None
4		8385		8385		8385	None
5		8118		8118		8118	None
6		6940		6940		6940	-8.4%
7		6358		6358		6358	-1.7%
8		6364		6364		6364	None
9	3312	1692	3500	1495	9	5004	-7.2%
10 ^b		4987		372	4615	4987	None
11 ^b	3720	1443	432	4707	24	5163	-0.8%
12 ^b							
13	2688	2085	8256	1829	88	4773	-5.0%
14		3278	18	1092	2168	3278	-3.5%
15	2160	1195	2002	1257	96	3355	-1.6%
16		3142	17	3046	79	3142	None
17	3144	211	32	475	2848	3355	-3.5%
18	3144	44	400	2780	8	3188	-1.7%
19		3076	16	3052	8	3076	None
20 ^b		3028	17	3003	8	3028	None
21 ^b							
22		2755	17	2730	8	2755	None
23		2623	16	25	2582	2623	None
24		2077	16	6	2055	2077	-3.3%
25		2078	16	5	2057	2078	-13.7%
26		1826	1696	5	125	1826	None
27		1152	16	1129	7	1152	None
28		1008	16	5	987	1008	None
29		192	16	7	169	92	None
30		648	5	475	168	648	None
31			4	31	4	39	None
32			5	126	24	155	None

^a See notes on next page.

^b Not accepted for life performance test. Generator 10 was placed on test at high ambient-temperature conditions in an early test even though it was not an acceptable prototype generator.

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Table 25 (Continued)

NOTES:Generator No. 6

The load voltage is down 8.4%, where accuracy of measurement is 3%. Initial resistance at 75°F, 8942 Ω; resistance as of 8/24/64, 10,545 Ω.

Generator No. 7

The load voltage is down 1.7%, where accuracy of measurement is 1%. Initial resistance at 75°F, 8944 Ω; resistance as of 8/24/64, 8856 Ω.

Generator No. 9*

The load voltage is down 7.2%, where accuracy of measurement is 1%. Initial resistance at -65°F, 9083 Ω; resistance as of 8/24/64, 10,170 Ω.

Generator No. 11

The load voltage is down 0.8%, where accuracy of measurement is 1%. Initial resistance at 75°F, 9783 Ω; resistance as of 8/3/64, 9985 Ω.

Generator No. 13*

The load voltage is down 5.0%, where accuracy of measurement is 1%. Initial resistance at -65°F, 8518 Ω; resistance as of 8/24/64, 8507 Ω.

Generator No. 14

The load voltage is down 3.5%, where accuracy of measurement is 3%. Initial resistance at 165°F, 9405 Ω; resistance as of 8/24/64, 9403 Ω.

Generator No. 15*

The load voltage is down 1.6%, where accuracy of measurement is 1%. Initial resistance at -65°F, 8470 Ω; resistance as of 8/24/64, 8498 Ω.

* On the morning of 8/14/64, the solenoid valve controlling the flow of liquid CO₂ into the low ambient chamber failed to close. The ambient temperature fell to approximately -120°F for approximately 15 minutes. New parts were installed in the solenoid and no other malfunctions have been observed.

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Table 25 (Continued)

Generator No. 17

The load voltage is down 3.5%, where accuracy of measurement is 3%. Initial resistance at 165^oF, 8947 Ω ; resistance as of 8/24/64, 8948 Ω .

Generator No. 18

The load voltage is down 1.7%, where accuracy of measurement is 1%. Initial resistance at 75^oF, 8983 Ω ; resistance as of 8/24/64, 9346 Ω .

Generator No. 24

The load voltage is down 3.3%, where accuracy of measurement is 3%. Initial resistance at 165^oF, 8918 Ω ; resistance as of 8/24/64, 8885 Ω .

Generator No. 25

The load voltage is down 13.7%, where accuracy of measurement is 3%. Initial resistance at 165^oF, 8766 Ω ; resistance as of 8/24/64, 7714 Ω .

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Fig. 29--Life performance curve for SNAP-15A generator No. 9

Fig. 30--Life performance curve for SNAP-15A generator No. 11

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Fig. 31--Life performance curve for SNAP-15A generator No. 13

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Fig. 32--Life performance curve for SNAP-15A generator No. 14

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Fig 33--Life performance curve for SNAP-15A generator No 15

Fig. 34--Life performance curve for SNAP-15A generator No. 16

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Fig. 35--Life performance curve for SNAP-15A generator No. 17

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Fig. 36--Life performance curve for SNAP-15A generator No. 18

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Fig. 37--Life performance curve for SNAP-15A generator No. 19

Fig. 38--Life performance curve for SNAP-15A generator No. 20

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Fig 39--Life performance curve for SNAP-15A generator No 22

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Fig 40--Life performance curve for SNAP-15A generator No 23

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Fig. 41--Life performance curve for SNAP-15A generator No. 24

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Fig 42--Life performance curve for SNAP-15A generator No 25

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Fig. 43--Life performance curve for SNAP-15A generator No. 26

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Fig. 44--Life performance curve for SNAP-15A generator No. 27

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Fig. 45--Life performance curve for SNAP-15A generator No. 28

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Fig. 46--Life performance curve for SNAP-15A generator No. 29

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Fig 47--Life performance curve for SNAP-15A generator No. 30

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Fig 48--Life performance curve for SNAP-15A generator No 31

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Fig 49--Life performance curve for SNAP-15A generator No 32

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VI. RELIABILITY

A preliminary reliability estimate was made of early models based on general experience with similar components in the aerospace industry. The inherent reliability of the SNAP-15A generator (based on Experimental Generator No. 3) for 5-year life was estimated to be 0.999 under the following assumptions.

1. Complete quality control inspection tests have been conducted on each unit to ensure correctness of connections, soundness of bonds, correctness of polarity, etc.
2. The failure rate for a twisted and brazed thermocouple junction is the same as the lower generic failure rate of a soldered joint. (See Section ME 55-50 of Ref. 8 for generic failure rates.)
3. The increase in failure rate resulting from exposure to the test environment approximates the magnitude of failure rate change encountered with similar components and environments in aerospace applications. (See Section ME 55-50 of Ref. 8 for failure rate adjustment factors.)
4. The reliability of the structural elements is such that no random failures can be reasonably expected during the test and operating phases. This assumption was made after careful examination of the structural sections and the manner in which these sections are bonded to each other.

Four design recommendations to increase reliability were made: (1) revision of O-ring installation; (2) use of electrical insulation on thermocouple wires which has better-known life and temperature properties; (3) potting of thermocouple circuit; and (4) use of lock wire on mounting studs. All recommendations except (2) were incorporated into later models. The recommendation of higher-temperature insulation is valid, but data were not available to substantiate a better choice than the Pyre-ML.

After fabricating $\sim 10^5$ thermocouple junctions and operating for $\sim 10^8$ junction-hours, there have been no known failures of the junctions. In some cases the increase of the internal resistance of generators on test by 330 Ω indicates an open circuit in one thermobundle. In all observable cases wire breakage has been the cause. In no case has the generator failed to perform to specifications because of an open-circuited thermobundle;

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thus, these failures cannot be specifically identified until the generators are dissected.

Short circuiting within generators has been identified by reduced open-circuit voltage and internal resistance. As in the case of open circuiting, the specific mode of failure must await dissection of the generators which at present are performing within specification because of the reliability built into the device by its redundant circuitry network. Failure of thermobundles by shorting in component life testing resulted from failure of the Pyre-ML electrical insulation (see Section 5.1). While improvement in fabrication techniques by learning and process changes appear to have reduced the failure rate, nondestructive breakdown voltage tests indicate that the Pyre-ML insulation is probably a marginal component in terms of achieving the desired reliability.

Generator seal leakage has caused degradation of the load voltage of the generator but is limited to a maximum of 11.5%, except under unusually high humidity, for extended periods of time. Some of the seal problems are attributable to contamination of the bonded surfaces by smears of Min-K insulation materials as the components are slid into the canister during the final assembly operation. This may be corrected by coating the Min-K with nonsmearing, noncontaminating material (such as epoxy) or replacing the seal with one of new design. Leaking of the temporary seals of the fuel port plug made to accommodate testing with electrical heaters has occurred. Because of the temporary aspect of the seal, it is not made with the materials or procedures to be used in final sealing and, therefore, is not considered to be a reliability factor.

There have been no structural failures observed during environmental testing, with the one exception where the Min-K insulation was damaged by a fuel capsule that vibrated loose in its holder. This came about by galling of the capsule holder plug which required retapping of the holder threads to make them slightly oversized and, thus, loose fitting. The possibility of this type of failure recurring has been avoided by elimination of the galling problem and using adhesive on the threads during final insertion of the fuel capsule.

It is not expected that the ambient temperature the generator will experience in operation will be the maximum design value of $+165^{\circ}\text{F}$ for much of its life. However, at that ambient temperature the hot end of the thermopile will be $<500^{\circ}\text{F}$. Although the results of the voltage breakdown test lead one to expect thermobundle failure at $\sim 3,000$ hr at about 530°F , thermobundles are continuing to operate without failure at 600° to 650°F for 4,000 to 10,000 hr or approximately three times that expected. According to the manufacturer's data, the expected life would be <500 hr at 625°F . Thus, the reliability of the thermobundles appears to be significantly better

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than Pyre-ML alone. This may be the result of redundant insulation coverage of ML in the critical temperature region by RTV-60 (see Fig. 50). As mentioned previously it is significant that 10 of the 12 thermobundle failures occurred in the first 12 bundles placed on life test and therefore are representative of the earliest fabrication efforts.

It is concluded, therefore, that reliability of the SNAP-15A generator is very high. Even further enhancement in the reliability can be obtained by replacing the Pyre-ML electrical insulation with one of higher temperature characteristics and redesigning the generator seals (probably using all welded construction).

Fig. 50--Thermocouple junction insulation detail

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VII. SAFETY

A safety program for SNAP-15A generators has been prepared and a report submitted to the AEC for approval. The program devised has been completed and the results are summarized below.

Safety of SNAP-15A generators is primarily concerned with the safety of the fuel capsule. Because of the extreme toxicity of Pu^{238} ($\text{MPC} = 1 \times 10^{-12}$ and $3 \times 10^{-6} \mu\text{c/ml}$ in air and water, respectively) and its chemical reactivity, encapsulation of the radioisotope and control of the capsules are necessary to prevent dispersion under all foreseeable conditions. Analyses of the accidents which may occur indicate that those during transportation are the most important both in probability of occurrence and severity. Fire, impact, and loss were considered to be of greatest concern. The capsules have been designed to withstand fire and impact under the maximum credible accident condition. Probability of loss is minimized by control procedures and, in event of loss, recovery plans and procedures have been written.

7.1. FIRE

The worst credible fire is that which could follow the crash of a fully fueled aircraft in an inaccessible location. The high concentration of burning fuel could lead to temperatures of 1700°F except in a few exceptional fires that may exceed 1700°F . Toward the end of its life when the internally generated helium pressure is greatest, temperatures of 1700°F will increase the pressure by more than a factor of three and at the same time reduce the strength of the Haynes 25 outer capsule by about a factor of two. To prevent rupture followed by dispersion of the isotope, the capsule has been designed to withstand 1700°F after twice its design life of helium accumulation (10 yr). A void volume of 120% of the isotope volume is provided to restrict the pressure to 6500 psi under these conditions.

In addition, the capsule will be contained in the generator in most instances where the thermal insulation of the generator will delay its exposure to elevated temperatures. The generator in turn will be transported in its shipping container designed to withstand 2000°F for 30 min as shown in Fig. 51. Oxidation of the Haynes 25 outer shell is not expected to be serious during the time and temperature of exposure.

Two tests have been devised to demonstrate the adequacy of the capsule design and fabrication--(1) a fire test and (2) a burst test. These tests have been successfully performed.

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Fig. 51--SNAP-15A generator and shipping cask

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In the fire test, three capsules were exposed for 30 min to 2000°F on 50% of their surface and then quenched in room-temperature water. Each capsule was subjected to two cycles without evidence of damage or leaking to $<10^{-9}$ cm³/sec.

In the burst tests, capsule temperatures were raised to room temperature, 500°, 1500°, 1725°, 2000°, and 2325°F. The internal pressure was then slowly raised, through an attached tube in one end of the capsule, to progressively higher levels and held for 15 min at each level. The procedure continued until each capsule burst. Photographs of some of the burst capsules are shown in Figs. 52 and 53. A total of ten capsules were burst with the results shown in Fig. 54 where burst pressure is plotted as a function of capsule temperature. The design burst-pressure point for these capsules is shown in Fig. 54 to be 7000 psi at 1700°F (corresponding to a 10 yr life). Also shown is the expected pressure of 2360 psia at 1700°F after five years, the design life of the generator. From this curve and the equations for helium accumulation as Pu²³⁸ decays, capsule life has been computed to be 12 years and 4.75 years when exposed to 1700°F and 2000°F fires, respectively. Thus, the capsules have performed slightly better than designed and are regarded to be safe in this respect.

7.2. IMPACT TEST

The worst impact would be the capsule falling at its terminal velocity in air against a rigid surface. This is a very improbable accident that could result only from a catastrophic aircraft explosion much more severe than any compressive impact that would be suffered in transportation accidents, because the generator and shipping container provide three thicknesses of aluminum, three thicknesses of insulation, and one thickness of steel to protect and cushion against external blows. The terminal velocity of the capsule in air starting from rest at a 10,000-ft height and falling without tumbling a distance of 7000 ft to impact on one end at 3000 ft above sea level is computed to be about 200 ft/sec. The impact pressure, estimated at 9000 psi, is less than the internal pressure for which the capsule is designed. Thus, the capsule should survive impact at terminal velocity.

Impact tests of SNAP-15A capsules were conducted at Sandia Corporation in Albuquerque. In these tests, the capsules were heated by infrared radiation to 255°F, the temperature computed to be attained at the moment of impact. The capsules were hung from fine wires and then impacted by a piece of granite carried by a bazooka rocket. Three sets of tests were performed. Preliminary testing of six capsules was conducted, but the results shown in Table 26 were inconclusive. In these capsules the plutonium fuel was simulated by increasing the bottom thickness of the tantalum liner to an equivalent mass of fuel. A second series of impacts

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Fig. 52--Photographs showing capsule before burst test and after test under different pressures at 500°F

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Fig. 53--Photographs showing burst capsule at three different pressures and two different temperatures

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Fig. 54--SNAP-15A capsule burst pressure versus temperature

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Table 26
TANTALUM-SIMULATED FUEL LOAD
IMPACT TEST RESULTS
(Series 1)

Attitude Θ (degrees)	Impact . Velocity (ft/sec)	Results
3	302	Survived
23	298	Ruptured
39	242	Ruptured
39	349	Ruptured
43	399	Ruptured
47	197	Ruptured

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was made using a stainless-steel capsule model. Thirty-two capsule models were impacted at five impact attitudes to determine the most critical attitude and the results are shown in Table 27. It is clear that an attitude of 45 degrees is the most severe, as indicated by the highest number of ruptures in the lowest velocity range. In the third series of impacts 30 capsules were tested with the results shown in Table 28. Since rupture occurred in three of ten tests at ~110% of computed free-fall terminal velocity when impacted at an attitude of 45 degrees, it is concluded either (1) that the capsule will require modification to survive such impacts or (2) that the probability of such impact will have to be demonstrated analytically to be sufficiently small to be an acceptable risk.

Table 27
IMPACT TEST RESULTS ON
STAINLESS-STEEL CAPSULE MODELS
(Series 2)

Attitude Θ (degrees)	Velocity Range (fps)	Results
0	292-449	6 survived, 2 ruptured
45	146-276	6 survived, 5 ruptured
90	294-415	3 survived
135	250-352	5 survived
180	258-399	5 survived

Table 28
TUNGSTEN-SIMULATED FUEL LOAD
IMPACT TEST RESULTS
(Series 3)

Attitude Θ (degrees)	Velocity (fps)		
	225	250	300
0	---	2	1
45	10(3F ^a)	6(3F)	1(1F ^a)
50	---	1(1F)	---
90	---	2	1
135	---	2	1
180	---	2	1

^aNumber of failures by rupture of outer capsule.

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The external radiation hazard from the SNAP-15A fuel capsule is almost negligible as may be seen from Table 29. This is to be compared with the normal AEC tolerance for laboratory workers of 7.5 mr/hr per 8-hr day. Thus, the capsules are not particularly hazardous as a source of external radiation. In the case of lost capsules, the gamma radiation emitted by the capsule as well as its temperature may be used as aids in its detection and recovery. Using standard scintillation counters, a SNAP-15A capsule should be detectable at a radius of 3.3 yd. Similarly, using infrared detectors of the type used by the military for night maneuvering and detection of enemy personnel, the detection radius of the SNAP-15A fuel capsule is expected to be 35 yd when the capsule is lying or standing in air free from any visual obstructions. In the case of a lost capsule that is not recovered, it is important to know the characteristics of the capsule in various corrosive environments. Haynes 25 alloy has been demonstrated to be resistant to most acids at room temperature. The resistance of the capsule to corrosion by salt water has been evaluated by immersion of one unloaded capsule below the ocean level at low tide and by another placed slightly above this level so that it was exposed to air twice a day. These capsules were examined after two months of exposure without any detectable corrosion. A second inspection at a later date revealed that one of the capsules had been lost while the second one showed no evidence of corrosion.

Table 29

DOSE RATE MEASUREMENT OF SNAP-15A GENERATOR
(Generator 18, Capsule 76)

Position	Distance From Center of Fuel (cm)	Dose Rate		
		Gamma (mr/hr)	Neutron (mrem/hr)	Total (mrem/hr)
Top	4.1	3.3	3.2	6.5
Side (0°)	3.3	6.4	3.9	10.3
Side (180°)	3.3	6.3	4.2	10.5
Bottom	8.6	0.37	0.21	0.58

Other tests to which the capsules were subjected to satisfy the requirements of the Interstate Commerce Commission were as follows:

- (1) Twenty-two capsules were placed on a soft pine board with the welded end facing up and were struck a blow of 10 ft-lb by a steel hammer. The capsules were examined for damage and leaks subsequent to this test and were found to be intact, without leaks.

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- (2) Twenty-two fuel capsules were subjected to a sinusoidal vibration of 34 to 2000 cps and an acceleration of 30 g in three orthogonal directions corresponding to the principal axes of the cylinder. No resonances were found after the capsules had been vibrated continuously for 2 hr.
- (3) Twenty-two fuel capsules were heated to 500^oF and held at this temperature for 40 min. They were subsequently removed from the furnace and plunged into a bath of dry ice in a nonflammable solvent. After 20 min of submersion, the capsules were removed from the bath and returned to the furnace. This procedure was repeated four times. The maximum time of transfer between the two environments was well below 1 min. The capsules were undamaged and were found to be free of leaks.
- (4) Eleven capsules were immersed in water at a pH of 7.0 and 70^oF for 1 week. No evidence of corrosion was found.
- (5) Eleven capsules were heated to 90^oF in the air and held at that temperature for one week. No evidence of corrosion was found.

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REFERENCES

1. RTV Silicone Rubber, General Electric Technical Data Book S-3B, Silicone Products Department, General Electric Company, Waterford, New York.
2. Emig, F., private communication, Du Pont Insulation Department, E. I. du Pont de Nemours and Company, Chicago.
3. Schweitzer, F. E., et al., "An Evaluation of Insulation System Based on Polymer ML," American Institute of Electrical Engineers, Paper T-137-16.
4. Shell Technical Bulletins SC: 60-60 Revised and SC:62-131, Plastics and Resins Division, Shell Chemical Company, Downey, California.
5. Technical Data on Plastics, Section 6, Manufacturing Chemists' Association, February, 1957, pp. 39-44.
6. Brenner, W., et al., High-Temperature Plastics, Reinhold Publishing Corporation, New York, 1962.
7. Collins, C. G., and V. P. Calkins, "Radiation Damage to Elastomers, Plastics, and Organic Liquids," Aircraft Nuclear Propulsion Department, General Electric Company, Report APEX-261, September, 1956.
8. Design Assurance Manual for Engineers, General Dynamics/Astronautics, San Diego, California.