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DESIGN OF THE SNAP-15A GENERATOR

by

R. J. Campana

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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GENERAL ATOMIC
DIVISION OF
GENERAL DYNAMICS

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I. INTRODUCTION

This report summarizes the considerations and analysis leading to the design of the SNAP-15A generator, a Pu-238 fueled, metal thermocouple generator providing about 1 milliwatt of output power at greater than 4.5 volts for 5 years with very high reliability even under extreme environmental conditions. The generator is being developed for the U. S. Atomic Energy Commission by General Atomic Division of General Dynamics Corporation under Contract AT(04-3)-167, Project Agreement 21.

The design approach begins with basic considerations of a generator which will perform according to the specifications established by the AEC at the beginning of the program as shown in Table 1. The basic considerations established the superiority of the metal thermocouple over the semiconductor thermocouple and resulted in the conceptual design. Throughout the design process particular choices were made so as to result in a highly reliable generator that could be built after a short development period and be based on existing technology.

Before the design was completed, a few experimental generators were built and tested. These generators influenced the final generator design, especially with respect to the transient response of the generator load voltage to step changes in the ambient temperature. The presentation of the work is made in the chronological sequence in which the design was evolved.

A model of the generator is shown in Fig. 1.

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 $^{\circ}$ to +165 $^{\circ}$ 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 <u>g</u>
Vibration	0-3000 cps at 10- <u>g</u> acceleration
Thermal cycling of	
ambient temperature	-65 $^{\circ}$ to +165 $^{\circ}$ to -65 $^{\circ}$ F, 5-min transient
Acceleration	60 <u>g</u> constant
Relative humidity	93% at 149 $^{\circ}$ F
Reliability	90% confidence of < 1 failure in 1000 units

Fig. 1--SNAP-15A generator model

II. DESIGN SUMMARY

2.1 GENERATOR DESCRIPTION

The SNAP-15A generator as developed is shown in Fig. 1; its estimated 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

ESTIMATED PERFORMANCE OF SNAP-15A GENERATORS*

Power output	1.55 mw
Open-circuit voltage	8.12 v
Load voltage	5.90 v
ΔV_L during ambient transient . . .	0.55 v
Load resistance	22.5 k Ω
Generator resistance	8.66 k Ω
Thermal input	1.46 w
Over-all efficiency	0.106%
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

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

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

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

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.,

$$q_t = q_h + q_b .$$

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_{hmin} , 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

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

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 will skill comparable to that already achieved with better known materials.

The figure-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 ($R_L = 22.5 \text{ k}\Omega$).

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. MnSi_2 , Cr_2O_3 , 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.

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

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

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

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.

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

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

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 ($k\rho$) of 9.7×10^{-6} . Min-K-503 in vacuum is next with a $k\rho$ value of 2.2×10^{-5} and operates at higher temperatures followed by Min-K-1301 in vacuum having a $k\rho$ 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 $k\rho$ 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

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

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

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,

$$R_h \gg R_c .$$

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).

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. 8. 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

Fig. 7--Temperature distribution determined by analog computation

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.

Fig. 8--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
Su	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.

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.

Table 10

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

Case	Heat In (w)	No. of Bundles	$\Delta T_{(-65^\circ\text{F})}$ ($^\circ\text{F}$)	$V_{L(-65^\circ\text{F})}$ (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

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.

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. 9.

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.

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 computed 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 11. 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

Fig. 9--Experimental Generator No. 5, basic configuration

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 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 11
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 12 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 12

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.