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**HIGH-TEMPERATURE RADIOISOTOPE
THERMOELECTRIC GENERATOR FOR
SPACE APPLICATIONS**

December 31, 1964

Astro - Electronics Division
Radio Corporation of America
Princeton, New Jersey

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HIGH-TEMPERATURE RADIOISOTOPE THERMOELECTRIC GENERATOR FOR SPACE APPLICATIONS

Prepared for

OAK RIDGE OPERATIONS OFFICE
U. S. ATOMIC ENERGY COMMISSION

December 31, 1964

Prepared by

ASTRO-ELECTRONICS DIVISION
DEFENSE ELECTRONIC PRODUCTS
RADIO CORPORATION OF AMERICA
PRINCETON, NEW JERSEY

Contract No. AT-(40-1)-3221

PREFACE

This report summarizes a cooperative effort performed by the U. S. Atomic Energy Commission, Division of Isotope Development, and the Radio Corporation of America, Astro-Electronics Division, in the design, construction, and testing of a radioisotope thermoelectric generator. Funds for building the generator were provided by RCA while the isotope and the hot cell were made available by AEC, Oak Ridge Operations Office, under contract AT-(40-1)-3221. This report covers the period from March, 1963 to December, 1964 during which the work was done.

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Frontispiece: Artist's conception of classical RTG in which the heat is rejected upwards and sideways. The Converter rejects its heat upwards. The load is connected to the IPU via cable and plug.

SECTION I. ABSTRACT

A 26.6-pound laboratory model of a radioisotope thermoelectric generator (RTG), resembling a flight unit in its salient parts, has been built and successfully tested for two months without apparent degradation in performance. The fuel used in the RTG was five pellets of strontium-90 isotope, in the form of strontium titanate, doubly encapsulated in 2 nested cylinders of molybdenum and Hastelloy X. This capsule produced 526 watts of thermal power. The use of a very efficient multi-foil insulation results in a heat loss of less than 15 percent; the remaining heat is channeled through the thermoelectric array.

Of the 66 silicon-germanium thermocouples called for in the design, only 32 were installed; thermal dummies were used for the remainder. Operating between average temperatures of 800°C and 250°C, the thermoelectric array produced 12.6 watts of electrical power. If the full complement of thermocouples had been used, in conjunction with 660 thermal watts of strontium 90, the electrical output would have been 28.6 watts.

The laboratory model, which included certain auxiliary components for experimental expediency, weighed 26.6 pounds. It is felt that a prototype flight generator can be built which weighs 21 pounds. This would demonstrate the achievement of 1.36 watts per pound with the high-temperature techniques which were employed. Performance could be improved to give a figure of 2.0 watts per pound using the denser strontium oxide or strontium fluoride now under development.

An artist's conception of the RTG is shown in the frontispiece. The figure suggests the possible use of the generator as a lunar beacon or as part of an unmanned scientific station.

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SECTION II. INTRODUCTION AND SUMMARY

A. HISTORY OF PROGRAM

During the Fall of 1962, the Radio Corporation of America investigated several alternatives to solar cells for use in low-level, long-term power supplies for space applications. (Information used for guidance in this investigation are as summarized in Figures 2-1, 2-2, and 2-3.) As a result of this study, thermoelectric generators using a radioisotope fuel appeared to be most promising for certain future spacecraft applications that RCA might be called upon to pursue. A subsequent and more detailed study suggested that such a radioisotope thermoelectric generator should employ high-temperature thermocouples. As such a generator had never been built before, it was deemed appropriate to fabricate a laboratory-model generator in support of the study. This report describes the design, development, and testing of this generator.

The program to fabricate an RTG, authorized on May 31, 1963, provided for the generator to be built at the Astro-Electronics Division of the Radio Corporation of America, located in Hightstown, New Jersey. Initial performance tests, with an electrical heater, were to be performed in the laboratory facility of the Astro-Electronics Division (AED).

Figure 2-1. Morphology of Space Power Systems

Figure 2-2. Applicable Space Power Systems in 1963

Figure 2-3. Applicable Space Power Systems in 1966

A fuel capsule was to be fabricated by AED and shipped to Oak Ridge National Laboratory (ORNL), Oak Ridge, Tenn. There it was to be filled with strontium titanate, sealed, and shipped to the Industrial Reactor Laboratory (IRL), Plainsboro, N. J. (6 miles from AED). The isotope was to be loaned to RCA for the duration of the program, by the Division of Isotope Development (DID) of the U. S. Atomic Energy Commission. The fuel capsule was to be inserted in the generator in a hot cell at IRL and tests run on isotopic heat.

On August 16, 1963, DID proposed that the isotopic heat test, for which they would provide a hot cell, be performed at ORNL. This was acceptable to RCA and contract AT-(40-1)-3221 was subsequently signed. The program was carried out according to the following time schedule:

1963	March to May	Preparation, initial design;
	May 31	Authorization of project;
	June to October	Design of generator;
		Fabrication of thermocouples at RCA*;
		Fabrication of generator components;
1964	November to January	
	February	Tests at component level;
		Debugging of laboratory equipment, including vacuum chamber and ovens;
	March to May	Further development of components;
		Extensive testing of foil insulation and modules;
	June	Final assembly of generator;
		Modules with 22 thermocouples replaced by modules with 6 thermocouples;
	July to August	Test of generator on electrical heat;
		Setting-up at ORNL;

*Direct Energy Conversion Operation, Harrison, New Jersey

1964 (Continued)	September to October	Test at ORNL on isotopic heat;
	November	Completion of isotope test, disassembly, and decontamination of generator and equipment;
	December	Data reduction and report.

B. LIST OF PERSONNEL AND ACKNOWLEDGMENTS

The following AED personnel took part in the program:

S. H. Winkler
 E. de Haas
 R. R. Laessig
 F. R. Schwarz
 R. J. Schmidt
 R. D. Wilkes

Considerable support from the DID was obtained through the services of Messrs. R. W. Shivers and A. Berman.

The thermocouples were fabricated by Direct Energy Conversion Operation, RCA, Harrison, N. J.; Mr. R. Buttle was Project Engineer.

The support of the following engineering personnel at the Isotope Development Center, ORNL, is gratefully acknowledged: W. Cox, W. Early, J. Gillette, E. Lamb, C. Ottinger, E. Pierce, R. Robinson. Valuable cooperation was contributed by R. Byrum and R. Sizemore, Oak Ridge operational personnel.

C. TECHNICAL REASONS FOR PROGRAM

Prior to the summer of 1963, RTG's had been built by others (References 9 and 10) using lead telluride as the semiconductor material. Such generators are restricted to hot-junction temperatures of approximately 600°C. In order to attain usable efficiency, the cold-junction temperature must usually be as low as 150°C. This necessitates a large radiator, clearly undesirable for space applications.

RCA felt that the usefulness of the RTG would improve if the radiator temperature were raised. This is possible with silicon-germanium which permits hot-junction temperatures between 800 and 850°C and above. In addition, when used in vacuum, silicon-germanium does not require encapsulation as does lead telluride.

The temperature of the fuel capsule must be 100 to 200 degrees higher than the hot-junction temperature, as heat is transferred by radiation only. Transfer by conduction, while attractive, would present difficulties in the form of differential expansion and chemical interaction between the thermocouples and the heat sources; hence, conduction transfer did not appear feasible at the time the program was initiated.

A high-temperature silicon-germanium generator requires thermal insulation superior to any used in previous RTG projects. Fortunately, since an excellent vacuum exists in outer space, use of multifoil insulation is both feasible and attractive. This is due to its ability to provide high thermal impedance at thicknesses equal to the length of the thermocouples. Since multifoil insulation had not been utilized before at the high temperatures under consideration, the need and the opportunity to develop and apply this technique were established by the RTG program.

Finally, the high temperatures employed in certain parts of the generator in vacuum were expected to present problems that had to be solved before the device could be considered acceptable as a spacecraft subsystem. These included, among others, the necessity for high-emissivity coatings on the isotope capsule and thermocouple hot junctions in addition to a high-emissivity, low-absorptivity coating on the radiator.

Since this combination of problems had never been solved in the earlier RTG work, RCA felt it necessary to build a laboratory model to demonstrate that the foregoing aims could be realized.

The laboratory model was to be identical to a flight model in all respects except where this would cause delays in the program. However, in no case were the components of the laboratory model to be lighter than the corresponding components of the flight model. The completed generator was to be performance-tested in a vacuum, first on electrical heat and then on isotopic heat. A life test of about two-months duration, using isotopic heat, was to complete the program.

D. PROGRAM RESULTS

1. General Results

The following are the general results of the program:

- The successful demonstration of an operating radioisotope thermoelectric generator, using the most recent development in thermoelectric element technology, sophisticated thermal design, and system optimization for space application.
- Availability of a prototype of a modular power supply which is readily applicable, in single or multiple units, to a variety of space power needs.

- Establishment of the competence of RCA to design and fabricate radioisotope power sources for use in spacecraft.

2. Specific Results

The following are the specific results of the program:

- A 26-pound generator has been built and operated on electrical heat and on isotope heat.
- A fuel container made from an alloy of titanium-zirconium-molybdenum (molybdenum base) has been machined, filled with five pellets of strontium titanate, and welded shut in a hot cell. The five pellets gave a total thermal power output of 526 watts. (The filling and welding were performed at ORNL.)
- The container was enclosed in an outer capsule of Hastelloy X which was successfully welded shut in a different hot cell at ORNL.
- The fuel capsule has functioned successfully for 2 months in a vacuum of 10^{-5} millimeters of mercury and through a temperature range from 1040°C to 1066°C.
- A cylinder of multifoil insulation, large enough to surround the fuel capsule, was tested in vacuum with an electrical heat source inside. With 23.6 watts supplied, the capsule temperature stabilized at 741°C. Later, when the vacuum chamber was filled with argon gas, it was necessary to supply 240 watts in order to bring the capsule to approximately the same temperature.
- The performance of the multifoil insulation remained stable during the 2-month isotope-heat test.
- The 32 thermocouples used in the final laboratory model appeared stable during the 2-month test period while being maintained at average operating temperatures of 800°C and 250°C.
- The output from the generator was 12.6 watts. No degradation of this value was observed during the 2-month test period at ORNL. If all the thermocouples had been in place, and 6 fuel pellets had been used, the output would have been 28.6 watts.
- The radiator was coated with white, high-temperature paint. This paint appeared stable at 250°C in vacuum and in high-radiation fields for the 2-month test period.

SECTION III. DESCRIPTION OF GENERATOR

A. RTG OBJECTIVES AND CONSTRAINTS

The following objectives governed the RTG design:

- A nominal output power of 25 watts at 28 volts, after one year of operation.
- Minimal weight with a minimal performance goal of 1 watt per pound.
- Suitability for space environment (including solar heat), launch, possible launch aborts, and dispersal reentry (burnup).
- A minimum life of one year.

The realities of material availability, scheduling, and funding-imposed constraints made it impractical to fully meet the objectives stated above. A decision was made to modify the objectives without relaxing the basic technical requirements so that, upon completion, the laboratory-model generator could be transformed into a flyable prototype without the necessity of having to solve further basic technical problems.

In accordance with this decision, the weight and operating temperature of the laboratory model were to be comparable to those of a flyable unit; modifications would be made which would not affect these parameters.

The design objectives, as modified by the noted constraints, dictated the following specifications:

- An output power of 30 watts at a voltage that may be considerably lower than 28 volts (4 or 5 volts, for example).*
- Minimal weight with a performance goal of at least one watt per pound.
- The generator need not demonstrate compliance with the environmental requirements, except those respecting vacuum operation. However, the fuel capsule is to be made heavy enough to survive launch abort and impact on hard ground at the terminal velocity of 90 meters per second.

*This implies that a complete power supply will consist of the RTG and a dc-to-dc converter. The converter is not included in this program.

- Existing technology and designs, of current silicon-germanium thermocouples manufactured by RCA, ** are to be used.
- The fuel will be strontium 90 in the form of strontium titanate.

B. FINAL DESIGN CONFIGURATION OF THE RTG†

The isotope fuel is contained in a cylindrical capsule, shown in Figure 3-1. This capsule fits into a central cavity in the generator frame. Three double rows of thermocouples, spaced 120 degrees apart, are located inside the cavity along its axis, i.e., along the bases of the radiator structures. (See Figure 3-2.) The fuel capsule, which is coated with a high-emissivity substance, radiates heat to the thermocouples, from which it is physically separated by a short distance.

Since the area of the "hot shoes" (i.e., that part of the thermocouple facing the capsule) is considerably smaller than the capsule surface area, insulation is used to channel as much heat as possible to the thermocouples. This insulation (called multifoil) consists of a number of metallic sheets, separated by fibrefrax sheets which form a closed cylindrical shell. The thermocouples are exposed to the fuel capsule by means of rectangular apertures in the multifoil. The fuel capsule is mechanically supported by three zirconia rods which penetrate the multifoil shell at the ends. These rods carry the load to two endplates which join the three radiators, as shown in Figure 3-3. The three junctions between the bottom endplate and the radiators act as pick-up points for the support truss. The top endplate (lid) is hinged which permits loading and unloading of the fuel capsule; it is locked by a quarter-turn fastener. The radiators are made of aluminum and are coated with white, high-temperature paint. An external view of the completed generator, mounted on a truss, is shown in Figure 3-4. The height of the generator, not including the truss, is 9 inches.

1. Thermocouples

The existing silicon-germanium thermocouples which were found satisfactory were obtained from RCA-Harrison. They consisted of three modules, each containing 22 thermocouples arranged in two parallel rows of 11 thermocouples each. Each module was mounted on one baseplate. The horizontally adjacent thermocouples were connected in parallel, giving 33 pairs of thermocouples. These 33 pairs were then connected in series. This arrangement gave, as a total electrical output, the voltage of 33 individual thermocouples and the current of two. Figure 3-3 shows an arrangement with 14 thermocouples per radiator subassembly.

**Direct Energy Conversion Operation, Radio Corporation of America, Harrison, N. J.

†See Section XI which shows how the generator, as finally constructed, differs from this description.

Figure 3-1. Isotope Fuel Capsule

Figure 3-2. Top View of Radioisotope Thermoelectric Generator with Fuel Capsule Removed

Figure 3-3. Detailed Drawing of Radioisotope Thermoelectric Generator

Figure 3-4. Complete Radioisotope Thermoelectric Generator with Truss

2. Isotope Fuel

The strontium-90 fuel is used in the form of titanate ceramic pellets and has a power density of 0.8 watt per cubic centimeter. Six disc-shaped pellets, each approximately 8.9 centimeters in diameter and 2.5 centimeters high, collectively produce about 635 watts of thermal power. An additional 25 watts of thermal power can be accommodated in the fuel capsule if a powdered fuel form is used.

The fuel pellets are enclosed by the fuel capsule which is a double container. The inner container is made from a titanium zirconium alloy of molybdenum (called TZM) and is 4.27 millimeters thick. The outer container is made from Hastelloy X and is 2.75 millimeters thick. Both containers are sealed by remote welding in a hot cell. The welding process limits the maximum diameter of the fuel pellets to about 8.9 centimeters which, in turn, makes an overall height of 15 centimeters necessary.

The space environment and design life-time imposed a severe constraint on the selection of materials since all substances are subject to evaporation when heated in a high vacuum. In this regard, coatings must be designed for proper thickness. This is often difficult, since the differential expansion rate between a coating, such as a metallic oxide, and metallic substrate, will usually limit the coating thickness to a value below that required by evaporation considerations. As the coating thickness is increased, the shear stress at the interface will increase until the adhesive bond is broken.

SECTION IV. OPTIMUM GENERATOR DESIGN

This section contains a description of the factors involved and the approaches taken in determining the final design of the RTG.* Historically, the design and development of the generator proceeded through a number of iterative refinements. That is, the initial design resulted in preliminary component specifications. These were followed by component development, the results of which were implemented in a better overall design. This design was, in turn, further refined.

Since knowledge of the historical details is not necessary to understand the approach, the following paragraphs will combine the iterations into a sequence of individual, consecutive steps. The explanation will be made as if the results of Sections IV through VIII of this report are already available.

The symbols employed in this and the following sections are defined in Table 4-1.

A. PERFORMANCE GOALS

The goal for the power supply of which the RTG would be the major part is to meet or exceed the specifications noted in Section III of this report. The prime criterion is a power output of 25 watts at 28 volts after one year, with a weight of 26.4 pounds (12 kilograms). Efficiency is of secondary importance. It can be shown that the generator with the highest power-to-weight ratio does not necessarily require the minimum amount of fuel. The block diagram in Figure 4-1 shows the specifications for the generator alone as 30.4 watts initial output for a weight of 25.6 pounds (11.65 kilograms). The initial results of the component development are shown in Table 4-2.

B. OPTIMIZATION OF THE GENERATOR

1. General Shape of the Generator

As the thermocouples receive heat from the fuel capsule by radiation only, the distance separating the capsule and thermocouples is not critical. This permits the thermocouples to be supported on the cold side only, avoiding the differential-expansion problem associated with thermocouples supported on both (hot and cold) sides. Further, it permits us to consider the fuel capsule and the remainder of the generator as two distinct entities which can independently change shapes with temperature.

*The complete power supply consists of a generator and a voltage step-up device (dc-to-dc converter). The design and construction of the dc-to-dc converter is not a part of this project.

TABLE 4-1. DEFINITION OF SYMBOLS
USED IN ANALYSIS OF RTG DESIGN

Symbol	Definition
T_H	Hot-junction temperature
T_C	Cold-junction temperature
$\bar{T}$	Average thermocouple temperature, $\bar{T} = T_H + T_C/2$
ρ	Electrical resistivity
ρ_p	Electrical resistivity of p-type semiconductor
ρ_n	Electrical resistivity of n-type semiconductor
I	Thermocouple current
K	Thermal conductivity
K_p	Thermal conductivity of p-type semiconductor
K_n	Thermal conductivity of n-type semiconductor
σ	Stephan-Boltzmann constant
S	Seebeck coefficient
Q_T	Total heat supplied to hot junction by heat source
Q_c	Heat conducted from hot to cold shoe
Q_P	Peltier heat
Q_j	Joule heat
T_{RA}	Temperature of radiator base
Q_{RA}	Heat dissipated by radiator
A_{RA}	Area of radiator
E	Open circuit voltage
R_i	Internal resistance of thermocouple
l	Length of thermocouple
A	Cross-sectional area of one thermocouple element
ϵ_{RA}	Effective emissivity of radiator
f_{RA}	Effectiveness of radiator

	GENERATOR ALONE	DC-TO-DC CONVERTER	SYSTEM
OUTPUT AFTER 1 YEAR .	29.4W		25 W
OUTPUT INITIALLY :	* 30.4 W		26 W
WEIGHT	* 11.65 kg	0.35 kg	12.0 kg

* DESIGN GOAL FOR PRESENT GENERATOR

Figure 4-1. Block Diagram Showing Design Parameters for Complete Power Supply

The fuel capsule is a cylindrical vessel. Initial calculations show that each flat surface may be between 60 and 100 square-centimeters and the round surface area between 500 and 700 square-centimeters. The total surface of the thermocouples is only between 50 and 80 square-centimeters. Thus the thermocouples can be located opposite either a flat or round cylinder surface. This difference in the magnitudes of the two areas leads to problems of insulation and of efficient channeling of heat to the thermocouple hot shoes.*

Thermal insulation is less of a problem if the thermocouples are mounted together in a block opposite a flat side, as shown in Figure 4-2. However, this arrangement makes it difficult to load and unload the generator repeatedly.

Therefore, a configuration was selected in which the capsule is supported at each end by a set of three zirconia tubes, as shown in Figure 4-3.

*The capsule is much larger than the smallest size required to give the thermocouples adequate exposure to the heat source. This mismatch is caused by the low power density of the isotope being employed. Improvement in this respect is possible with denser isotopes such as strontium oxide, plutonium 238-oxide, and curium 244-oxide.

TABLE 4-2. INITIAL CHOICES OF DESIGN PARAMETERS AND MATERIALS

Radioisotope:	strontium 90 as SrTiO_3 initial output: 0.22 W(t)/cm^3 (average) density: 3.6 g/cm^3 (average)
Container materials:	inner: TZ molybdenum, wall thickness 4.27 mm outer: Hastelloy X, wall thickness 2.75 mm shape: Squat cylinder, O.D. up to 10-11 cm
Thermocouple material:	Silicon germanium alloy, approx. 65 atom per- cent Si, balance Ge Hot junction temperature not to exceed in vac- uum: 1100°K in air: 1275°K Maximum cold junction temperature in vacuum: 775°K in air: 675°K
Thermocouple dimensions:	p and n doped elements have the same dimen- sion effective length of each element: 2.65 cm area of each element: 0.393 cm^2
Thermal insulation:	main insulation: approximately 25 foils, sepa- rated by fibrous material; supporting insula- tion: $\text{Min } K \text{ } K_i = 0.035 \text{ W/}^\circ\text{Km}$ (in vacuum)
Radiator material:	Aluminum, minimum thickness 0.45 mm
Support for capsule:	Zirconia tubing, capped with buttons of Hastel- loy X
Assumed parameters of dc-dc step up device:	Output voltage: 28V Input voltage: approx. 4V weight: 350 g efficiency: 85% (this device is not included, but its properties are needed to specify the performance of the generator)

The thermocouples can be mounted either clustered on one side of the cylinder, as shown in Figure 4-3 or symmetrically, as shown in Figure 4-4. The former configuration gives fewer insulation problems but makes it harder to design a radiator. Hence, the latter configuration was ultimately decided upon.

Figure 4-2. Capsule Supported on Curved Surface, Thermocouples Mounted at One End

Figure 4-3. Capsule Supported at Ends, Thermocouples Mounted Opposite Curved Surface

Figure 4-4. Capsule Supported at Ends, Thermocouples Mounted in Three Groups Opposite Curved Surface

2. Influence of the Radiator Temperature

The major independent parameter to be determined is the temperature of the radiator. The area of the radiator varies inversely as the fourth power of the absolute temperature in order to reject a constant amount of heat.

Therefore, in relative terms, a radiator which dissipates heat at a high temperature is a light radiator. However, a high radiator temperature gives rise to a smaller temperature difference between the thermocouple junctions and, consequently, to a lower electrical output. There must be, then, an intermediate radiator temperature at which the power-to-weight ratio is optimum.

In the following paragraphs, the weights of all major components are expressed as functions of the radiator temperature, T_{RA} , or of the cold-junction temperature, T_C . Graphic analysis then yields the optimum radiator temperature.

3. Thermocouples

The configuration of fuel container, one thermocouple, and radiator, are shown in Figure 4-5. The equivalent electrical circuit of one thermocouple is shown in Figure 4-6.

With the hot-junction temperature constant at 1100°K , the electrical and thermal characteristics of the thermocouples are direct functions of the cold-junction temperature. Then, the relation between cold-junction temperature and radiator temperature, T_{RA} , depends essentially on the thermal impedance of the ceramic insulation between the two. Calculations and initial tests show that under normal full operating conditions:

$$T_C - T_{RA} \simeq 20^{\circ}\text{K}.$$

Applying the equations for the salient parameters, the following results are obtained:

Open circuit voltage

$$E = S (T_H - T_C) \times 0.97 \text{ for one thermocouple}$$

$$E = (450 + 0.16 T_C) (1100 - T_C) (10^{-6}) (0.97) \dagger$$

$\dagger$ The factor "0.97" has been found by experience; it accounts for a possible slight mismatch between elements, etc.

Figure 4-5. Symbol Identification and Configuration of Fuel Container, Thermocouple, and Radiator

E = ELECTROMOTIVE FORCE = OPEN CIRCUIT VOLTAGE
 R_c = CONTACT RESISTANCE
 R_i = INTERNAL RESISTANCE
 R_e = EXTERNAL RESISTANCE
 $E = E_p + E_n$
 $R_e = R_i = R_p + R_n + R_c$

Figure 4-6. Equivalent Electrical Circuit for One Thermocouple

Internal resistance for one thermocouple

$$R_i = \rho \frac{\ell}{A} + y \dagger$$

$$R_i = \left(4.25 + \frac{2.15}{1000} T_C \right) \frac{2.65 \times 10^{-2}}{3.93 \times 10^{-5}} + y$$

Substitution of the values $T_C = 400^\circ\text{K}$ and $T_C = 800^\circ\text{K}$ gives, respectively,

$$R_i = 34.2 + 6 \text{ and } 39.9 + 6 \text{ milliohms.}$$

This illustrates the fact that the contact resistance materially reduces the output power of the thermocouple. The efficiency of the thermocouple is therefore lower than the theoretical efficiency of the materials.

All calculations will be performed for the range of cold-junction temperature

$$400^\circ\text{K} \leq T_C \leq 800^\circ\text{K}.$$

This corresponds to an average thermocouple temperature, $\overline{T}$,

$$750^\circ\text{K} \leq \overline{T} \leq 950^\circ\text{K}$$

where

$$\overline{T} = \frac{T_H + T_C}{2}.$$

Disregarding second order effects we find

$$\rho = \rho_p + \rho_n = \left(4.25 + 2.15 \frac{T_C}{1000} \right) \times 10^{-5} \text{ ohm-meter}$$

$$S = (450 + 0.16 T_C) \times 10^{-6} \frac{\text{volts}}{^\circ\text{K}}$$

$$K = 4.55 - 0.0011 T_C$$

$\dagger$ The term "y" accounts for the contact resistance at the hot junction; average value is 6 milliohms.

where

ρ is the electrical resistivity,

ρ_p is the electrical resistivity of p-type semiconductor,

ρ_n is the electrical resistivity of n-type semiconductor,

S is the Seebeck coefficient, and

K is the thermal conductivity.

The power, P , produced in the external resistance, R_e , for $R_e = R_i$ is

$$P = \frac{E^2}{4R_i}.$$

Results of the computations for various values of T_C are listed in Table 4-3.

TABLE 4-3. WEIGHT OF THERMOCOUPLES AS A FUNCTION OF T_C

Parameter	$T_C = 400^\circ K$	$T_C = 500^\circ K$	$T_C = 600^\circ K$	$T_C = 700^\circ K$	$T_C = 800^\circ K$	
E(V):	0.349	0.308	0.265	0.218	0.168	for one thermocouple
R_i (milliohm):	40.2	41.6	43	44.5	45.9	
P (watts):	0.756	0.571	0.407	0.268	0.154	
Number of thermocouples to produce 30.4W:	40	53	75	113	198	
Weight of thermocouples (kg):	0.72	0.95	1.35	2.04	3.56	
Assumptions: $T_H = 1100^\circ K$;						
Weight of one thermocouple, complete with baseplate and connections = 18 grams.						

4. Fuel

The design parameters for the fuel, as previously given in Table 4-2, are accurate only to 10 percent. The discrepancies are caused by variations in shrinkage during the sintering process, over which the supplier, ORNL, as yet has little control.

The amount of fuel is directly proportional to the useful heat flowing through the thermocouples and the heat leaking past them. Both are strongly dependent on T_H or T_C .

The heat flow for one thermocouple is determined as follows. The heat, Q_C , which passes from the hot to the cold shoe due to thermal conduction is

$$Q_C = (T_H - T_C) (K_p + K_n) \frac{A}{l}.$$

The Peltier heat, Q_P , removed from the hot junction is

$$Q_P = \pi_{pn} I = T_H (S_p - S_n) I$$

where

$$I = \frac{E}{2R_i}$$

and hence

$$Q_P = \frac{T_H (S_p - S_n)^2 (T_H - T_C)}{2 R_i}.$$

Also a certain amount of Joule heat, Q_j , is produced in the thermocouple. Half of this heat is returned to the hot junction. In order to maintain the temperature T_H , the total amount of heat, Q_T , supplied by the heat source to the hot junction is now

$$Q_T = Q_C + Q_P - 1/2 Q_j.$$

Substitution of all material constants yields the data in Table 4-4. The total useful heat flow permits us then to make an initial estimate of the weight and volume of the fuel. To this estimate will be added 20 to 40 percent to cover the losses.

5. Containers

With the initial fuel volume determined, the approximate dimensions of the containers can be established. Since the containers should be short but limited to an outer diameter of 10 or 11 centimeters, the internal height can be initially computed to range from 9.0 centimeters for $T_C = 400^\circ\text{K}$ to 18.2 centimeters for $T_C = 800^\circ\text{K}$.

TABLE 4-4. HEAT FLOW DATA AS FUNCTIONS OF T_C

Parameter	$T_C = 400^\circ\text{K}$	$T_C = 500^\circ\text{K}$	$T_C = 600^\circ\text{K}$	$T_C = 700^\circ\text{K}$	$T_C = 800^\circ\text{K}$
Q_C :	8.50	7.10	5.80	4.50	3.27
Q_P :	2.53	2.23	1.90	1.56	1.20
$-1/2 Q_j$:	-0.38	-0.29	-0.20	-0.13	-0.08
Q_T :	10.65	9.04	7.50	5.93	4.39
Number of thermocouples:	40	53	75	113	198
Total heat flow through all thermocouples (W):	427	478	564	669	870
Initial estimate of fuel quantity to provide useful heat flow — weight (kg):	1.94	2.17	2.56	3.04	3.96
Volume (cm^3):	541	605	714	847	1100

If a heat loss of 20 percent and a void volume of 5 percent is assumed, the actual size of the container can be estimated. This, in turn, gives the total area which the insulation has to cover. Now the losses through the foil and block insulation can be found. To this must be added the losses through the capsule supports and through some minor structural details. The amount of fuel needed to supply these heat losses is then compared to the 20 percent originally assumed, and the calculation is repeated with more accurate figures. The results are given in Table 4-5.

TABLE 4-5. FINAL WEIGHTS OF FUEL AND CONTAINERS AS FUNCTIONS OF T_C

Parameter	$T_C = 400^\circ\text{K}$	$T_C = 500^\circ\text{K}$	$T_C = 600^\circ\text{K}$	$T_C = 700^\circ\text{K}$	$T_C = 800^\circ\text{K}$
Total heat flow supplied by fuel (including losses), in watts:	535	589	680	791	1003
Weight of fuel (kg):	2.43	2.68	3.09	3.60	4.56
Weight of TZM and Hastelloy containers (kg):	3.41	3.63	4.04	4.55	5.47

6. Insulation

The insulation consists essentially of 25 foils separated by sheets of fibrefrax. The weight is proportional to the area covered. The weight of the blocks depends on the number of thermocouples and on the temperature difference:

$T_C (^{\circ}\text{K}) =$	400	500	600	700	800
Total insulation weight (kg) =	0.735	0.780	0.855	0.945	1.120

7. Radiator

The radiator weight depends on the amount of heat, Q_{RA} , and the temperature, T_{RA} , at which it is rejected, according to

$$Q_{RA} = \sigma T_{RA}^4 A_{RA} \epsilon_{RA} f_{RA}$$

where

Q_{RA} is the heat rejected by the radiator

T_{RA} is the effective rejection temperature

σ is the Stefan-Boltzmann constant

A_{RA} is the radiator area

ϵ_{RA} is the effective emissivity

f_{RA} is the effectiveness of the radiator

The factor f_{RA} would be unity for an ideal, thick, isothermal radiator which was fully exposed to space.

Laessig (Reference 13) has done a number of optimization studies on space radiators from which he concludes that a value of about 0.7 for radiator effectiveness results in the lightest radiator for this application. The weights of the temperature-dependent components as functions of T_C are shown in Figure 4-7. For mechanical and structural reasons a unit weight of 4 kilograms per square-meter is assumed. The corresponding radiator data are listed in Table 4-6; ϵ is assumed to be 0.8.

8. Selection of Design Point

The variable weights for the five major components can now be added and compared. Table 4-7 and Figure 4-7 show that the optimum design point lies at $T_C = 530^{\circ}\text{K}$ and $T_{RA} = 510^{\circ}\text{K}$. These values were accepted for the completion of the design and construction of the generator.

Figure 4-7. Weight of Temperature-Dependent Components of Radioisotope Thermoelectric Generator

C. COMPONENT SPECIFICATIONS

To obtain a workable system it is necessary that the components meet the specifications summarized in the following. (These specifications will form the basis for the discussions in Sections V through VIII of this report.)

1. Fuel

A mass of 2.8 kilograms of strontium titanate produces initially 620 watts of thermal power.† The fuel volume equals 776 cubic-centimeters, to which a void volume of 5 percent is added.

†When, during assembly, a number of thermocouples were replaced by dummy heat conductors, it became desirable to reduce the heat production to 526 watts. To accomplish this, one of the six pellets of strontium titanate was replaced by a disc of stainless steel before the container was sealed.

TABLE 4-6. RADIATOR AREA AND WEIGHT AS FUNCTIONS
OF T_C AND T_{RA}

T_C ($^{\circ}\text{K}$) =	400	500	600	700	800
T_{RA} ($^{\circ}\text{K}$) =	380	480	580	680	780
Heat load rejected by radiator (W):	505	559	650	761	973
A_{RA} (m^2):	0.74	0.32	0.17	0.10	0.07
Weight of radiator (kg):	2.96	1.27	0.68	0.40	0.28

TABLE 4-7. ESTIMATED TOTAL WEIGHT AS A FUNCTION OF T_C

Assembly	$T_C =$ 400 $^{\circ}\text{K}$	$T_C =$ 500 $^{\circ}\text{K}$	$T_C =$ 600 $^{\circ}\text{K}$	$T_C =$ 700 $^{\circ}\text{K}$	$T_C =$ 800 $^{\circ}\text{K}$
Fuel	2.43	2.68	3.09	3.60	4.56
Containers	3.40	3.63	4.04	4.55	5.47
Thermocouples	0.72	0.96	1.35	2.04	3.55
Insulation	0.74	0.78	0.86	0.95	1.12
Radiators	2.96	1.27	0.66	0.40	0.28
Subtotal	10.25	9.32	10.00	11.54	14.98
Add for fixed weight	1.00	1.00	1.00	1.00	1.00
Estimated total weight (kg)	11.25	10.32	11.00	12.54	15.98

2. Containers

- Outer container material: Hastelloy X for corrosion protection.
- Inner container material: TZ molybdenum for strength.
- Material of liner inside inner container* : stainless steel.
- Maximum design temperature for outer container: 1450°K.

3. Thermocouples

- Number of couples: 66
- Connections: each pair of thermocouples in parallel, eleven pairs in series forming a module; three modules at 22 thermocouples each, in series.
- Area per element: 0.393 square-centimeters
- Effective length per element: 2.65 centimeters
- Material for elements and for hot shoes: silicon-germanium
- Hot-junction temperature: 1110°K
- Cold-junction temperature: 530°K

4. Insulation

- 25 sheets of 0.8-mil rhodium foil interspaced with 10-mil fibrefrax material.

5. Radiator

- Material: Aluminum 6061 T6
- Radiator base temperature: 510°K

*This liner was added during fueling for convenience in handling the pellets. It has no strength at the operating temperature.

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SECTION V. FUEL AND FUEL CAPSULE

A. HEAT SOURCE

A thermal power of from 500 to 700 watts is required from the heat source to produce 25 watts of electrical power. The former figure is equivalent to 20,000 curies for some alpha sources or about 100,000 curies for beta sources. These are large values, considering that millicuries are the standard unit of measure in other branches of isotope physics (e.g., tracer work, static electricity dischargers, etc.).

At present, the only supplier of isotopes in kilocurie quantities in the United States is the U.S. Atomic Energy Commission. Deliveries can be made from one of the national laboratories or from one of the AEC's contractors. As beta isotopes are reactor byproducts, while alpha isotopes must be specially made, the former are cheaper and more abundant. Long-lived alpha source material corresponding to only 100 watts of electrical power existed in the United States during 1964, as shown by Table 5-1. Therefore, upon RCA's request for isotope material, the AEC restricted the RTG program to beta sources. Since a long half-life was needed, strontium 90 was chosen. RCA was then granted a loan of up to 100 kilocuries of strontium 90 (corresponding to 660 watts of thermal power).

Fresh strontium 90 produces 432 watts of thermal power per pound of isotope (950 watts per kilogram) but it cannot be obtained in pure form. The best end-product of the refining process contains 56 atom percents of strontium 90. The remainder consists of stable strontium isotopes and small amounts of barium and calcium. Moreover, strontium is chemically active and must be converted into a chemically stable and inert compound. Initially, the AEC wanted to make the strontium compound so stable that the radioactive material would be contained even in case of an accident. They developed strontium titanate, SrTiO_3 , an extremely inert compound which does not react with ordinary containers at high temperature, is insoluble in water, and has a high melting point (1950°K).

Strontium makes up only one-half the weight of strontium titanate and only part of the strontium is the active isotope. This reduces the heat production to 91 watts per pound of compound, (200 watts per kilogram). Thus, the fuel alone will take up some 6.6 pounds (3 kilograms) of the 26 pounds (11.8 kilograms) allowed for the generator. At present this is acceptable, but in the future it would be undesirable since it rules out construction of light-weight power sources. Therefore, other strontium compounds were briefly investigated. Strontium oxide and strontium

TABLE 5-1. ISOTOPES FOR SPACE POWER

Name of Isotope	Strontium	Cesium	Cerium	Promethium	Polonium	Thorium	Uranium	Plutonium	Curium(1)	Curium(2)
Isotope Symbol	Sr90	Cs137	Ce144	Pm147	Po210	Th228	U232	Pu238	Cm242	Cm244
Half-life (years)	28	30	0.78	2.7	0.38	1.9	74	86	0.45	17.6
Radiation-primary	β	β, γ	β, γ	β	α	α, γ	α, γ	α	α	α
Radiation-secondary	γ	—	—	—	—	—	—	—	—	—
Chemical Compound	SrTiO ₃ (SrO)	glass	CeO ₂	Pm ₂ O ₃	Po	ThO ₂	UO ₂	PuO ₂	Cm ₂ O ₂	Cm ₂ O ₂
Initial Output - W(t)/g	0.21 (0.35)	0.067	3.8	0.28 (0.14)	140	141	3.3	0.4	98	2.3
Initial Output - W(t)/cm ³	0.79 (1.14)	0.22	24.5	1.8 (0.9)	1320	1270	33	3.9	1150	27
Initial Output - W(e)/kg	10.4 (17.5)	3.35	190	14 (7)	7000	7000	165	20	4900	115
Initial Output - W(e)/dm ³	39.5 (57.0)	11	1225	90 (45)	66,000	64,000	1650	195	57,000	1350
Selected Mission (years)	3	3	0.5	2	0.33	1	3	3	0.33	3
Fuel decays to%	92	93	64	60	55	69	97	97	60	90
Inverse of % decay	1.08	1.07	1.56	1.67	1.82	1.44	1.03	1.03	1.67	1.11
Initial curies/W(t)	154	209	124	2700	32	3.5	3.2	30	28	33
Initial curies/final W(t)	167	224	194	4500	58	5	3.3	31	47	37
Available kW(t) - 1964/yr	18	4.5	demand	0.075 (0.037)	3.7	0	0	2	6	0.02
Available W(e) - 1964/yr	900	225	demand	4 (2)	185	0	0	100	300	1
Cost - 1964 - k\$/W(e)/yr	10	9	1.93	80 (160)	3.4	—	—	20	3.8	?
Planned kW(t) - 1965/yr	30	15.6	18	0.125 (0.062)	3.7*	0	0	5	6	0.10
Planned W(e) - 1965/yr	1500	780	900	6 (3)	185*	0	0	250	300	5
Cost/W(e) during 1965/yr	10*	9*	1.93	80 (160)*	3.4*	—	—	20	3.8	?
Possible kW(t) - 1966/7/yr	60	45	520	7.5 (3.75)	74	5 ⁺	5 ⁺	>5	60	3
Possible W(e) - 1966/7/yr	3000	2250	26,000	375 (187)	3700	250 ⁺	250 ⁺	>250	3000	150
Cost/W(e) after 1966/7/yr	0.42	0.45	0.018	1.82 (3.64)	1.25	0.8 ⁺	7 ⁺	20	3.8	40(10)

Notes: Conversion from W(t) to W(e) assumed as 5% efficient
 Availability and cost figures allow for decay during selected mission
 Figures in () for Promethium refer to material that has been aged
 one half-life in order to reduce the γ emitting contaminant
 Pm 148

Proposed information marked ⁺, unconfirmed data marked*

Sources: AEC Division of Isotope Development (R. Shivers), October 1963
 AEC Report HW 76323, Rev. 1, October 15, 1963
 AEC Report HW 77770, July 1963
 Nucleonics, April 1963

fluoride were found promising. Strontium oxide contains 85 percent strontium and may yield up to 182 watts per pound (400 watts per kilogram). Since the results of contracts for study and development of this and other fuels were not yet available, design of the present generator is based on use of the heavier strontium titanate.

The material is made first as a powder which is then compressed in a cylindrical die. The resultant cylindrical cake, with a diameter of approximately 10 centimeters and height of 2.5 centimeters, is sintered at about 1700°K, whereby all dimensions shrink on the order of 10 to 20 percent.

The final parameters are:

- Thermal output: 100 watts per pound (220 watts per kilogram), and
0.79 watts per cubic-centimeter
- Density: 3.6 grams per cubic-centimeter

B. CONTAINER* DESIGN AND SELECTION OF MATERIAL

1. General

The generator described here is not intended to be flight qualified. However, it should resemble flyable hardware as much as possible. The container must satisfy two requirements: (1) It must perform at operating temperature during the mission; and, (2) it must not break when hitting hard ground with terminal velocity after a near-launch abort.

The second of the above requirements is the more severe of the two. Terminal velocity depends on the aerodynamic shape of the capsule and what is left of the surrounding structure. For the strength calculation, it is assumed that the abort causes an explosion, which rips away all structures exterior to the capsule which then obtains a terminal velocity of approximately 90 meters per second (Reference 28).

The affect of impact depends considerably on the temperature of the capsule when impact occurs. The most conservative approach would assume that it is at operational temperature, i.e., 1300°K. A more realistic calculation would take into account the slow heating during ascent and the cooling during descent.

The following calculations apply to a capsule with dimensions and weights as shown. These figures will differ somewhat from the final ones but will be close enough for a semi-quantitative discussion of the capsule strength. (Reference 21.)

*The container is the empty vessel. Filled with isotope material, it is called the capsule.

Inside diameter of container:	9 cm
Internal height:	16 cm
Preliminary wall thickness:	0.5 cm
Weight of isotope:	3 kg
Preliminary weight of container:	3 kg
Preliminary total weight:	6 kg
Specific heat of capsule (estimated):	3000 joules/ $^{\circ}$ K

Assuming that the generator is kept cool on the launch pad by blowing air through the spacecraft under the shroud, the radiator is kept at or near air temperature, or about 50°C , which is 200 degrees lower than normal operating temperature. Furthermore, the presence of air diminishes the insulating properties of the insulation and lowers the capsule temperature another estimated 200°K . The capsule temperature at launch is therefore 900°K .

With a specific heat of 3000 joules/ $^{\circ}\text{K}$ and a thermal power of 650 watts, the capsule temperature rises after launch at an approximate rate of 13°K per minute. Not more than 5 minutes should be allowed between launch and abort because, if the abort occurs later, the vehicle will be over the ocean or in orbit. Thus, after 5 minutes, the maximum temperature which the capsule attains during ascent is 965°K .

After suborbital abort, the capsule is surrounded by moving air, at least during the latter part of the descent (e.g., below a height of 10 kilometers). The air will cool the capsule. Given enough time, the capsule surface would reach an equilibrium temperature (near temperature of air) of 300 to 400°K . It is not possible to calculate the exact temperature at impact. However, assuming that descent usually lasts longer than ascent, it may be stated that the capsule surface will probably be cooler than, and in no case materially hotter than, 900°K . It shall be assumed that this is the worst case; strength calculations will be based upon it, and a capsule material to match it will be sought.

With the advent of jet propulsion, considerable development has taken place in high-temperature, high-strength metals. Strength as a function of temperature is shown for some of the newer materials in Figure 5-1; the approximate composition of these materials is given in Table 5-2.

Since the operating temperature is intended to be about 1300°K , Inconel 600 cannot be considered. At 900°K , Hastelloy C and Haynes 25 have the advantage of higher strength over TD Nickel. For this reason, the first containers for strontium compounds have been made of Hastelloy C (Reference 10).

Figure 5-1. Tensile Strength as a Function of Temperature for Container Materials

TABLE 5-2. APPROXIMATE COMPOSITION OF SOME HIGH-TEMPERATURE MATERIALS

Trade Name	Supplier	Reference	Composition (%)										
			Ni	Co	Cr	Fe	Mn	W	Mo	Ti	Zr	ThO ₂	Si
TZ Molybdenum	Climax	25							99	0.5	0.08		
Thoria Dispersed Nickel	DuPont	24	98									2	
Haynes 25	Haynes	22	10	49	20	3	2	15					1
Hastelloy X	Haynes	22	43	2	23	20	1	1	10				
Hastelloy C	Haynes	22	54	2	16	6	1	4	16				1
Inconel 600	INCO	23	74	74	15	9	1						1
Stainless Steel 316	Various	—	12		17	66	2		2				1

Because it is felt that a container must withstand higher temperature, (a first requirement for future improved RTG designs,) the relatively new molybdenum alloy TZM (Titanium 0.5 percent Zirconium 0.08 percent) has been selected. This substance exhibits considerably better heat-resistant properties at 1300°K and above. Since the welding technique for TZM is not yet completely established, test welds are made as part of construction of the generator.

The exact analytical calculation of the stresses on the containers on impact falls outside the scope of this report. The wall thickness of the containers has been conservatively selected based on the test described in Reference 12. Stress-strain curves for TZM are shown in Figure 5-2. This reference describes tests that have been carried out on containers of Hastelloy. The largest of these have the following dimensions and weights.

Inside diameter of container:		3.84 cm
Internal Height:		19.8 cm
Wall thickness:		0.46 cm
Container weight:		1130 gm
Fuel weight:	approx.	600 gm
Stainless steel liner:	approx.	270 gm
Total Weight:		<u>2000 gm</u>

Figure 5-2. Stress-Strain Curves for TZM

2. Double-Container Design

The calculations of the preceding section have suggested that 5 to 6 millimeters is the proper order of magnitude for the wall thickness of a TZM container which can survive impact on abort. Since, however, public safety depends on absolute containment of the isotope, the feeling is that two welded containers — one inside the other — are safer than one.

There is also a more direct reason for a double container. The inner container is filled with isotope and then welded shut in a "dirty" hot cell. The latter step is done as described because the multi-kilocurie quantities of unsealed isotope (including RCA's 100-kilocurie quantity) that are normally handled in such a cell might deposit some radioactive dust on the floor and walls of the cell, and on the tools and items that come in contact with them. Thus, it seems probable that the outside wall of the inner container will be contaminated (this will probably be confirmed in practice). Decontaminating the surface by washing, grinding, or both is very difficult because it must be done remotely in a separate clean cell which might then itself become contaminated by the grinding dust. Also, it is doubtful that decontamination would be successful before the grindstone had appreciably changed the dimensions of the container.

The inner container would be moved to a clean cell where it would be enclosed in a second, outer container which would then be welded shut. The exterior of the second container would be clean if normal precautions were taken.

The foregoing supports the decision to employ a double-wall container.

3. Choice of Materials

The selection of the container materials gives rise to several interesting problems. First, there is the question of whether or not the outer container can be depended upon for strength. If it can, the wall thickness of the inner container may be reduced correspondingly. It is felt that, in principle, the answer will be affirmative if the stress-strain curves of the two materials are approximately equal at the temperature at which the container may be during an abort occurring shortly after launch. The fact that at operating temperature, the outer material may be considerably weaker than the inner one, is irrelevant** since the inner material itself is amply strong for operating conditions. This is, however, only an approximate statement and careful tests on the new, double container would be necessary if the generator is to be flight-qualified. However, for the generator described here, such qualification tests are not required.

**Provided it has some strength left.

TABLE 5-3. SHORT-TIME ULTIMATE TENSILE STRENGTH
AS A FUNCTION OF TEMPERATURE

Material \ Temperature	300	600	940	1100	1270	1450
TZ Molybdenum Sheet	10	8.6	7.6	6.2	5.5	4.9
TD Nickel	4.8	3.3	2.2	1.9	1.4	1.1
Haynes 25 Sheet	10.2	9.2	7.4	4.0	2.5	0.47
Hastelloy X Sheet	8.2		5.9	3.7	1.6	
Hastelloy C Sheet	8.7	7.6	6.9	5.0	2.3	
Inconel 600	6.4	6.4	4.6	1.6	0.53	
Stainless Steel 316	5.9	4.5	2.8	1		
Temperatures in degrees Kelvin, Strength in 10^8 N/m^2 Data are derived from Refs 22 thru 25 on the basis of $10^8 \text{ N/m}^2 = 14000 \text{ psi}$.						

A second problem is concerned with the thermal expansion of the two containers. The expansion coefficient of the inner container should be the greater of the two to assure an easy assembly while still guaranteeing a perfect fit at operating temperature. (See Table 5-4.) The expansion coefficient of the fuel should, in turn, be greater than that of the inner container.

Corrosion of the outer container is a third consideration since the future spacecraft which uses the RTG may be sitting, fully assembled, on the launch pad for days or longer. Surrounding and cooling the generator with dry nitrogen is possible, but nitrogen may not always be available. At best, this approach would add complications.

If nitrogen is used, it would be gradually replaced by air after launch until a high vacuum is attained by virtue of increased altitude. However, since launch occurs only once and takes only a few minutes, this is not a major consideration.

The laboratory-model generator will be tested in a vacuum chamber, as explained. Many starts and stops are anticipated, each of which may require filling the vacuum

TABLE 5-4. LINEAR THERMAL EXPANSION COEFFICIENTS

Material	Temperature (°K)	Expansion Coefficient * $\left(\frac{10^{-6}}{^{\circ}\text{K}}\right)$
T D Nickel	300 - 1400	17.5
Hastelloy X	300 - 1400	17.0
Haynes 25	300 - 1400	17.7
T Z Molybdenum	300 - 1400	5.6
Inconel 600	300 - 1400	17.3
Strontium Titanate	300**	11.2
Stainless Steel 316	300 - 1400	19.8
Silicon Germanium 63-37	700	5.1
Tungsten	300 - 600	4.6
Copper	300 - 600	17.8
Aluminum	300 - 600	26
Nickel	300 - 600	14.8
<p>* The coefficients listed are average values for the temperature range of interest to the generator. Second-order effects are neglected.</p> <p>** Data for strontium titanate are not available for temperatures other than 300 °K.</p>		

chamber with air and slowly pumping it down. This will expose the outer container to the possibility of corrosion. Preventive measures are therefore necessitated.

4. Configuration

After considering the preceding problem areas, it was decided to enclose the isotope in a container of Hastelloy X with a wall 1-millimeter thick. The outer container would be TZM with a wall 5-millimeters thick and coated with molybdenum disilicide (MoSi_2) for corrosion-protection. This substance appeared to be one of the few coatings for molybdenum that combines resistance to high temperature with resistance to corrosion. If broken in spots, the coating heals itself in an oxidizing atmosphere, particularly at about 1600°K (Reference 13).

TABLE 5-5. THERMAL CONDUCTIVITY FOR REPRESENTATIVE MATERIALS AT TEMPERATURES OF INTEREST TO THE DESIGN OF THE RTG

Material	Thermal Conductivity $\left(\frac{W}{^{\circ}K\ m}\right)$	Temperature ($^{\circ}K$)	Melting point ($^{\circ}K$)
Copper	357	375-1110	1356
Platinum	71	300	2046
Rhodium	150	300	2239
Stainless Steel 316	16.2	373	1600-1680
	21.4	773	
Inconel 600	20.2	675	1660-1720
	28.6	1150	
Hastelloy X	16.6	675	1550-1650
	25.0	1075	
Hastelloy C	14.1	675	1560-1640
	17.1	875	
Haynes 25	16.6	675	1620-1700
	24.4	1075	
TD Nickel	90	300	1750
TZ Molybdenum	158	300	2880
	112	1075	
	90	1475	
63.37 Silicon	5.4	300	1470
Germanium	4.2	700	
	3.5	1000	
Tungsten	120	675	3643
	112	1475	
Aluminum	226	575	933

In cooperation with a supplier who had considerable experience with this material, a technique for recoating the welded seams in the hot cell was developed. Briefly, the molybdenum disilicide would be applied with a brush held by a master-slave manipulator.

As explained in Reference 13 however, the slightest imperfection in the coating would jeopardize the container. In addition, the self-heating effect would be absent in vacuum at a temperature level of 1300°K.

The removal of the dip-coating installation and drying oven from the supplier's plant to the hot cell was considered. However, the distance and the extra time for moving and setting-up would have resulted in considerable extra cost and a resultant overburdening of the budget.

A technically better solution, which was next proposed, was to coat the molybdenum with platinum. This worked out very well, with the exception that, here also, the final coating would have had to be done in the hot cell, and the expectation followed that the platinum bath would become contaminated with radioactivity. Replacing the platinum bath would be even more expensive than renewing the molybdenum disilicide installation; therefore, this approach was also abandoned.

5. Reverse Configuration

It was finally decided to dispense with molybdenum container coating and change the design instead. A reversal of the containers was effected: The inner container would be of molybdenum and the outer one would be of Hastelloy X.

Since Hastelloy expands more than molybdenum, a difference of approximately 0.8 millimeter will exist between the diameters at operating temperature. This introduces a thermal impedance between the two surfaces of 0.06 thermal ohm, raising the temperature drop between them from a negligible value to one as high as 40 to 50°K.

The actual temperature drop depends on the emissivity of the two surfaces and on the gas, if any, that fills the inner space.

In selecting this gas, air is to be avoided since it would react with the molybdenum. Of the inert gasses, helium is the best thermal conductor, as shown in Table 5-6 (Reference 26).

However, since it is easier to weld with argon, a mixture of 50-percent helium and 50-percent argon was selected as a compromise.

TABLE 5-6. THERMAL CONDUCTIVITY FOR CERTAIN GASES
AT ONE ATMOSPHERE $10^{-2} \left(\frac{W}{^{\circ}K m} \right)$

Temperature	1000°K	1200°K	1400°K
Nitrogen	8.28	9.30	10.30
Argon	4.07	4.60	5.08
Helium	34.4	38.7	42.7
Hydrogen	50.4	56.8	62.7

The surfaces of both containers were coated with Rokide C (a trade name for a chrome oxide, (Cr_2O_3) which has an emissivity of 0.79 at 1300°K. Both measures helped to reduce the temperature drop, due to the diameter disparity, to approximately 20°K. †

A wall thickness of 5.1 millimeters was selected for the molybdenum and one of 1.5 millimeters for the Hastelloy. The latter value was selected to be as small as possible consistent with the requirements of mechanical handling and welding.

In the design review, another thermal problem which conceivably could have resulted in the melting of parts of the outer container was discovered. As explained by Laessig (Reference 13), the heat is radiated from the molybdenum to the Hastelloy at a rate which is uniform over the periphery of the inner cylinder. However, beyond the Hastelloy cylinder, as effected by design, heat is channelled only to the thermocouples ("A" in Figure 5-3) and not to the area between them ("B"). This results in a temperature increase of about 100°K of the Hastelloy at "B". This brings the temperature of the Hastelloy to 1470°K which is only 85°K below the published melting point. Since the analytically determined temperature includes an error of 30°K, it was felt that the above design would be unsafe. Therefore, the Hastelloy wall thickness was increased to 2.75 millimeters; this results in a temperature at "B" which is 115°K below the melting point. A weight penalty of approximately 700 grams resulted which was compensated for by a reduction of the thickness of the molybdenum wall to 4.27 millimeters. Figure 5-4 shows the temperature at "B" in relation to the melting point.

† When, during the actual testing, the chrome-oxide coatings started to peel, they were removed altogether. The Hastelloy X was oxidized and it was found that the natural oxide layer adhered very well. In addition, the emissivity was found to be very satisfactory at a value of 0.86 (Reference 27).

Figure 5-3. Schematic Diagram of Double-Walled Container

Figure 5-4. Maximum Temperatures of Hastelloy Container

It was further decided that future prototypes and flight hardware be built with the molybdenum container on the outside, protected against corrosion by platinum. The present generator is still a valid engineering model even though the molybdenum container is thinner than the value required for safety on impact.

SECTION VI. THERMOELECTRIC ARRAY DESIGN

A. GENERAL THERMOELECTRIC THEORY

1. History

The application of thermoelectricity to power generation dates to its discovery by Seebeck in 1822. This early work showed that an EMF is obtained when the junctions of two dissimilar materials forming a thermocouple loop are maintained at different temperatures. Thus, the thermoelectric generator is basically a heat engine which utilizes the Seebeck effect.

The electrical power obtained in the early work on thermoelectric devices was disappointingly low due to two properties of the metals used:

1. Small Seebeck coefficients (thermoelectric power given in terms of potential difference per degree centigrade).
2. Large thermal conductivities.

With the advent of semiconductors and their large thermoelectric power and with the development of a basic understanding of these materials, there has been a renewed interest in thermoelectrics. For example, the Seebeck coefficient of copper constantan (a metal) is 40 microvolts per degree centigrade, in contrast to that for semiconductor alloys at approximately 550 microvolts per degree centigrade.

2. Basic Principles

The schematic diagram of an ideal thermocouple is shown in Figure 6-1.

Figure 6-1. Schematic Diagram of an Ideal Thermocouple

In this ideal example, the dissimilar materials forming the thermocouple are n- and p-type semiconductors, joined at their ends by metallic conductors. Heat is supplied to the hot junction at a temperature T_H , from an external source. The other (cold) junction is maintained at a fixed, lower temperature, T_C .

As a result of the temperature difference, $T_H - T_C$, a current, I , flows through the thermocouple and through the external load resistance, R_L . The ideal thermocouple converts heat directly into electrical energy with an efficiency, η , given by

$$\eta = \frac{\text{electrical energy supplied to load}}{\text{heat absorbed at hot junction}}$$

The useful power delivered to R_L is $I^2 R_L$.

3. Characteristics

The characteristics of a thermoelectric couple may be derived from those properties of its constituent materials which are functions of temperature.

a. Figure of Merit

The figure of merit Z^* , is a term which, in terms of physical parameters, reveals the suitability of a substance for use in thermoelectric applications. The higher the value of this term, the better are the thermoelectric properties of the material. The figure of merit is defined by

$$Z = \frac{S^2}{\rho K}$$

where

S is the thermoelectric power (Seebeck coefficient),

ρ is the electrical resistivity, and

K is the thermal conductivity.

Let the resistance of the branches of the thermocouple, R_a and R_b , be matched to give Z a maximum value; then we have

$$\frac{R_a}{R_b} = \frac{\rho_a K_a}{\rho_b K_b}$$

*Originated by the Russian scientist Ioffee.

where

- ρ_a is the resistivity of branch A,
 ρ_b is the resistivity of branch B,
 K_a is the thermal conductivity of branch A, and
 K_b is the thermal conductivity of branch B.

Then Z may be expressed, in terms of material constants only, by

$$Z = \frac{(S_a - S_b)^2}{\left(\sqrt{\rho_a K_a} + \sqrt{\rho_b K_b}\right)^2}$$

where

- S_a is the thermoelectric power of branch A, and
 S_b is the thermoelectric power of branch B.

If

$$S_a = -S_b, \text{ and}$$

$$\rho_a K_a = \rho_b K_b$$

then

$$Z = Z_a = \frac{S_a^2}{\rho_a K_a}.$$

Thus, the figure of merit is now defined in terms of material constants of a single branch of the thermocouple.

b. Heat Absorbed at Hot Junction

The useful power is $I^2 R_L$. If the Thompson heat is neglected (it is a small percentage of the total heat absorbed), the heat absorbed at the hot junction, Q_{TH} , is the sum of the Peltier heat, Q_p , and the heat withdrawn from the hot junction by conduction, Q_C .

That is,

$$\begin{aligned} Q_{TH} &= Q_p + Q_c \\ &= S I T_H + K (T_H - T_C) \frac{A}{\ell} - \left(\frac{1}{2} I^2 R_L\right) \end{aligned}$$

where

$$Q_P = S I T_H, \text{ and}$$

$$Q_C = K (T_H - T_C) \frac{A}{\ell} - \left(\frac{1}{2} I^2 R_L\right).$$

c. Efficiency

The efficiency is given by

$$\eta = \frac{I^2 R_L}{S I T_H + K (T_H - T_C) - \left(\frac{1}{2} I^2 R_L\right)}.$$

Under optimum current load conditions, the expression for maximum efficiency is

$$\eta_{\text{Max}} = \frac{T_H - T_C}{T_H} \cdot \frac{1 + Z T - 1}{\sqrt{1 + Z T + \frac{T_C}{T_H}}}$$

where

$$T = \frac{T_H + T_C}{2}, \text{ and}$$

$$Z = \frac{S^2}{\rho K}.$$

The first factor in the equation is the thermodynamic efficiency of a reversible Carnot cycle. The second factor represents the decrease in this efficiency due to the irreversible heat conduction along the branches and to power dissipation in the form of Joulean heat.

B. SELECTION OF THERMOELECTRIC MATERIAL

The figure of merit mentioned earlier in this section is only one of several characteristics which determine the choice of the thermoelectric material.

Several other properties require investigation. To be acceptable, the material must meet minimum standards with regard to each property. In the following, the acceptable standards will be established and then compared with the data presented for various materials. The standards refer to an isotope power supply fueled with strontium 90 (titanate). In order to successfully compete with solar cells, the generator must produce electrical energy at a rate of not less than 1 watt per pound (2.2 watts per kilogram) with a preferred figure of about 1-3/4 watts per pound.

1. Efficiency and Figure of Merit

Strontium 90 (titanate) produces 100 watts of thermal power per pound of compound. Assume that the container weighs as much as the isotope and the two together as much as the remainder of the generator. This represents a weight of 4 pounds for the 100 thermal watts. With the above lower limit of one electrical watt per pound of generator weight, the minimum acceptable limit for the efficiency of the generator is 4 percent. There is a difference between the thermoelectric efficiencies of the material, the thermocouples, and the complete generator. If an efficiency figure of 4 percent is required for the latter, the material efficiency must be not less than 6 percent. This of course only an estimate since there exist other isotopes with higher power-to-weight ratios. On the other hand, this extra power would be needed for future performance beyond that of 1 watt per pound. In summary then, materials with efficiencies significantly below 6 percent (e.g. 4 percent) are of little interest for the present application.

Table 6-1 shows the maximum efficiencies for several proposed thermoelectric materials (based on published values for Z) for cold-junction temperatures of 400°K, 440°K, and 500°K. The last value is in the vicinity of 530°K, as specified in Section IV.

Table 6-1 shows that bismuth telluride is not acceptable because of its low hot-junction temperature. The other materials are all equally acceptable.

2. Mechanical Strength

The general requirement of low weight precludes elaborate clamping and other support for the thermocouples. They must withstand their own acceleration and vibration during launch; hence the thermoelectric material must be mechanically strong at launch temperatures.

TABLE 6-1
MAXIMUM EFFICIENCY OF THERMOELECTRIC MATERIALS

Thermoelectric Material	$\left(\frac{\bar{z}}{z_K} - 1 \right) \times 10^3$	Reference	Maximum T_H (°K)	Efficiency (%)		
				$T_C = 400^\circ\text{K}$	$T_C = 440^\circ\text{K}$	$T_C = 500^\circ\text{K}$
BiTe	1.8	30	525	3.9	2.7	0.8
PbTe	1.2	31	860	9.4	8.6	7.3
AgSbTe ₂ (p-type only)	1.6	29	775	9.6	8.5	7.0
90% GeTe 10% AgSbTe ₂	1.3	29	875	10.2	9.3	8.0
SiGe	0.6	2	1175	8.6	8.2	7.5

Of the materials mentioned, silicon-germanium has a published yield strength, in tension, of 5000 pounds per square-inch. For the other materials, this value is lower; e.g., for lead telluride, it is 1000 pounds per square-inch.

3. Operational Lifetime

Operational space systems with operational life-times of less than 6 months to a year are usually not attractive in view of the large amounts of time and money spent for fabrication, testing, and launching. Hence a power supply, specifically the thermocouples in this case, should have a design life-time of at least 1 to 2 years. During this time, the semiconductor material should not change its thermoelectric properties; it should not chemically react at high temperatures with any other contiguous materials, (insulation, container, etc). In addition, it must withstand the high-vacuum conditions encountered in prelaunch oxidation and in space.

4. Stable High-Temperature, Low-Resistance Bonds

The thermoelements must be bonded to each other and to the structure of the generator. These bonds must remain stable for the life-time of the device. This is a major metallurgical problem because the choice of bonding materials is, in general, limited to those which have the same coefficient of expansion as the semiconductor. The bonding material must also be chemically stable and be a good electrical conductor.

5. Silicon-Germanium

The results of the comparison are shown in Table 6-2. Since lead telluride and silicon-germanium are acceptable, a decision must now be made based on properties, other than thermoelectric ones.

Lead telluride has been employed successfully for a number of terrestrial and space missions (Reference 3 and Table 6-2). The thermoelements must be encapsulated and must be mechanically supported; both of these requirements cause additional heat losses, and prevent or restrict the use of multi-foil insulation.

Silicon-germanium is lighter than lead telluride; this will be important in those generators where the fuel capsule is so light that the weight of the thermoelements become significant (Polonium 210, for example). A similar argument can be made for the radiator. Lead telluride requires a relatively low radiator temperature (up to 500°K). This becomes a significant restriction for future generators with high power-to-weight ratios. Silicon-germanium gives the designer the freedom to raise the cold-junction and radiator temperatures to 600 or even 700°K. (The weight of a 700°K radiator is one-quarter of that of a 500°K radiator).

With silicon-germanium on the other hand, the low value of Z forces the designer to use a high hot-junction temperature and a high capsule temperature. This requires developing a high-temperature technology and superior thermal insulation; however, once these are achieved, the silicon-germanium has more promise for future space-power application than does the lead telluride.

TABLE 6-2
COMPARISON OF THERMOELECTRIC MATERIALS

Parameter \ Material	BiTe	PbTe	AgSbTe ₂	90% GeTe- 10% AgSbTe ₂	SiGe
Material efficiency 6 percent or more		X	X	X	X
Sufficient mechanical strength	X	When adequately supported			X
Proven Life	X	X			X
Proven stable, low-resistance bonds	X	X			X

Since the goal of this project is to advance the state of the art, we have accepted the challenge of high-temperature technology rather than being limited by the properties of a thermoelectric material. Thus, we have selected silicon-germanium as the semiconductor material.

The silicon-germanium alloy and its properties are described in References 4 and 5, and in Figures 6-2, 6-3, 6-4, and 6-5. The composition is approximately 2 atoms of silicon and 1 atom of germanium. The specific weight is 3.5 and the melting point, 1475°K. The positive elements are doped with boron, the negative ones with phosphorus.

Life tests in air have shown stability for over 1000 hours at approximately 1275°K. In a hard vacuum, with fewer test data available, a temperature level lower by 100°K appears to be called for. To secure reasonable operation, it was decided to lower the hot-shoe temperature to 1100°K.

6. Irradiation Effects on Silicon-Germanium

In the generator the thermocouples have been exposed to gamma radiation (bremsstrahlung) at a level which has been measured at 32,500 rads per hour. This is 4.6×10^7 rads for 1414 hours or 2.8×10^8 rads per year. During the 1414 hours, there was no measurable change in the silicon-germanium thermocouples. Since this period is short compared to 1 year, published results on lead telluride and germanium telluride may be used as guides on the long-term behavior of the thermocouples.

Reference 6 describes semi-quantitatively how germanium telluride and lead telluride have been exposed to neutron fluxes equal to or exceeding 4.5×10^{18} thermal neutrons per square-centimeter and 1.5×10^{20} fast neutrons per square-centimeter. Although direct comparison between the damage due to gamma radiation and that due to neutron radiation is not possible, a conservative approach suggests that 4.5×10^{18} neutrons (velocity-thermal) compares with 10^9 to 10^{10} rads of gamma radiation. This exceeds the expected total dose for the generator by one to two orders of magnitude.

Reference 6 indicates that the thermal neutron irradiation caused certain increases in the Seebeck coefficient, and in the thermal and electrical conductivities; these increases vanish by annealing at temperatures up to 575°K.

The thermocouples for this generator are designed to operate at temperatures between 550 and 1100°K. This, with the fact that the integrated dose for the thermocouples is considerably lower than the doses mentioned in Reference 6, gives us confidence that the silicon-germanium thermocouples for the present generator will not be adversely affected by the bremsstrahlung from the strontium-titanate fuel.

Figure 6-2. Electrical Resistivity of Silicon-Germanium

Figure 6-3. Seebeck Coefficient of Silicon-Germanium

Figure 6-4. Thermal Conductivity of Silicon-Germanium

Figure 6-5. Figure of Merit of Silicon-Germanium

C. DESIGN OF THERMOCOUPLE AND MODULE

The Radio Corporation of America has developed two different types of silicon-germanium thermocouple designs. In the first type, the silicon-germanium thermoelements are terminated with nickel-copper plated tungsten shoes, as shown in Figure 6-6. The tungsten shoes are brazed to other metal components of a generator structure. This type of thermocouple permits complete heat transfer from heat source via thermocouple to radiator by thermal conduction. At the time the generator was designed, the upper limit for this technique was approximately 800°K. As this would also limit T_H to 800°K, a different thermocouple was developed, where the tungsten hot shoe was replaced by silicon-germanium. The cold shoe remains tungsten, as shown in Figure 6-7. Since the silicon-germanium semiconducting materials employed are oxidation-resistant and stable at high temperatures, thermocouples of "all semiconductor" construction are suitable for unprotected use both in high-temperature air and in vacuum environments. The cold junctions are bonded to electrical connections by conventional metallurgical means. The expression "air-vac thermocouple" has been coined to indicate the environmental capabilities of this construction.

Experimentally determined operating temperatures indicate that the air-vac thermocouple can give reliable performance at temperatures in excess of 850°C. The air-vac thermocouple, as shown in Figure 6-7, has a hot shoe which is a rectangular plate composed of n-type and p-type silicon-germanium joined by the hot junction. This design permits close packing of groups of thermocouples and provides a convenient heat-acceptance area which may be exposed directly to high-temperature heat sources.

The n-type and p-type silicon-germanium thermoelements are semi-cylindrical in shape. The requirements for high-temperature thermocouple operation in isotope-fueled air and vacuum environments appear satisfactorily met with the air-vac thermocouple.

The thermocouple, when bonded to a modular platform, becomes a self-supporting cantilever structure requiring no special attachments. The basic configuration of the module is shown later in this report (Figure 11-2).

The module shown consists of 22 air-vac thermocouples. Based on considerations of thermal flux-density and mechanical strength, a cross-sectional area for the hot shoes of 0.39 square-centimeters was selected. Once this cross-sectional area has been selected, the length of the element is the only physical parameter remaining for controlling the performance characteristics of the device. Therefore, the selection of the element length required a systemized approach that concomitantly included electrical, mechanical, and thermal considerations.

Figure 6-6. Silicon-Germanium Thermocouple with Tungsten Shoes

Figure 6-7. Silicon-Germanium "All Semiconductor" Thermocouple with Silicon-Germanium Hot Shoe

Electrical considerations in terms of voltage and power output requirements indicated that an effective element length of 2.67 centimeters would result in a 22-couple module. This module could be effectively used as a "building block" for a three-finned generator. Such a generator would yield a terminal voltage of either 3, 6, or 9 volts and have power ratings in the range of 25 to 33 watts. The calculated performance characteristics of the 22-couple module design were:

Terminal voltage: 3.0 volts

Power output: 10 watts (into matched load)

Material efficiency: 6.0 percent (when operated with a module hot-junction temperature of 825°C, and a cold-junction temperature of 250°C).

However, in order to determine the practicality of the element length arrived at on the basis of electrical considerations, it was important that generator mechanical considerations as well as the heat transfer properties of the cold-junction heat sink be evaluated.

An important structural requirement is that the modules be so constructed that a number of them can be arranged to form concentric rings around an isotope capsule heat source. For the purpose of integrating the module structure to a generator structure and also to take into consideration the possibility of replacing a module in the field, it was decided that the module would be soldered to the radiator and mechanically fastened to a generator structure by bolting the heat sink to supporting frames. Structural considerations suggested the practicality of fastening thermocouple modules to the radiators while thermal conduction requirements suggested soldering. This technique fulfilled the support requirement by arranging cantilever-supported modules around the cylindrical isotope capsule.

D. EMISSIVITY OF SILICON-GERMANIUM AT ELEVATED TEMPERATURES

The emissivity of the silicon-germanium hot shoe is another important design parameter. Its determination is described herein.

Inasmuch as silicon-germanium is a special alloy with few applications besides thermocouples, many of its physical properties, including the emissivity, were not available in the literature. The emissivity was determined by using the standard arrangement of equipment shown in Figure 6-8.

The silicon-germanium was welded to a tungsten support which was heated in a small oven. The temperature of the tungsten was measured with a thermocouple made of platinum and platinum-rhodium. The sample was made as thin as possible (0.5 millimeter thick) in order to reduce the temperature drop from the measuring thermocouple to the front of the sample.

Figure 6-8. Schematic Diagram of Equipment for Testing Emissivity of Silicon-Germanium

The black-body control oven was adjusted to the same temperature as that of the sample. The energy radiated by the sample was compared with the energy from the black body at various wavelengths using a two-position mirror, a monochromator, and a receiving thermocouple. The tests were performed at temperatures of 475°K, 875°K, and 975°K. Typical results are given in Figure 6-9.

Figure 6-9 shows the radiation intensities for the sample and the black body at 875°K as a function of the wavelength. The emissivity is the ratio of the areas under the curves.

The curves for the other temperatures, which are not shown, have similar shapes. The results are listed in Table 6-3.

Figure 6-9. Measured Emissivity of Silicon-Germanium Alloy at 875°K

TABLE 6-3. EMISSIVITY OF SILICON-GERMANIUM AT VARIOUS TEMPERATURES

Temperature	Emissivity
475°K	0.73
875°K	0.77
975°K	0.78

BLANK

SECTION VII. THERMAL INSULATION

A. SELECTION OF THE INSULATION

The thermal insulation which surrounds the isotope-fuel capsule and channels heat to the thermocouple hot shoes is characterized by the value of its thermal conductivity, K_i . This characteristic is given by

$$K_i \simeq \frac{Q_i d}{A_{CA} (T_{CA} - T_{RA})}$$

where

- Q_i is the heat leakage through the insulation (watts),
- d is the radial distance between the surface of capsule and the base of radiator (centimeters),
- A_{CA} is the surface area of the isotope capsule (square-centimeters),
- T_{CA} is the temperature at the surface of the isotope capsule ($^{\circ}\text{K}$), and
- T_{RA} is the temperature at the base of the radiator ($^{\circ}\text{K}$).

In the preliminary design given in Section IV, the thermal leakage, Q_i , was limited to a maximum value of 50 watts. This limitation severely restricts the choice of insulating material as indicated in the following approximate calculation.

Substituting the following approximate values of the parameters in the equation above

$$\begin{aligned} Q_i &= 50 \text{ watts,} \\ d &= 2 \text{ centimeters,} \\ A_{CA} &= 900 \text{ square-centimeters, and} \\ T_{CA} - T_{RA} &= 800^{\circ}\text{K,} \end{aligned}$$

the maximum value for thermal conductivity is

$$\begin{aligned} K_i &\simeq \frac{(50) 2}{(900) (800)} \\ &\simeq 1.4 \times 10^{-4} \frac{\text{watts}}{^{\circ}\text{K} - \text{centimeter}}. \end{aligned}$$

Numerical values of K_i for some typical insulation materials are listed in Table 7-1. This information shows that materials with a desirable (low) thermal conductivity cannot be used at high temperatures while the reverse condition is also true. While Min K* is the best insulator when in a vacuum, it is still deficient by a factor of 2.5.

B. MULTIFOIL INSULATION

Since the generator is intended to function in a "hard" space vacuum, the solution lies in the use of "multifoil" insulation. This material has been applied successfully in containers for cryogenic fluids (Reference 1). Under these conditions, the shields are made of aluminized mylar from 50 to 200 in number depending on the application. Heat transfer rates corresponding to conductivities of 10^{-6} to 10^{-5} watts per degree centigrade per centimeter are obtainable.

Since mylar and aluminum cannot be used at high temperatures, this generator requires other materials which have a high melting point, low weight, very low emissivity (at the wavelengths of interest), and resistance to corrosion.

The order of magnitude value for the emissivity, ϵ , of the foil is derived from the formula for heat transfer by radiation

$$Q_i = \sigma \epsilon_{\text{eff}} (T_{\text{CA}}^4 - T_{\text{RA}}^4) A_{\text{CA}}$$

where

ϵ_{eff} is the effective emissivity of a stack of radiation shields, and
 σ is the Stefan-Boltzmann constant.

ϵ_{eff} is related to ϵ by

$$\frac{1}{\epsilon_{\text{eff}}} = \frac{1}{\epsilon_{\text{oca}}} + \sum_{1}^n \frac{2}{\epsilon} - n$$

where

ϵ_o is emissivity of container surface,
 ϵ is emissivity of the foil, and
 n is number of shields.

*Trade name for a silica product with a 3-percent phenolic binder manufactured by the Johns-Manville Co., Manville, New Jersey.

TABLE 7-1. THERMAL CONDUCTIVITY FOR TYPICAL INSULATION MATERIALS

Material	Thermal Conductivity $\left(\frac{W}{^{\circ}C \text{ cm}}\right) \times 10^{-4}$	Maximum Temperature ($^{\circ}C$)	Remarks
Eiderdown	1.9	30	Shown for comparison only
Cork	3.6	80	
Bees' Wax	4.	30	
Silk	4	30	
Fir-wood perpendicular to grain	4	80	
Diatomaceous earth	8	5	
Light concrete	10	225	
Asbestos	24	500	
Insulating tiles	35 (varies)	1000	
Zirconia	93 - 170	up to 1400	
Min K 2000	6.5	1000	Trade name for 90% SiO ₂ fibers by Johns-Manville
Min K 2000 (in vacuum)	3.5	1000	
Zirconia Foam	13	1200	
Zirconia A	90	1100	
Zirconia B	100	2400	
Microquartz	9	1300	
Tipersul	4 - 6	1100	Trade name for Potassium Titanate by DuPont
Refrasil	10 - 16	1075	Trade name for 99% SiO ₂ fibers by H. I. Thomson, Los Angeles

Since only approximate data are needed to select the material, a simplified equation is acceptable. T_{RA} is less than half of T_{CA} and may be neglected. The influence of ϵ_0 is also small, hence it may be neglected. ϵ is assumed to be constant. These simplifications yield

$$Q_i = \sigma \frac{\epsilon}{2n - \epsilon n} T_{CA}^4 A_{CA}.$$

Substitution of

$$\begin{aligned} Q_i &= 50 \text{ watts,} \\ A_{CA} &= 900 \text{ square-centimeters,} \\ T_{CA} &\approx 1450^\circ\text{K} \\ \sigma &= 5.67 \times 10^{-12} \frac{\text{w}}{\text{cm}^2 \cdot (\text{K})^4} \end{aligned}$$

gives

$$\frac{\epsilon}{2n - \epsilon n} \approx 2.2 \times 10^{-3}$$

or

$$n \approx \frac{450 \epsilon}{2 - \epsilon}.$$

This expression permits computing the weight of the foil stack as a function of ϵ . Foils thinner than 15 microns are not considered because they are difficult to obtain commercially and difficult to handle.

Table 7-2 gives the weight for stacks of foils with specific gravity of 3 (typical for light metals), 10 (iron to rhodium metals) and 20 (heavy metals). Figure 7-1 shows this information in graphic form. (Reference 21.)

The preliminary weight allowance for the foil insulation is 1 pound (0.46 kilogram); the upper limit is 2 pounds (0.91 kilogram).

If it could be assured that the generator would operate solely in vacuum, then a combination of copper foils (for the lower temperatures) and tantalum foils (for the higher ones) would be desirable. However, the generator is intended to operate in air from time to time. Under those conditions, both copper and tantalum would oxidize very rapidly and thus lose their insulating value.

TABLE 7-2. WEIGHTS OF STACKS OF INSULATING FOILS

Emissivity	Number of Foils (n)	Specific Gravity = 3	Weight of Foils (kg) Specific Gravity = 10	Specific Gravity = 20
0.05	12	0.05	0.16	0.32
0.1	24	0.10	0.32	0.64
0.15	37	0.15	0.50	1.00
0.2	50	0.20	0.67	0.135
0.3	79	0.32	1.07	2.13
0.4	112	0.45	1.51	3.02
0.5	150	0.62	2.08	4.16

Notes

1. Quantity of foil is that required to insulate capsule of 900 cm² surface area.
2. Thickness of foil assumed to be 15 microns.
3. See References 8-12 and 8-13.

Therefore, Hastelloy X and aluminum, which are corrosion-resistant materials, have been selected. However, tests showed that it was not possible to prevent some initial oxidation of the Hastelloy. The first few foils lost their low emissivity and the temperature of the adjacent foils increased. The aluminum would have been melted had the test not been terminated.

The next possibility was to plate a light, high-temperature-resistant material with a corrosion-resistant (precious) metal or to select a pure precious metal. Several alternate solutions are compared in Table 7-3.

Beryllium foil was available but very expensive due to extreme difficulties in fabrication. It was not considered because of its high price.

The other thin-base foils were found to be commercially available. In addition, techniques for plating 1 micron of a precious metal on thicker-base (0.5-millimeter) foils were found to be well established. However, the technique of plating a 1-micron layer on a base foil 13 to 25 microns thick was not established. The high prices quoted for these processes, shown in Table 7-3, essentially represent the cost of a considerable development program by the plating industry. The delay of the program caused by such development could not be considered.

Figure 7-1. Weights of Stacks of Insulating Foils as a Function of Emissivity and Specific Gravity

TABLE 7-3. WEIGHT AND COST OF ALTERNATE FOIL INSULATIONS
WITH EQUAL INSULATING VALUE

Base Foil		Plating		Number of Foils (n)	Weight of Stack (kg)	Approx. Cost (\$)
Material	Thickness (Microns)	Material	Thickness on Each Side (Microns)			
Hastelloy	25	Platinum	1	37	0.89	3000
Hastelloy	25	Rhodium	1	24	0.54	2000
Titanium	13	Platinum	1	37	0.33	3000
Titanium	13	Rhodium	1	24	0.18	2000
Platinum	15	—	—	37	1.06	3400
Rhodium	15	—	—	24	0.41	3000
Beryllium	15	—	1	24	0.12	22000
Beryllium	15	—	—	24	0.07	20000

For this reason, an arrangement of 26 layers of rhodium foil was selected, although rhodium was neither the lightest nor the cheapest material. Tests (see C., this section) showed that it also oxidized after 1 or 2 hours of heating in air. However, measurements by Betz, Olson, and Morris (References 14 and 15) and by AED personnel confirmed that the oxidation layer disappears in vacuum. We therefore accepted the possibility of slight oxidation of the rhodium at the start of the pump down on the assumption that the foil stack would regain full insulating value in high vacuum. This reasoning was considered applicable to future flight hardware on the assumption that the flight through air after launch would last only minutes.

C. EMISSIVITY OF FOIL

Reference 14 gives the emissivity of rhodium as follows:

Temperature (°K):	500	1000	1500
Emissivity:	0.02	0.05	0.08

These data have been applied in the initial design of the generator. However, since the precise values are very influential to the success of the project, it was decided to verify the data. Interest centered chiefly on the emissivity of foils, 15 microns thick without a substrate. The test method and equipment were similar to those described for the emissivity of SiGe described in Section VI, D.

Adequate test results were difficult to obtain because the foil contained pinholes through which radiation passed to the detector from the oven behind the sample. It was also difficult to connect the platinum/platinum-rhodium thermocouple properly to the fragile sample. Brazing was not possible because the brazing material would change the surface properties of the foil. After many attempts at regular resistance welding failed, ultrasonic welding was used. After exercising great care in handling the sample, a few readings in agreement with Reference 14 were obtained.

To further verify the behavior of the material, foils (0.25 millimeter thick) were brazed to supports of Hastelloy and measured to have an emissivity of 0.008 at 1100°K. However, after 1 hour at this temperature, the foil visibly oxidized and the emissivity rose to 0.5. Subsequent heat treatment at 1100°K in vacuum or 1100°K in hydrogen caused the oxide layer to disappear. It was noted that the 15-micron foil samples that went through one oxidation and reduction cycle lost only about 0.1 percent in weight. It was concluded from these tests that the material is acceptable as a radiation shield for the generator inasmuch as vacuum operation is intended. Even if the material becomes oxidized by accident, it can be reduced to its pure state without lasting damage. This is an advantage over foils of the cheaper refractory materials such as tantalum. Tantalum, when severely oxidized, could be reduced to a powder under similar conditions.

D. SEPARATOR MATERIAL

The following are the requirements which apply to the separator material.

1. Low thermal conductivity.
2. High temperature resistance.
3. Minimal weight.
4. Flexibility and sheet strength.
5. High vapor pressure at 2000°F.
6. Chemical inertness to metals at 2000°F.

These requirements suggested a ceramic or glass material. The final choice was "Fibrefrax". This is the tradename for a material consisting of long staple ceramic fibers and an organic binder (for strength)* matted into a paper.

The Fibrefrax contains an organic binder which evaporates at high temperature, leaving the material without strength. Hence, when winding the insulation, it is better to use fresh Fibrefrax, rather than that which has been heated to a high temperature. However, this entails the risk that the foil might become coated with the decomposition products of the binder when the generator is brought up

*Manufactured by the Carborundum Co.

to temperature for the first time. The emissivity of the foil would then go up to such a level that it would become worthless as insulation.

In order to evaluate this risk, two samples of foil were wrapped in Fibrefax and heated to 1170°K for 15 minutes in a vacuum furnace at a pressure of 5×10^{-3} millimeters of mercury.

The foil showed no visible change. This prompted the conclusion that it was not affected. The insulating material discolored to a dark gray, suggesting that the organic binder decomposed into volatiles and carbon. The deposited carbon disappeared when the paper was afterwards heated in air to 700°C.

E. MULTIFOIL INSULATION FABRICATION TECHNIQUES

The problems of manufacture have strongly influenced the decision on the final form of the multifoil insulation. Keeping in mind the need for precision fits at the movable end-closure and at all other joints, in order to keep heat losses to a minimum, a cylinder with mitered end plates became a clear choice. Mitering the cylinder and the end plates is called for in order that every foil edge touch only those mating edges which are at the same temperature. (See Figures 7-2 and 7-3.)

The insulation cylinder was rolled on a special machine that maintained a given compressive force between layers. The wound cylinder was then removed from the machine and placed on a rotary table. Here, under a specially designed, high-speed oscillating knife, the mitering operation was performed and the side cutouts for thermocouple access were made. The end closures for this cylinder were made differently because of the need for round holes passing through the foil stack at 45 degrees to the normal. This situation arises from the fact that the fuel-capsule support tubes (zirconia) which pass through the end closures are designed for compressive loading (only) regardless of load direction. These holes could be drilled with conventional twist drills or end mills if the foil separator material was replaced by a metallic shim. The compression in the end closure, being the same as the cylinder for equal thickness in order to have a 45-degree miter angle, is insufficient to prevent severe tearing with drills or end mills. Substituting shims for the ceramic paper, equal in thickness to the compressed paper thickness, allows the hole cutting operation and mitering of the edges to be accomplished using a conventional drill and engine lathe respectively. The ceramic paper is cut in the stacked form using ordinary paper as a substitute for the rhodium foil. Angled holes are cut using an alignment fixture and a hollow tube with a sharpened and serrated edge. Mitering was done using an oscillating blade guided by the fixture. The complete end closure was then assembled by alternately stacking the foil and pre-cut discs of ceramic paper and then sewing the pack together (with the proper compression value) with platinum wire.

Figure 7-2. Schematic Diagram of Multifoil Insulation

Figure 7-3. Detail of Figure 7-2 Showing Gap causing Heat Loss

The insulation cylinder is provided with a stainless-steel cage-like outer enclosure that maintained the compression and provided attachment points for the cylinder. The inside of the foil cylinder was also fitted with a cage support made of Hastelloy X. This cage serves several functions (1) it maintains the cylindrical shape and diametrical stability of the foil; and (2) it provides a protective margin for the thermocouples when the fuel capsule is inserted, since the couples are at a radially greater distance from the center than are the cage bars.

F. BULK INSULATION

The edges of the rhodium foils would cause short circuits if they were in direct electrical contact with the thermocouples. Therefore, the couples are surrounded by a fibrous material called Kaowool*. The space between the couples is filled with the same material.

In the corners of the modules, Min K-2000 bloc insulation is applied. Since this material was relatively new when first employed, a few simple tests were performed with it. The bloc insulation was advertised as Min K-2000 suggesting an operating temperature of 2000°F (1370°K). Because verification of this feature was desired, Min K-2000 was soaked at this temperature for 24 hours. Surprisingly, the shrinkage was close to 20 percent.

Consultation with the manufacturer brought out the fact that the material had been developed for application as pipe insulation; in such usage only the inner layer would be at the peak temperature. The manufacturer stated further that at 1300°K the shrinkage is greatly reduced and at 1150°K it is negligible. When it is used as pipe insulation, the temperature ranges from 1370°K at the inner diameter to about 500°K at the outer diameter. The overall shrinkage is then nominally less than 1 percent. In the original design, some of the Min K would have been exposed to a temperature of 1350°K. In order to avoid shrinkage problems, the foil insulation was made somewhat wider, so that it would partially shield the Min K from the hot fuel capsule. That part of the Min K which remains exposed is located so close to the thermocouple hot shoes (which operate at 1150°K) that its temperature is limited to between 1150 and 1200°K.

G. REACTION BETWEEN MIN K AND SILICON-GERMANIUM

Silicon-germanium is a stable material at temperatures exceeding the operating temperature of the present generator. This has been proven during approximately 18-month life tests by the supplier and by a number of users. However, we have found only very limited data on the behavior of the Min K insulation in contact with silicon-germanium at high temperatures.

*Manufactured by Babcock and Wilcox, New York, N. Y.

Since the insulation material consists of 92-percent silicon-dioxide, it was considered possible, though not probable, that oxygen could diffuse from the insulation into the thermocouple and disturb the thermoelectric properties. In order to investigate this possibility, a life test was performed in which one thermocouple was kept in contact with Min K under operating conditions for 38 days. The installation contained an electric heating element mounted 12 millimeters from the hot shoe. The heat entered the thermocouple by radiation and left by conduction via a small heat sink mounted on the cold junction. The hot- and cold-junction temperatures were checked continuously with Chromel Alumel thermocouples. They were adjusted daily whenever necessary.

The output of the couple was measured daily. It proved to be constant, as shown in Figure 7-4. This established confidence that the silicon-germanium and Min K were compatible at the 1100 to 1200°K level. Min K was subsequently used in the generator. The single thermocouple life test was continued further for 6000 hours with no apparent degradation.

Figure 7-4. Life Test on Min K Insulated Thermocouple

SECTION VIII. RADIATOR AND STRUCTURE

A. RADIATOR MATERIAL SELECTION

In order to keep weight to a minimum, the radiator functions as the main structure of the generator. This calls for a material which is light, strong, and also a good heat conductor. This material should be able to function continuously at approximately 540°K.

Experience with aircraft and spacecraft suggested that the choice be limited to commercially pure beryllium, an aluminum alloy, and a magnesium alloy. Table 8-1 lists the salient properties of these three substances.

TABLE 8-1. PROPERTIES OF RADIATOR MATERIALS AT 540°K
(Per References 28, 29, and 30)

Material Property	Symbol	Units	Beryllium	Aluminum Alloys		Magnesium Alloy HK 31A, T6
				2024 - T4	6061 - T6	
Nominal Composition	—	—	BeO 2% max	Cu 4.5% Mg 1.5% Mn 0.6%	Mg 1% Si 0.6% Cu 0.25% Cr 0.25%	Th 3% Zr 0.7% Mn 0.15%
0.2% yield strength	σ_y	$10^8 \frac{N}{m^2}$	2.5	0.7	0.35	1
Thermal conductivity	K	$\frac{W}{oK \cdot m}$	125	190	180	78
Density	ρ	$\frac{kg}{m^3}$	1840	2770	2700	1800
Figure of merit*	$\frac{K\sigma_y}{\rho}$	arbitrary units	1.68	0.48	0.23	0.43
*A high figure of merit indicates a desirable material. However, there is no linear relation between the numerical value of the figure of merit and the weight of the radiator.						

Beryllium has the highest figure of merit but it is expensive (\$200 per kg compared to \$1 per kg for aluminum). It is also difficult and costly to machine and is somewhat toxic if not handled correctly.

Since the present generator is not subjected to shock and vibration tests, the extra strength of the beryllium is not required. In the interests of economy, therefore, the choice was restricted to aluminum and magnesium with the understanding that other substances may be considered for future flight applications.

With the requirements for higher strength eliminated, the ratio $\frac{K}{\rho}$ now acts as a revised figure of merit. Aluminum has the higher value. Since 6061-T6 is easier to join than 2024-T4, it was selected as the radiator material.

B. RADIATOR COATING

The radiator must have a high emissivity, particularly in the 5-micron region of the spectrum. At the same time, the absorptivity in the visible region must be low so that when in orbit, the generator does not absorb appreciable solar heat. This suggests covering the radiator with a flat white paint. The paint should not darken in ultra-violet light or under the influence of gamma radiation. It should have a life expectancy of several years, not evaporate in vacuum, and not blister or peel at the 500 to 600°K level. On application, the coating should not warp or deform the radiator 0.5 millimeter thick. Several of these characteristics had been worked out independently but attempts to combine all the needed properties presented difficulties. The most desirable material appeared to be alumina, Al_2O_3 , which could be applied by several refractory type processes. However, application must be preceded by sandblasting, which would destroy the thinner parts of the radiator.

Mixtures of aluminum and zinc oxides were prepared using waterglass (sodium silicate) as the binder; this was sprayed on the surface. A coating with an emissivity of 0.80 to 0.85 and an absorptivity for visible light of 0.15 to 0.20 was produced. However, the coating did not adhere sufficiently to the surface during 24-hour tests at 600 to 650°K.

We felt that with further work a coating meeting all specifications would be obtained. However, the schedule did not permit us to experiment beyond this. Therefore, for the present generator the specification was relaxed to permit use of a commercial, high-temperature paint.

The final choice was an automobile paint originally developed for the missile industry.* It showed good adhesion at 600°K and an acceptable emissivity, although not as high as desired.

*Manufactured by Sperex Corp. Los Angeles, Calif (Reference 16)

C. RTG STRUCTURE

The structural integrity of the RTG is provided by the radiators and their interconnections. The radiators are bolted together at their flanges to form the basic structural framework as shown in Figure 3-3. End plates enclose the cavity thus formed and comprise the support members for the fuel capsule. The radiators are dip-brazed assemblies of aluminum having tapered-sheet sections and liquid cooling tubes at their apices. The thickness necessary to meet the thermal requirements is the same as that necessary to meet the mechanical requirements for a longitudinal and transverse loading of 30 g. This is based on the assumption that the generator is cantilever-mounted from three fittings bolted to the radiators at the point of attachment of the bottom end closure.

The baseplate of the thermocouple module must be in close thermal contact with the radiator at operating temperatures in vacuum conditions. This baseplate is made of copper and as such has a thermal expansion rate different than that of the aluminum radiator. This mismatch is a possible source of trouble because stresses may occur in the thermocouples; this is clearly undesirable because silicon-germanium is brittle.

The fuel capsule is supported by two sets of three zirconia tubes set in aluminum holders and bolted to each end closure at opposite ends of the radiator assembly. Each tube is set at 45 degrees to the axis of the fuel capsule; the three tubes are equally spaced. Each end of the fuel capsule is provided with a cavity with walls which slope 45 degrees; this cavity receives the zirconia tubes in such a manner that the tubes perpendicularly bear upon the cavity walls.

By providing the zirconia tube ends with rounded sapphire tips (to prevent reaction with and welding to the capsule), the resulting low friction coupling to the capsule limits the tubes principally to compression loading. In this compressive-loading mode, this material is capable of great strength at the operating temperature of 1100°C.

The aluminum, sheet-metal end closures which receive the zirconia tubes are reinforced with angle sections to carry the capsule load to the radiators and out to the supporting truss. Due to a multiplicity of expansion rates, temperature levels, and gradients, the zirconia tubes supporting the capsule do not touch the capsule at the top end at room temperature but exert a nominal compressive force of only 20 pounds at this temperature.

D. SPECIAL FABRICATION TECHNIQUES

The triple requirements (lightness, strength, and reliability in space environment) have led to the development of certain fabrication techniques or to the use of existing techniques in new fields. The present generator employs a few such methods which may be of sufficient interest to warrant recording here.

The two biggest changes from conventional to space-type fabrication engineering are due to operation in the hard space vacuum; this vacuum may be as high as 10^{-13} millimeters of mercury in cislunar space. If air is absent, heat does not flow freely between adjacent surfaces even if they are bolted together. The reason for this is that such surfaces normally make point contact only, as shown schematically in Figure 8-1.

On earth the trapped air (shaded areas in the figure) provides a low-impedance heat-flow path because the distances are small. In space the air is absent. Heat is transferred partly by conduction across the point contacts but mostly by radiation. This gives

Figure 8-1. Two Surfaces in Contact

rise to large temperature drops at low-temperature levels. A brief calculation shows that if the heat from the baseplates of the thermocouple modules were transferred to the radiators solely by radiation, the cold-junction temperature would rise from approximately 540°K to approximately 880°K; this would completely prevent the generator from performing the design function. Thus, wherever heat must flow from one body to another, there must be a solid metallic contact between them.

The other problem is, in some respects, the reverse of the foregoing. In ultra-vacuum, the thin layers of oxides, similar materials, or any foreign matter which are normally adsorbed on metallic surfaces, may be absent. If like metals are in contact, atoms may diffuse freely between surfaces, ultimately welding them together.

1. Dip Brazing

The shape of the radiator has evolved as shown in Figures 8-2 and 8-3. The original single fin has been replaced by two to give more strength to the structure without increase in weight. This has led to the use of thin sheet metal. At the same time, the fins must be built to rather close tolerances because the radiator serves as the main structure. We have considered fabrication by bending only but this is not practical because there are two locations at which three surfaces meet. Arc welding is not practical because it does not appear possible to avoid distortion of the thin sheet metal. Electroforming is possible, except that the tapered fins present problems. Soldering, the next possibility, was rejected because 520°K is too high an operating temperature for the normal soft solders; they melt or lose their strength. There must also be some margin in the design in order to avoid the risk that parts of the generator fall off during a brief temperature excursion. Special solders mostly contain cadmium or zinc, both of which have vapor pressures which are too high at the temperature levels of interest.

The final decision was on dip brazing. By this method the individual aluminum parts are mounted in a fixture. Brazing compound is applied at the joints and the assembly is dipped in a bath of molten salt. The temperature of the bath is just below the melting point of aluminum.

Dip brazing requires considerable experience. The supplier did not meet the specification completely. The thin sheet near the tips of the fins was distorted and required substantial reworking in our own shop. Had we known all the problems beforehand, we would perhaps have made the fins of uniform thickness and selected a different fabrication method, at the expense of 500 grams of extra weight. On the other hand, the chosen method has yielded useful experience for the fabrication of future lightweight radiators for larger spacecraft. To wit, the larger the generator, the more important the radiator structure and the method of joining thin sheet metal.

Figure 8-2. Original Radiator

Figure 8-3. Stronger Radiator of Approximately the Same Weight

2. Fabrication of the Insulation

Multifoil in vacuum has insulation qualities that are far superior to those of solid material. But for this very reason, small leakage paths cause appreciable heat losses. For example, if the multifoil has an average area of approximately 900 square-centimeters, it passes about 10 watts. However, if as little as 1 square-centimeter of the 1450°K capsule were permitted to "see" the radiator area, the heat loss would triple.

The application of the foil thus becomes a mechanical problem, in particular because the insulation under the top cover must be removable to permit insertion or removal of the fuel capsule from time to time.

Multifoil insulation of cryogenic tanks and the like is usually accomplished by preparation of small stacks of foil, which are placed overlapping. For example, a sphere can be insulated by preparing a dozen foil stacks shaped slightly larger than half spheres and packing them so that they overlap with the laps staggered.

In the present case, the presence of the thermocouples prevents this simple solution. Therefore, it was planned to prepare stacks of foil and fibrefrax and to insert these

stacks in between the block insulation. However, it was not possible to guarantee absolutely tight packing at the edges.

RCA personnel then developed a better method of fabrication, which was ultimately adopted. The foil and Fibrefrax were wound as a cylinder with 25 layers. The end plates were simple stacks of 25 circular foils and Fibrefrax. The critical problem was to assure full contact of all horizontal foils with their vertical counterparts, since mismatch would mean a thermal short circuit. Gaps would likewise mean extra heat losses. (See Figure 7-2 and 7-3.)

The solution effected was to clamp the edges between a mandril and a support ring, and to miter them with a high-speed saw. The same method was applied to the bottom and top covers.

The top cover was furthermore lined with a sheet of soft insulating material to prevent damage to the foils. The windows for the thermocouples were cut with the high-speed saw.

3. Remote Welding in a Hot Cell

The bottom plates of the inner and outer containers can be attached to the cylinder walls by conventional means. For example, the bottom of the TZM container is an integral part of the can, the can having been machined from solid bar stock. However, the tops must be attached when the containers are filled with the radioactive material, which requires remote handling and remote welding in a hot cell.

Remote handling with master slave operators (manipulators) is a well-established technique. Remote welding of TZM has proven to be more difficult, partly due to the technique, partly due to the material. The method was worked out by W. Early of Oak Ridge National Laboratory in consultation with RCA.

The TZM can is positioned by manipulators in a copper block which acts as the welding fixture. The block and the welding electrode are mounted in a metal box approximately 1 by 0.6 by 0.6 meter which can be hermetically closed. It can be evacuated or filled with a welding gas such as argon or helium under a pressure of up to 2 atmospheres. The box in turn is located in the hot cell.

The welding fixture is supported by a shaft which is slowly rotated by an electric motor during the actual welding operation.

The method was worked out on a number of TZM samples with the same diameter (10 centimeters) as the inner container. However, to save a material and machining cost of about \$1000 per container, the height of the samples was reduced to 2.5 centimeters. After completed welding, the samples were checked with gamma rays and then metallographically checked on the cross section.

The first welds were unsuccessful. Sometimes the penetration was not deep enough; sometimes the sample cracked after welding. To improve quality of the welds, modifications were made to the cleaning techniques used before welding; in addition to being washed in acetone, the parts were placed in a hydrogen reduction furnace (1600 to 1700°K) for 30 minutes (Briggs, Reference 17).

The welding atmosphere was carefully controlled to exclude oxygen and nitrogen, both of which have a detrimental effect on ductility. Reasonable limits were below 0.005 percent for oxygen and below 0.1 percent for nitrogen (Reference 18). Briggs further recommended a preheat of 500°K and a postheat of 1300°K in hydrogen or vacuum for 15 to 30 minutes, with very slow cooling afterwards.

A hydrogen furnace was installed in the hot cell, all the safety requirements of the combustible gas and of the 100-kilocurie source were met, and the remote welding technique described earlier was used. The results were satisfactory and the welding technique was accepted.

After the method had been worked out for TZM, the welding of Hastelloy presented few problems.

SECTION IX. DESCRIPTION OF EXPERIMENTAL EQUIPMENT USED IN TESTS WITH AN ELECTRICAL HEAT SOURCE

The development of the generator required the installation of a variety of experimental equipment. The two most significant items acquired for this program are the vacuum chamber and the electrical heater.

A. VACUUM CHAMBER

Because the generator can yield the rated output only in a vacuum, a vacuum chamber has been acquired for test purposes. The chamber is shown in Figure 9-1. The size is purposely somewhat larger than is presently required in order to accommodate future, larger power supplies.

This chamber has several special features which are not normally found in similar equipment. The chamber contains a thermal shroud through which a cooling fluid can circulate by means of pipes. The interior of the shroud is coated to give it a high emissivity for infrared. The shroud absorbs the heat radiated outward by the generator; this simulates an outer space environment. Depending on the temperature of the radiator and the required accuracy of the simulation, the shroud, when cooled with water, attains about 300°K, or when cooled with liquid nitrogen, as low as 77°K. For most applications, water cooling suffices.

The base of the chamber and the bell jar are made of stainless steel to facilitate cleaning in the event the chamber becomes contaminated with radioactivity. A glass disc, 30 centimeters in diameter, covers a viewport. A smaller glass disc permits illumination of the interior by an exterior light source. The glass, which was specially selected, is resistant to discoloration due to gamma rays. The base-plate contains a cable connection with about 200 electrical feed through pins of three types: copper, chromel, and alumel. The last two materials are those of which the monitoring thermocouples are made. It is highly desirable that connecting wires from monitoring thermocouple to measuring instrument be of the same material.

The chamber is specially designed to fit into a hot cell. It is mounted on casters to provide some measure of mobility.

Thermal testing does not require a very high vacuum. For many heat transfer problems a pressure of 10^{-4} millimeters of mercury is sufficient and 10^{-5} millimeters of mercury is considered hard vacuum. However, since the option of opening and closing the chamber repeatedly during a working day is desired, two 6-inch

Figure 9-1. Photograph of Vacuum Chamber Used for Tests with Electrical Heat Source

diffusion pumps, each with a speed of 1500 liters per second at 10^{-4} millimeters of mercury, have been provided. The oil is Dow Corning 704 which is not affected by gamma rays up to a total dose of 5×10^7 rads.

The controls are arranged for remote operation. The control console is located outside the hot cell and all parameters needed for monitoring or controlling the chamber are telemetered to it.

B. ELECTRICAL HEATER

The electrical heater for the initial tests consists of an alumina core on which heater wire has been wound. The assembly is surrounded by a Hastelloy X container with outside dimensions and coating as the isotope capsule.

The heater presented a few unique problems. The core material was selected so that it contains very little binding material which would outgas in vacuum. The heater wire is made of an alloy* of 5.5-percent aluminum, 22-percent chromium, 0.5-percent cobalt, and 72-percent iron. Kanthal wire of the type used resists corrosion in air up to temperatures of 1500 to 1600°K because the aluminum compound oxidizes rapidly on the surface and the oxide protects the under-lying material. In vacuum, however, the oxide coating disappears and the aluminum slowly evaporates out of the alloy.

The matter of aluminum evaporation in vacuum was discussed at length with the supplier who suggested that the oxide layer be reformed by operating the heater in air for a few hours after every hundred hours operation time in vacuum. This procedure was used and has proven successful.

C. OTHER EQUIPMENT

The other equipment needed for the electrical tests is quite conventional. Included are a variety of automatic temperature recorders, alarm and protective devices, and several furnaces for component testing. The largest of these furnaces is approximately 90 by 90 by 120 centimeters and can provide temperatures up to 1000°K; a second one measuring 20 by 30 by 45 centimeters can operate at 2000°K.

*Produced by Kanthal AB, Hallstahammer, Sweden

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SECTION X. RESULTS OF TESTS WITH ELECTRICAL HEAT SOURCE

The initial tests, in which the electrical heat source is substituted for an isotopic heat source, cover three aspects:

- (1) Bench tests of modules in air;
- (2) Test of multifoil insulation;
- (3) Test of complete generator.

A. TEST OF MODULES

Every module, after fabrication, was given a 72-hour aging test at the manufacturer's facility. Subsequently, depending upon the phase of the program in which they were received at the Astro-Electronics Division, the modules were either connected with screws to dummy radiators or were bonded to the final radiators. In both cases, they were placed on simple furnaces made of fire bricks and exposed to the radiant heat of a glow-bar. The characteristics of the thermocouple modules were measured daily for several weeks. A typical load curve (I-V curve) for module number 17-15 (containing 14 couples) is shown in Figure 10-1 and one for module number 39-2 (22 couples) is shown in Figure 10-2.

Figure 10-1. Typical Load Curve for a 14-Couple Module (No. 17-15)

Figure 10-2. Typical Load Curve for a 22-Couple Module (No. 39-2)

B. TEST OF MULTIFOIL INSULATION

During the fabrication of the insulation, a cylinder consisting of 25 layers of rhodium and alternate layers of Fibrefrax, was wound around the capsule. This was then equipped with a temporary top and bottom of Min K and foils of aluminum and Hastelloy X, as shown in Figure 10-3.

The electrical heater was mounted in the capsule and the assembly, equipped with 12 monitoring thermocouples, was placed in the vacuum chamber. The purpose of the test was to bracket the effective emissivity of the insulation by measuring the temperature at which the capsule stabilized for several fixed inputs of electrical heat.

Due to time limitations, the tests were limited to a few combinations of temperature and heater input as shown in Table 10-1. In all cases the temperatures were allowed to become stable.

It is interesting to note that upon replacing the vacuum by argon gas at atmospheric pressure, the heat flow through the insulation increases by one order of magnitude.

Figure 10-3. Multifoil Insulation Used in Electrical Heat Test

TABLE 10-1. TEMPERATURES OF CAPSULE WITH ELECTRICAL HEAT SOURCE

Temperature of Capsule	Heater Input	Environment and Pressure	Shroud Temperature
675°C	19.7 watts	Vacuum; 1.1×10^{-5} mm Hg	14°C
741°C	23.6 watts	Vacuum; 3.3×10^{-6} mm Hg	13°C
745°C	241 watts	Argon, 760 mm Hg	13°C

Using the above figures, the heat flow through the insulation at various temperatures can be estimated. Since the top and bottom of the cylinder consist chiefly of Min K, they allow a slightly larger specific heat flow than the cylinder wall. However, a conservative calculation shall be made ignoring this fact and assuming that the entire area of the cylinder (1030 square-centimeters) is made up multifoil.

The exposed area A of the electrical heater capsule is 845 square-centimeters. The heat flow through the insulation is given by

$$Q_i = \epsilon_{\text{eff}} A (\sigma T_{\text{CA}}^4 - \sigma T_{\text{SH}}^4).$$

Since T_{CA}^4 is much greater than T_{SH}^4 , the equation simplifies to

$$Q_i = \epsilon_{\text{eff}} A T_{\text{capsule}}^4.$$

Substitution of

$$\begin{aligned} Q_i &= 23.6 \text{ watts,} \\ A &= 845 \text{ cm}^2, \text{ and} \\ T_{\text{capsule}} &= 1014^\circ\text{K,} \end{aligned}$$

gives

$$\epsilon_{\text{eff}} = 0.0047.$$

The heat which flows through the insulation consists of: (1) a conduction term which increases linearly with T_{CA} , and (2) a radiation term which increases with T_{CA}^4 .

In both cases, T_{SH} is assumed constant. For a conservative calculation, we assume that the conduction term is small and that the heat flow increases with T_{CA}^4 . The resulting computed heat flows are given in Table 10-2.

TABLE 10-2. HEAT FLOW THROUGH INSULATION WITH ELECTRICAL HEAT SOURCE

T_{CA}		Heat Flow (watts)	Notes
$^{\circ}\text{C}$	$^{\circ}\text{K}$		
741	1014	23.6	1. Calculated heat flow through multifoil insulation consisting of 25 foils of rhodium
800	1073	29.6	
850	1123	35.5	
900	1173	42.4	2. T_{SH} is assumed constant
1000	1273	59	3. T_{SH}^4 is greater than T_{CA}^4
1066	1339	71	

C. TEST OF COMPLETE GENERATOR WITH AN ELECTRICAL HEAT SOURCE

After the generator was assembled, it was tested on electrical heat in a vacuum for about 4 weeks. During this period the following modules formed the component:

No. 39-2 = 22 couples, 1 inch, nominal length of couple (2.67 cm)

No. 17-15 = 14 couples, 1 inch, nominal length of couple (2.67 cm)

No. 7, 8, 9 = 6 couples each, 3/4 inch nominal length of couple (2.03 cm).

The input to the heater was raised in a number of steps from 100 watts to 530 watts. At each step, the input was held constant for at least a day to ensure thermal equilibrium. Temperatures and electrical output values were measured and I-V curves taken. The following typical results are shown in Table 10-3 and Figure 10-4. The heat flows through the individual components are given in Table 10-4.

TABLE 10-3. ELECTRICAL OUTPUT OF COMPLETE GENERATOR
WITH ELECTRICAL HEAT SOURCE

Parameter \ Module No.	39-2*	17-15	7	8	9
Hot-Shoe Temperature (°C)	772	810	765	766	767
Cold-Shoe Temperature (°C)	228	248	252	252	252
Electrical Output (watts)	4.06	4.71	1.50	1.62	1.75
Thermal Input = 510 watts; Capsule Temperature = 973°C					
*Module 39-2 was later replaced by a dummy

Figure 10-4. Load Curves for Complete Generator
with Electrical Heat Source

TABLE 10-4. HEAT FLOW THROUGH INDIVIDUAL COMPONENTS

Module No.	Heat Flow (watts)
39-2	154
17-15	106
7	
8	159
9	
Multifoil Insulation	51
Supports and Other	40
Total = 510 watts	

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SECTION XI. DEVIATIONS FROM INITIAL DESIGN

During the course of tests intended to verify the adequacy of the initial design, a number of changes were deemed necessary. The principal one among these was due to the difficulty experienced with the thermoelectric modules. As described, these consisted of three 22-couple modules. The initial test consisted of operating each module in air using an electric source and a convective radiator attached to the module baseplate. The object was to measure the electrical performance to serve as a base line for all subsequent operations.

During the test and while being handled, all three modules experienced some couple fracture at the cold junction. Metallurgical investigation revealed these modules had defective bonds between the couples and the cold junction. Additional stress imposed by the tests (which involved temperature cycling and handling) caused many additional fractures. Only one module out of the initial group of four did not fail or degrade in any way. Additionally, a 14-couple module originally procured with the four 22-couple modules did not fail or degrade. These five modules were identical in manufacture. Consultation with the manufacturer on this problem revealed no specific causes for this mode of failure. It was learned, however, that the modules had been built as preliminary units before the manufacturing controls, which were very critical with this particular design, had been established. Changes in the process which promised substantial improvement in bond quality had occurred in the interim. Modules of this new design were currently available in the 6-couple, series-connected configuration. Four of these were procured and the RTG was then assembled with the following module complement: one 22-couple module, one 14-couple module, and three 6-couple modules. The 6-couple modules shown in Figure 11-1 are shorter and hence require more heat flux per couple to sustain a given temperature difference. Thus, the three 6-couple modules are roughly equivalent to one 22-couple module. The use of the 14-couple module necessitated reducing the amount of capsule heat output to 526 thermal watts to match the new total thermal impedance of this module complement.

Subsequently, the 22-couple module was replaced by a thermal dummy of Hastelloy, which conducted approximately one-third of the heat from the capsule to the radiator.

Another area of difficulty was in the fabrication and assembly of the Min K insulation around the thermoelectric modules. These were intricately machined pieces from block material which were intended to clam-shell around the module, as shown in Figure 11-2. The thermal fit required between the machined

Figure 11-1. Three 6-Couple Modules Mounted on Radiator Base

Figure 11-2. 22-Thermocouple Module with Min K Insulation

insulation and couples is stringent when one considers that the heat loss due to a gap is 100 watts per square inch. There are 54 couples having an interface "length" of some 40 inches with the block insulation. The allowable average gap for an arbitrary heat loss of, say, 5 watts would be 0.0013 inches. This would be achievable if compressive force were exerted between the insulation and couple as well as high tolerances and custom matching at assembly. Matching cannot be avoided due to the complex assortment of mechanical errors (angular and linear) possible in module fabrication. The compressive forces needed to achieve the gap requirement could not be tolerated because the attendant bending moment introduced into the cantilevered couple is highly dangerous. Experience gained in handling these modules indicated a change to a very low force-insulation system was in order. A change was made to Kaowool loose ceramic fiber insulation. This was meticulously "stuffed" between all couples and in all free spaces between modules and metallic insulation cylinder. The forces employed were very low and therefore resulted in a low density packing factor that is not comparable to the insulative qualities of Min K.

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SECTION XII. TESTS WITH A RADIOACTIVE HEAT SOURCE

A. HOT CELL

The quantity of strontium 90 used, approximately 100 kilocuries, produces no primary gamma radiation. However, the Y-90 daughter produces a 2.26 megavolt beta particles which, upon collision with surrounding material, give rise to secondary gamma rays, the so-called bremsstrahlung. Hecht (Reference 19) has calculated the intensity of such bremsstrahlung for strontium titanate. Nichols and Arnold (Reference 20) have presented test data which are in substantial agreement. With allowances made for the selfshielding of the isotope and the shielding effect of the TZM container, the radiation intensity 1 meter from the center of the fueled generator was measured to be 130 to 150 rads per hour.

Safety regulations allow personnel an exposure of only 6 millirems per hour (equal to 6 millirads per hour for gamma rays). Evidently the intensity must be lowered by a factor of from 20,000 to 25,000 by shielding walls of extra heavy concrete, 40 centimeters thick, or regular concrete 60 centimeters thick.

The normal procedure is to enclose the radioactive material in a small room (hot cell) with walls, floor, and ceiling of no less than the prescribed thickness. Such cells are sometimes standardized to handle 10,000 curies of cobalt 60 (which quantity requires walls of extra heavy concrete, 90 centimeters thick. Such a cell is shown in Figure 12-1.

The free space in the hot cell is 2.5 by 1.8 meters. The cell contains a window of lead glass which permits the operator to observe the interior of the cell. Mechanical manipulators (not shown) enable him to handle the equipment. The manipulators can handle loads up to 10 kilograms; heavier loads, such as the bell jar, are lifted by a remotely controlled, one-ton electrical hoist.

An important auxiliary facility is the ventilation. Air passes through the cell and is exhausted in the smoke stack through a filter. The air in the cell is always under slightly lower pressure than the air in the building.

The vacuum chamber has been designed to fit in the hot cell. The viewport is at the same height as the cell window. There is further room in the cell for the lead shipping container. When the strontium 90 is not used in the generator, it can be placed in this container which is then closed. Then, if the cell is not otherwise contaminated, personnel can safely enter the cell through the door at the back to make any necessary adjustments (to the vacuum chamber, etc.).

Figure 12-1. Schematic Diagram of Vacuum Chamber Within Hot Cell

B. INITIAL PREPARATION AND SETUP*

The vacuum chamber and associated support equipment were shipped to the Oak Ridge National Laboratories. The entire test setup was then assembled in a laboratory area and tested with an electrical heat source. The purpose of this electric heat test was to determine if any changes in generator performance had occurred during its transfer from RCA to ORNL. As a result of this initial test, it was noticed that the performance of the 6-couple module, number 8, was not as it should have been. This module was removed and replaced with a new 6-couple module, number 10, during which time the electrical test setup was broken down, and the vacuum chamber and all necessary support equipment were installed in the hot cell.

The strontium 90 isotope and encapsulating materials (TZM and Hastelloy X) together weighed 18.96 pounds. A "dummy" capsule was made by loading the electrical heating capsule with lead shot to a weight of 18.96 pounds; this simulated the isotope capsule in size and weight. By this time, the vacuum chamber had been installed in the hot cell and the RTG had been placed on the platen (flat bottom section of the shroud) of the vacuum chamber. (See Figure 12-2.)

Figure 12-2. RTG Mounted on Vacuum-Chamber Platen (as seen through Door of Hot Cell)

*The work in and around the hot cell was performed by Messrs. R. Byrum and R. Sizemore of ORNL.

The dummy capsule was placed in the hot cell along with a special screw-eye and lifting hook. The screw-eye was screwed into the hole on the top of the capsule and then coupled to the lifting hook. The operator then used one manipulator hand to lift the capsule from the hot cell tray into the RTG. After the capsule had been placed in the generator, the lifting hook and screw-eye were both removed and the lid on the generator was closed. By reversing this procedure, the generator was opened and the dummy capsule removed.

During these simulated loading tests the instrumentation and power cabling was installed between the RTG and the instrumentation racks behind the hot cell. The shipping cask containing the strontium 90 was then placed in the hot cell on the right-hand side and the lid bolts were loosened. The arrangement inside the hot cell is shown in Figure 12-3. The vacuum chamber is shown on the left, the isotope shipping cask on the right. The plastic covering is intended to protect against contamination by residual alpha particles from previous tests.

C. FUELING OPERATION

The fuel capsule, containing the strontium 90, was shipped in a special carrying case.

After placing the carrying case inside the hot cell, the bolts on the lid were removed by the manipulators and the lid was lifted by the overhead crane. The fuel

Figure 12-3. Test Set-up Within Hot Cell (as seen through Hot-Cell Window)

capsule was removed by the manipulators, as seen in Figure 12-4, and placed on the stainless steel tray. The lid was then placed on the carrying case.

The vacuum-chamber bell was then lifted by the overhead crane and moved aside so that the top of the RTG was accessible. The hinged top of the RTG was opened and the isotope capsule guide for protecting the insulating foil was set in place on the top of the RTG. The capsule, by means of a screw eye and hook, was lifted by the manipulator hand and moved to a position above the RTG. The capsule was then slowly lowered into the RTG. (See Figure 12-5.) After the capsule was completely within the RTG, the lifting hook and screw eye were removed. The hinged top of the RTG was then closed.

A test of the electrical output characteristics of the unit made at this point showed it to be functioning normally; the vacuum-chamber bell was then set in place over the RTG. When the vacuum chamber was sealed, the vacuum pumping was started, and the pressure inside the chamber was ultimately reduced to 3×10^{-6} Torr.

A graph of hot-shoe temperature and chamber pressure as functions of time for the initial pumping period is shown in Figure 12-6. After approximately 10 hours of pumping, the capsule had reached operating temperatures and the vacuum had essentially reached operating level.

Figure 12-4. Fuel Capsule Being Removed From Carrying Case

Figure 12-5. Fuel Capsule Being Inserted into the RTG

Figure 12-6. Hot-Junction Temperature and Chamber Pressure as Functions of Time at Beginning of Test at ORNL

D. TEST RESULTS

During the entire testing phase of this program, the thermal power provided by the strontium 90 remained essentially constant at 526 watts. During the test, temperature was monitored at 18 points on the capsule, thermocouple hot and cold shoes, radiator, and lid. Also measured were the chamber pressure, the temperature of the inlet and outlet water supply for the thermal shroud, and the flow rate of this water. The electrical power output from the generator was calculated from the current-voltage (I-V) curves drawn for each thermocouple module with respect to its individual temperature differences and resistive load values. Potentials across these loads were also recorded.

A short chronicle of the important events that occurred during the isotope testing phase of the generator is presented in the pages preceding discussion of test results, providing general information pertinent to test operations and sequences.

1. Chronicle of RTG Testing at ORNL

8/5/64	RTG laboratory model and associated test equipment packed and ready for shipment to ORNL.
8/10/64	Equipment and personnel depart for ORNL.
8/11/64	Trailer-truck transporting the equipment involved in an accident.
8/13/64	Equipment arrival at ORNL. The vacuum-chamber bell, shroud and air compressor found damaged. Temporary repairs at ORNL made on these components.
8/20/64	Repair of vacuum leaks on the vacuum chamber (result of the accident).
8/21 to 8/23/64	Electrical heat tests of RTG conducted outside the hot cell.
8/24/64	Initiation of installing the vacuum chamber, fuel carrying cask, and RTG into the hot cell.
8/31/64	Installation and checkout of equipment inside hot cell. RTG, isotope carrying case, and vacuum chamber in place. Module number 8 replaced by module number 10.
9/1/64	RTG fueled with 526 watts of strontium 90 at 1347 hours. Generator performed as expected.

- 9/28/64 Module number 9 shorted out. Upon disassembly of the generator on Nov. 2, 1964, the teflon sleeving on the power lead of 6-couple module was found to be cracked and brittle. This is what caused the short on Sept. 28, 1964.
- 10/14/64 Short in module number 9 corrected itself of this date. Generator running at expected output.
- 10/21/64 During installation of a radiation detector in hot cell, an air hose was accidentally disconnected and a pressure switch closed all the vacuum valves. During the procedure necessary to resume normal operating conditions, the generator was exposed to atmospheric conditions for a brief period. After vacuum conditions were reinstated, the result was an increased power output, probably due to higher emissivities as a result of oxidation occurring.
- 10/28/64 Vacuum chamber filled with argon gas. Generator performance and characteristics recorded during this phase of test.
- 10/29/64 Pressure in vacuum chamber reduced to 4×10^{-6} Torr. The generator performance in vacuum was compared to previous vacuum trails. No change in the generator performance as a result of the argon exposure.
- 10/30/64 After 1414 hours of operation, the vacuum system was sealed and argon gas bled into the chamber to reduce generator temperatures. The generator was opened, but the capsule could not be removed, because of the fusing, as described.
- 11/2/64 The generator was disassembled so that the capsule could be removed.
- 11/4/64 Upon removal of the disassembled generator from the hot cell, it was found to be contaminated with cesium 137.
- 11/5/64 Decontamination started on the generator and equipment.
- 11/12/64 14-couple module heated to operating conditions in air.
- 11/13/64 Vacuum chamber cleaning started.
- 11/17/64 Calibration of monitoring thermocouples initiated.
- 11/23/64 Majority of test equipment sent back to RCA after decontamination.
- 11/24/64 The RTG contaminated and disassembled, sent to the Industrial Reactor Laboratory, Plainsboro, N. J.

2. I-V Curves

During the 1414 hours of continuous testing of the generator, temperatures and current-voltage (I-V) curves were plotted at least once daily.

Examples of the I-V curves obtained from the four thermocouple modules during the isotope test are shown in Figures 12-7 through 12-10, inclusive. In each case, an I-V curve is shown for the beginning of the test, middle of the test, and at the end of the test after the generator had been exposed to air on October 21, 1964. On the same graphs, the power output as a function of the voltage is also plotted. This allows the determination of the maximum power output point of the thermocouple module for the temperature conditions stated.

Additional graphs, Figures 12-11 through 12-14, show the maximum output of each module as a function of the external resistance.

The major purpose of the tests has been to determine whether or not the thermocouples would degrade during the 2-month exposure to the isotope. Figures 12-15 through 12-18, show the internal resistances of the four modules as functions of time. These show that the three 6-couple modules did show a slight increase in resistance with time, while the 14-couple module did not. However, because an increase in resistance which is accompanied by an increase in the square of the Seebeck coefficient is not considered degradation, this latter parameter was added to the graph.

The result was that modules numbered 17-15, 7, and 10 remained stable, while number 9 apparently degraded. Further checking revealed short circuits in external test leads around module number 9, which suggests that the results be disregarded.

Figure 12-7. Current and Power Output as Functions of Voltage: Module No. 17-15

Figure 12-8. Current and Power Output as Functions of Voltage: Module No. 7

Figure 12-9. Current and Power Output as Functions of Voltage: Module No. 9

Figure 12-10. Current and Power Output as Functions of Voltage: Module No. 10

Figure 12-11. Power Output as a Function of External Resistance: Module No. 17-15

Figure 12-12. Power Output as a Function of External Resistance:
Module No. 7

Figure 12-13. Power Output as a Function of External Resistance:
Module No. 9.

Figure 12-14. Power Output as a Function of External Resistance: Module No. 10

Figure 12-15. Seebeck Coefficient and Internal Resistance as Functions of Time: Module No. 17-15

Figure 12-16. Seebeck Coefficient and Internal Resistance as Functions of Time: Module No. 7

Figure 12-17. Seebeck Coefficient and Internal Resistance as Functions of Time: Module No. 9

Figure 12-18. Seebeck Coefficient and Internal Resistance as Functions of Time: Module No. 10

In the next set of graphs, Figures 12-19 through 12-22, the power output for each module is plotted as a function of time. For the 14-couple module, the power output remained constant throughout the entire test with the exception of the 21st of October when the generator briefly was exposed to atmosphere. At this time the power output increased from 5.2 to 5.7 watts. This was probably due to oxidation of the fuel capsule and the hot shoes of the module. Oxidation would increase the emissivity of the capsule and thermocouple module, thus lowering the temperature differential between them. With the capsule temperature relatively fixed, the hot junctions would get hotter thereby increasing the power output from the 14-couple module.

The power output from the 6-couple modules, except number 7, decreased slightly over the test period. This decrease in power was not due to any degradation in the thermoelectrics but was a result of a decreased hot-junction temperature caused by a change of emissivity of the hot shoes and subsequently an alteration of the heat flow inside the generator. This emissivity variation is a recognized variable and a program to stabilize this situation is currently in progress at RCA.

Figure 12-19. Power Output as a Function of Time: Module No. 17-15

Figure 12-20. Power Output as a Function of Time: Module No. 7

Figure 12-21. Power Output as a Function of Time: Module No. 9

Figure 12-22. Power Output as a Function of Time: Module No. 10

However, because major interest centered on the verification of the degradation, if any, of the thermocouples, the temperature effect was eliminated as follows. The power produced by modules 10 and 9 was normalized by dividing it by the square of the temperature differential and then plotted against time, as shown in Figure 12-23. This graph shows that the thermocouple power for number 10 was constant throughout the test. Thus, it is concluded that the silicon-germanium did not undergo any material degradation as a result of a high-temperature vacuum environment in a high gamma-radiation field. Module number 9 did degrade slightly, but this may be attributed to the short circuit in the measuring leads mentioned previously.

3. Thermocouple Performance

Based on the results of the isotope test at ORNL and the electrical heat tests at RCA, the power generated per thermocouple was plotted as a function of the temperature differential, $T_H - T_C$. This is shown in Figure 12-24. The plots were made for the 14-couple module, number 17-15, which has an effective length of 2.67 centimeters and number 10, a 6-couple module with an effective length of 2.03 centimeters.

Figure 12-23. Power Output as a Function of Time (Normalized for Changing Hot Junction Temperature Increment): Module Nos. 9 and 10

Figure 12-24. Power Output per Thermocouple as a Function of Temperature Differential: Module Nos. 10 and 17-15.

4. Thermal Balance

It has not been possible to accurately determine the useful heat flow and heat losses in the generator during the isotope tests due to the presence of one dummy thermocouple module. The data were therefore approximated through calculation and extrapolation.

Prior to the assembly of the generator, the complete cylinder of rhodium foil and fibrefax (before any openings had been cut out) had been tested in a vacuum with an electrical heat source. Under these conditions the inner foil reached 741°C with an input of 23.6 watts. This data point was extrapolated, using the T^4 rule, to 973°C and 1066°C (temperatures which were later reached with the completed generator) as follows:

Calculated input to maintain 973°C = 46 watts

Calculated input to maintain 1066°C = 70 watts

During one of the typical trials using electrical heat (after the openings in the insulation had been cut), data, either observed or calculated, were compiled as shown in Table 12-1. The capsule temperature and total heat supplied by heater were measured; the remaining values were computed.

Between the completion of the electrical heat test and the start of the test on isotopic heat, the 22-couple module was replaced by a dummy module. This dummy was not calibrated at the time because the schedule did not allow it. It was not possible to calibrate it after the tests, because it had been filed down (in a vain effort to decontaminate it from cesium 137).

TABLE 12-1. THERMAL FLOW FOR THERMOCOUPLE MODULES,
ELECTRICAL HEAT

Observed Capsule Temperature = 973°C

Thermal Flow (watts)

Conductive (three 6-couple modules):	144.5
Peltier (three 6-couple modules):	14.5
Conductive (14-couples module):	92.4
Peltier (14-couples module):	13.6
Conductive (22-couple module):	142.7
Peltier (22-couple module):	11.5
Joule-heat total for all modules:	-6.8
Losses (bulk insulation except through multifoil):	40
Subtotal Thermal Flow:	466 watts
Observed total heat supplied by heater:	510 watts
Through multifoil (510-466):	44 watts*

*The figure of 44 watts agrees with the 46 watts calculated previously.

During the isotope tests, the capsule output was stable at 526 watts. A typical series of values, either calculated or measured, is shown in Table 12-2.

TABLE 12-2. THERMAL FLOW FOR THERMOCOUPLE MODULES,
ISOTOPIC HEAT

Observed capsule temperature = 1067°C

Thermal flow (watts)

conduction through three 6-couple modules: 144

conduction through one 14-couple module: 100

conduction through dummy module: 143

conduction through all insulation except
through the multi-foil but including heat
leaking around the edges of the foil at
the windows: 49

Subtotal Thermal Flow: 436 watts

Observed total heat from capsule: 526 watts

Flow through multi-foil insulation (526-436): 90 watts

The discrepancy between 70 and 90 watts is caused in part by the inaccuracy in the various calculated partial flows. It is not possible to evaluate the test results any closer, and a detailed determination of the efficiency of the thermocouple modules must await the repetition of the test, should a second laboratory model be built.

E. RADIATION LEVELS AND EFFECTS

Radiation levels inside the hot cell of the bare capsule and with the capsule inside the generator were monitored. The generator was regarded as an unshielded system; the radiation levels opposite the radiators for 6- and 14- couple modules, and the foil insulation pack were plotted as functions of the distance from the center of the strontium 90 source. A plot of radiation levels as a function of distance was made for the bare capsule also. These are plotted in Figure 12-25. This source contained 83,500 curies of strontium 90 in the form of strontium titanate. During this test, the thermocouples were exposed to 46×10^6 rads and the foil experienced a dosage of 44.6×10^6 rads. Neither component experienced any degradation as a result of this level of radiation exposure.

Figure 12-25. Dosage Rate as a Function of Distance from Center of Capsule

F. COMPARISON OF ACHIEVED PERFORMANCE AND DESIGN OBJECTIVES

In the final section of this chapter, the achieved performance of the generator and the design performance are compared. This comparison is somewhat inaccurate because of the presence of the thermal dummies. Figure 12-26 shows the comparison, with allowance made for the capsule heat reduction to 526 watts.

G. EXAMINATION OF GENERATOR AFTER TEST

After 1414 continuous hours of test, the vacuum was terminated (using Argon gas) and the test officially was stopped. The lid of the generator was opened and, as was done previously, the lifting hook was employed with a manipulator. However, when a lifting force was exerted, the capsule was found to be stuck fast. This necessitated complete disassembly of the generator using the manipulator. This task required 9 hours and included the removal of 39 screws or nut and bolt combinations. The fuel capsule was "stuck" because the two inner metallic insulation layers and the inner cage were welded to the fuel capsule. It appeared that the insulation layers and inner cage bars had been drawn toward the capsule. Their radial position from the generator center-line had decreased; this involved a bending of the cage bars, since the ends of the cage are held at a constant radius by two end-hoops or rings.

Figure 12-26. Comparison of Design, Achieved, and Extrapolated Performances

The cause of this is postulated as a lack of venting within the metallic foil assembly. In the course of testing the generator, argon or air was admitted to the vacuum chamber on two occasions, followed by establishment of another vacuum. The generator was not inspected between these steps. At the time of pumping, the inner insulation layers and cage were at a temperature of about 800°C (equilibrium). Pumping was fast and the materials are weak at this temperature, resulting in the decompression failure described above. Only the inner layers are effected because they are the hottest (hence, the weakest) and can buckle under compression.

Unfortunately, the exterior of the fuel capsule had become contaminated with cesium 137 while being fueled in another hot cell prior to the start of the generator test. This material sublimed and then condensed extensively above the generator. Chemical analysis and close inspection of the generator parts was thus made impractical. As a result, the following observations on the condition of the generator at disassembly are necessarily very limited.

One thermocouple was broken off of each of two 6-couple modules during efforts to free the fuel capsule after completion of the test. In addition, all thermocouple hot shoes as well as the thermal dummy were coated with a black-gray, sooty deposit which was about 25 to 50 microns thick.

Preliminary chemical analysis indicated that this substance contained the constituents of Hastelloy X, which is the external material of the fuel capsule. The fuel capsule appeared to have the same dark grey-black coating of oxidized Hastelloy X which was present at the start of test. At the points where the Hastelloy X cage bars were welded (so tightly stuck, the prying action of a screwdriver was required to loosen them), the base metal had the appearance of a clean, sandblasted surface.

Upon unwrapping the metal insulation, the outer (coolest) layers of the separator material were clean and white. Progressive darkening to a grey-black color was observed as the inner (hottest) layers were approached. The metal was very clean and shiny on the outside and likewise darkened in an inward direction. The last two layers were very dark and the surface was extremely wrinkled. The innermost layer was stuck fast to the fuel capsule; scraping and chipping were necessary for removal.

All insulation of the Min K and Kaowool type was very dark grey-black on the surface facing the fuel capsule progressing to white at the furthest surface.

One failure with instrumentation wiring occurred due to sublimation of the teflon insulation. This resulted in an intermittent, high-resistance short during the test. As stated earlier, however, none of the above, except the intermittent short, had a detrimental influence on the generator output.

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SECTION XIII. RECAPITULATION AND PROJECTION

At the close of this 2-year program it seems appropriate to critically discuss the work and to indicate how the results compare to expectations. The results are described both qualitatively and quantitatively.

A. QUALITATIVE DESCRIPTION OF RESULTS

1. Preparation of Strontium Titanate Pellets

The program required that ORNL prepare, for the first time, pellets of strontium titanate with diameters as large as 8 or 9 centimeters.

During the sintering process, the pellets shrank more than expected; this produced a fuel density somewhat higher than that calculated. The resulting extra volume could have been filled with additional isotope in crushed form. This would have produced an additional 30 or 40 watts of thermal power. Since the additional power was not necessary, this was not done.

2. Use of TZ Molybdenum for Encapsulation

The program required the first use of TZ molybdenum for the encapsulation of isotopes. In addition, after initial problems were overcome, the technique of remote welding was successfully employed.

TZ molybdenum is considerably stronger at high temperatures than regular molybdenum and its use represents a step forward in the development of high-temperature capsules. A technique of coating the molybdenum after welding in order to prevent oxidation has yet to be developed. A possible subsequent development may lead to the use of thorium dispersed (TD) nickel for the main capsule since it combines strength at high temperatures with resistance to oxidation. The problem not yet solved is that of welding TD nickel while maintaining the desirable properties of the material. At present, the thorium dispersion disappears during welding and the properties of the material revert to those of ordinary nickel. A high-emissivity coating for Hastelloy which does not deteriorate or disappear at high temperatures in vacuum has yet to be developed.

3. Use of Silicon-Germanium Thermocouples in Vacuum

The program was the first in which silicon-germanium thermocouples were used in a vacuum for an isotope thermoelectric generator.

The thermocouples used in the generator were built with preliminary tooling and to preliminary specifications. The techniques of producing all silicon-germanium couples were first developed in early 1963; some of the first modules from that period were employed. Some of these failed during initial testing and were replaced. These were replaced by modules of the same dimensions but in which the active element length was 19 millimeters instead of 26 millimeters. Each of these modules contained 6 couples; the bonding of these couples was slightly different than those replaced. These proved more successful in that they did not degrade during the 2 month test on isotope heat. In one case, the pressures of scheduling and funding made it necessary to replace a defective module with a dummy thermal conductor.

While the program was underway, the Direct Energy Conversion Department of RCA developed thermocouples with a hot shoe made of a silicon alloy which permitted higher efficiency. Since these couples are, in other respects, equally good or better than the couples used in this program, it is felt that the latter will be employed in future programs.

4. Miscellaneous Results

A problem still to be solved is the apparent reduction in the emissivity of the hot straps. Coatings must be developed that permit an emissivity value of 0.90. These coatings must be unaffected by radiation, high temperatures, and vacuum. The newer thermocouples will have silicon-alloy hot shoes whose area is considerably larger than the cross sectional area of the active elements. When these couples are mounted side by side in arrays, there will be considerable space between the couples. This space must be filled with thermal insulation. Calculations show that employment of the best solid insulation material (Min K-2000) causes heat leakage of 10 to 30 percent. This is not tolerable because it would reduce the efficiency of the generator by a corresponding amount.

In view of the above, RCA is pleased with the considerable promise shown by the newly developed high-temperature multifoil insulation. In the present program, 25 layers of Fibrefrax have been wound into a cylinder. Techniques have been worked out to miter the layers of the cylinder ends to provide a low-leakage path all around the heat source. Rhodium is also a reasonably light material (with respect to the weights of the platinum elements). Still to be checked is the evaporation, if any, of the foil in a vacuum.

In the present generator, small amounts of heat (e.g., 10 watts) are lost through the zirconia tubes supporting the capsule. This might be avoided by making the foil load-bearing; this would be worth investigating in a subsequent program.

The radiator functions as the generator structure. Its thickness is chiefly determined by the thermal conductivity of the aluminum. In a subsequent program, it may be

necessary to replace the aluminum by beryllium; suitable fabrication techniques would then have to be developed.

The high emissivity and low absorptivity of the radiator coating have been adequate, but many more tests are required to prove that it will survive long-time exposure to ultraviolet rays, gamma rays, thermal vacuum, and high temperatures.

B. QUANTITATIVE DESCRIPTION OF RESULTS

The quantitative results of the program cannot be judged as clearly as the qualitative end product. The funding limitations mentioned earlier made it necessary to replace one of the thermoelectric modules by a thermal dummy instead of by another module. This forced us to calculate the efficiency and the power-to-weight ratio of the generator rather than measure these quantities directly.

The output of 12.6 watts has been extrapolated to 28.6 watts; the latter value is the output which the generator would have produced if all 66 thermocouples had been present and the isotope capsule had been charged with 660 watts instead of 526 watts. Since the generator as built weighs 26.6 pounds (12 kilograms), the power-to-weight ratio would have been 1.08 watts per pound (2.38 watts per kilogram). (Refer to Table 13-1.)

TABLE 13-1. WEIGHTS OF COMPONENTS OF RTG LABORATORY MODEL

Component	Weight	
	Pounds	Kilograms
Five pellets of strontium titanate	5.60	2.54
TZM inner container, including lid	6.03	2.74
Hastelloy outer container, including heavy impact depressors	5.08	2.31
Three thermoelectric modules, 22 couples each	2.6	1.16
Complete radiator	2.43	1.08
Thermal insulation	2.0	0.87
Miscellaneous	2.86	1.30
Total =	26.6	12.00

C. DESIGN PROJECTIONS

The present generator design was developed during the second half of 1963. It is now of interest to project the performance that could have been obtained with the materials and techniques available in early 1965. This will at the same time provide a conceptual design for a Mark II generator.

1. Weight Considerations

First, however, corrections will be made by subtracting the weights of certain items which were added to the laboratory model for expediency. Also, there are additional weight items that were shown to be superfluous by the tests or subsequent calculations.

The present generator weighs 26.6 pounds (12 kilograms). From this can be deducted the overweight on the two containers and the impact depressors.

The two containers have a combined wall thickness of 7 millimeters (275 mils). Subsequent calculations* for similar containers suggest that these thicknesses are more than twice that necessary to guarantee absolute containment of the isotope during all earth abort conditions. Assuming a conservative overweight factor of 2, the weight of the two container walls can be reduced from 8.7 pounds (3.95 kilograms) to one-half that amount, or 4.35 pounds (1.97 kilograms).

The impact depressors, which form the end-caps of the outer container, were changed just before final assembly from the original thin-wall design to that of a much heavier body. This was done to save machining time and also to guarantee adequate stiffness during the isotope test should the actual temperature of the container have been higher than the calculated temperature. During the test, the container was cooler than expected. Hence, the weight of the heavy impact depressors totaling 2.28 pounds (1.03 kilograms) may, in this discussion, be replaced by the original weight of 0.9 pounds (0.41 kilograms).

These two deductions bring the generator weight down to 20.8 pounds (9.41 kilograms) or in round numbers 21 pounds (9.5 kilograms).

2. Techniques and Materials Available in 1965

The following paragraphs discuss the potential impact of 1965 technology upon RTG performance.

a. Strontium Oxide

Comparison of the weights and volumes for 660 watts of thermal power shows that strontium oxide is denser than strontium titanate and that a smaller net mass of strontium oxide would be required to fuel the RTG.

*By Hittman Associates, (Ref. Report AED R-2496 A, October 2, 1964).

	Weight	Volume
Strontium Titanate	3 kilograms	900 cm ³
Strontium Oxide	1.9 kilograms	625 cm ³

b. Fuel Containers

Leaving the wall thickness unchanged gives the following expression for the ratio of the container weights.

$$\frac{W_2}{W_1} \approx \frac{V_2}{V_1} \approx 2/3$$

where

W_1 is the weight of container walls and impact depressors made for strontium titanate,

W_2 is the weight of container walls and impact depressors made for strontium oxide,

V_1 is the volume of strontium titanate fuel, and

V_2 is the volume of strontium oxide fuel.

3. Radiator and Thermal Insulation

The 1965-type radiator may be made of beryllium instead of aluminum. This does not reduce weight because the radiator design is restricted for thermal reasons. However, it will make the radiator stronger and stiffer; these changes may facilitate integration with the spacecraft.

Since the generator is somewhat smaller in size than the 1963 model, the thermal insulation may be reduced in weight by 100 grams.

4. Thermocouples

The thermocouples, of the type developed during 1964, have silicon alloy hot shoes instead of a silicon-germanium hot shoes. They are 10 percent more efficient. They can be built with the same ratio of length to cross sectional area but with all dimensions considerably reduced except the shoes. The present copper baseplate could thus be replaced by one of aluminum. This would permit a reduction in the weight of the three modules from the 1.18 kilograms to approximately 0.7 kilograms.

5. Generator Performance

Combining the above data leads to a 1965 version of the generator which has an electrical output of 31.5 watts (28.6 + 10%) at an output voltage in the range of 5 to 7 volts. The weight of the complete generator is 15.8 pounds (7.2 kilograms). The performance figure is 2 watts per pound (4.4 per kilogram).

These figures do not include the dc-to-dc converter. Addition of such a device, 85 percent efficient, weight 0.35 kilograms, would reduce the performance figure to 1.61 watts per pound (3.55 watts per kilogram).

E. ISOTOPES OTHER THAN STRONTIUM

Strontium has the advantage of being readily available but has the disadvantage of the production of bremsstrahlung. This is a secondary gamma radiation the intensity of which is lower by two orders of magnitude than the radiation from the same quantity (in thermal watts) of primary gamma sources such as cobalt or cerium. Reference 21 shows that for many space missions the post-launch radiation from the strontium is not objectionable. However, prior to launch there may be sufficient difficulty associated with handling the spacecraft and power supply to warrant the use of an alpha emitter such as plutonium 238 or curium 244. A detailed optimum design of a generator with one of these fuels falls outside the scope of this report. It may be of interest, however, to calculate the weights of 1965 versions of the generator in which only the fuel and containers are replaced. The results of this speculation are given in Table 13-2.

TABLE 13-2. PROJECTED WEIGHTS OF 1965 VERSIONS OF RADIOISOTOPE THERMOELECTRIC GENERATOR

Fuel Parameter	SR 90** (as SrO)	Pu 238* (as PuO ₂)	CM 244* (as Cm ₂ O ₃)
Generator output in watts at 5 to 7 volts	31.5	31.5	31.5
Generator weight in kg	7.2	6.38	4.08
Performance in W/kg	4.4	4.9	7.7
Performance in W/lb	2.0	2.25	3.5

*Assumed void volume equal to 100 percent of fuel volume

**Assumed void volume equal to 10 percent of fuel volume

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