

**MND-P-2342**  
**PHYSICS AND MATHEMATICS**

# **100-WATT CURIUM-242 FUELED THERMOELECTRIC GENERATOR--CONCEPTUAL DESIGN**

**SNAP Subtask 5.7 Final Report**

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May 1960

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Baltimore, Maryland

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Generator--Conceptual Design

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Martin Company  
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Project Engineers

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## FOREWORD

This is the final technical report submitted to the U.S. Atomic Energy Commission under Subtask 5.7 of Contract AT (30-3)217. It covers work done by The Martin Company in developing a conceptual design for a radioisotope-powered, 100-watt thermoelectric generator using Curium-242 as the heat source.

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## SUMMARY

A thermoelectric generator which produces 100 watts of electrical power continuously over a six-month operational life in a space environment has been designed. It employs the heat produced by the decay of Curium-242 as the source of power.

The principal design parameter considered was the method by which neutron shielding for safe ground handling was accomplished. Of three configurations analyzed, the one recommended for ultimate use employs a borated water shield which is divided between the internal volume of the generator and the region external to the generator. This results in a design which is optimized for minimum overall weight.

Uniform power output over the operational life of the generator is accomplished by means of a thermally actuated shutter which maintains the hot junction temperature of the thermoelectric converter at a constant figure by varying the amount of surplus heat which is radiated directly to space from the heat source.

The isotopic heat source is designed to safely contain the Curium-242 under conditions of launch pad abort and rocket failure, but to burn up upon re-entry to the earth's atmosphere from orbital velocity.

Thermoelectric performance of the generator has been analyzed by means of an IBM-709 code developed for this purpose.

## I. INTRODUCTION

The use of radioisotopes as heat sources permits the design of reliable thermoelectric generators that can be adapted readily to the external environment. Isotope-powered generators are lightweight, mechanically rugged and versatile in application. The importance of these characteristics for space auxiliary power units is obvious. The Nuclear Division of The Martin Company has been doing considerable work in this field.

The objective of this subtask was to develop a conceptual design for a thermoelectric generator that would use Curium-242 as the source of heat and be capable of delivering 100 watts of electric power continuously for six months when in a space environment. The term "conceptual design" is defined as a design based on the present knowledge of materials and which shows the general configuration of the generator and the arrangement of major components. Finer details and design changes which might follow experimental tests are omitted.

The generator was not designed to satisfy any specific application but to provide, with reasonable assurance, an electrical power output of 100 watts when the generator is in space. Thus, the details of integrating the generator with the devices it will supply power for were not considered, but the problems of launch environment, an external vacuum and weightlessness governed the design to some extent.

Since the specified operational life of the generator was six months, the half life of any isotope to be considered for this application was limited to about the same time interval, principally to minimize the investment in isotope cost. Longer lived isotopes, while exhibiting flatter power-time characteristics, would have lower power densities. To attain the same initial hot junction temperature and heat flow rate would then require an increase in the weight of the heat source. Alpha emitters are more economical because of their high disintegration energy, and the shielding requirements are also alleviated.

Only two isotopes that decay with half lives of approximately six months are in current or potential supply in the quantities desired. These are Polonium-210 ( $T_{1/2} = 138$  d) and Curium-242 ( $T_{1/2} = 163$  d). Of the two, Curium-242 can be produced at a cost per thermal watt of about 1/30th of that of polonium and can be used in elemental form or converted chemically into higher density compounds than can be attained with polonium (and thus exhibit a proportionately higher power density). Further considerations in selecting the isotope, its chemical form and a supporting matrix material are discussed later in the report.

It was determined that the interests of the AEC would best be served by relying heavily on the technology developed under the SNAP-IA Program in designing the new generator. The SNAP-IA Program is being carried out concurrently for the Commission by The Martin Company. The electrical power outputs are in the same region and and both are to operate in a space environment. The operational lives-- and consequently the isotopes employed--were different, as were the environmental conditions to be experienced by the generators during the rocket launch-to-flight sequence. Extensive reference was made to all phases of the SNAP-IA effort and continuous liaison between the two project groups maintained. The design of the curium-fueled space probe generator may be considered as an extension of the SNAP-IA work, specifically, optimizing it to somewhat different operational parameters.

The important conditions which had to be satisfied by any acceptable generator design concerned efficiency, weight, electrical power regulation, materials temperature limitations, reliability and radiological hazards. The overall generator efficiency should be as high as possible to reduce the isotope investment and the attendant radiation shielding problems. A minimum efficiency of 5% is desired at the end of the operational life of the generator. For a space application, minimum weight is of paramount importance; a limit of 100 pounds is required, but 70 pounds is desirable. The electrical power of 100 watts must be maintained with sufficient constancy during the six-month operational period that the static d-c to d-c converter can accomplish power regulation to  $\pm 1/2\%$ . The choice of materials for various components was governed to some extent by the temperature; the selection of fuel form, fuel container and thermoelement materials, etc., will be discussed later. The generator had to be designed so that it could operate with a very high degree of reliability in a space environment, following its subjection to the acceleration, vibration and shock associated with a typical space probe launching vehicle. Thus, moving parts are undesirable. However, if they have to be used, they must be few in number, simple, rugged and have slow, restricted movements. The presence of a radioisotope affects the heat source design, since the fuel must be contained during or after any abort that occurs from the ignition of the first stage through the final stage ignition, whereas the fuel is to be released as very fine particles above the biosphere in the event of normal re-entry. The biological shielding required before launch has profoundly influenced the design of the generator, as will be demonstrated.

## II. DESIGN AND ANALYSIS OF GENERATOR CONFIGURATIONS

Three generator configurations were selected for study under this project. The first, designated Type A, employed forced convection of water to cool the cold junction surface and to transfer the heat to a radiator located in the satellite skin. Figure 1 illustrates the general configuration.

The second, Type B, utilized radiative transfer of heat from the heat source to the hot junction skin. The volume between the source and skin was to be filled with a liquid to provide biological shielding during ground handling and prelaunch operational sequences (see Fig. 2).

Type C was similar in design to Type B. However, the biological shielding was distributed between the volume internal to the hot junction skin and the region external to the generator (see Fig. 3).

Each of the generators considered consisted of seven basic components and associated structure and hardware. The basic components are:

- (1) Heat source, consisting of a fuel compound, container, cooling coil and ablative cladding (for some designs).
- (2) Collector or hot junction.
- (3) Converter (or thermoelectric elements or pairs), consisting of assembled devices having the necessary thermal and electrical characteristics.
- (4) Insulation.
- (5) Radiator or cold junction.
- (6) Power flattening controls or thermal shutter.
- (7) Biological shield or neutron or gamma ray shielding.

The general configuration of the assembled generators was essentially the same throughout all of the preliminary and final designs, i.e., a right cylindrical heat source surrounded by a collector and a radiator. The two latter components were modified spheroids and were arranged confocally with each other and the heat source except that, in one configuration, the heat source was located closer to one end along the longitudinal axis. The converter, consisting of many thermoelectric pairs embedded in a thermal insulation, was located between the collector and radiator in a uniform pattern.

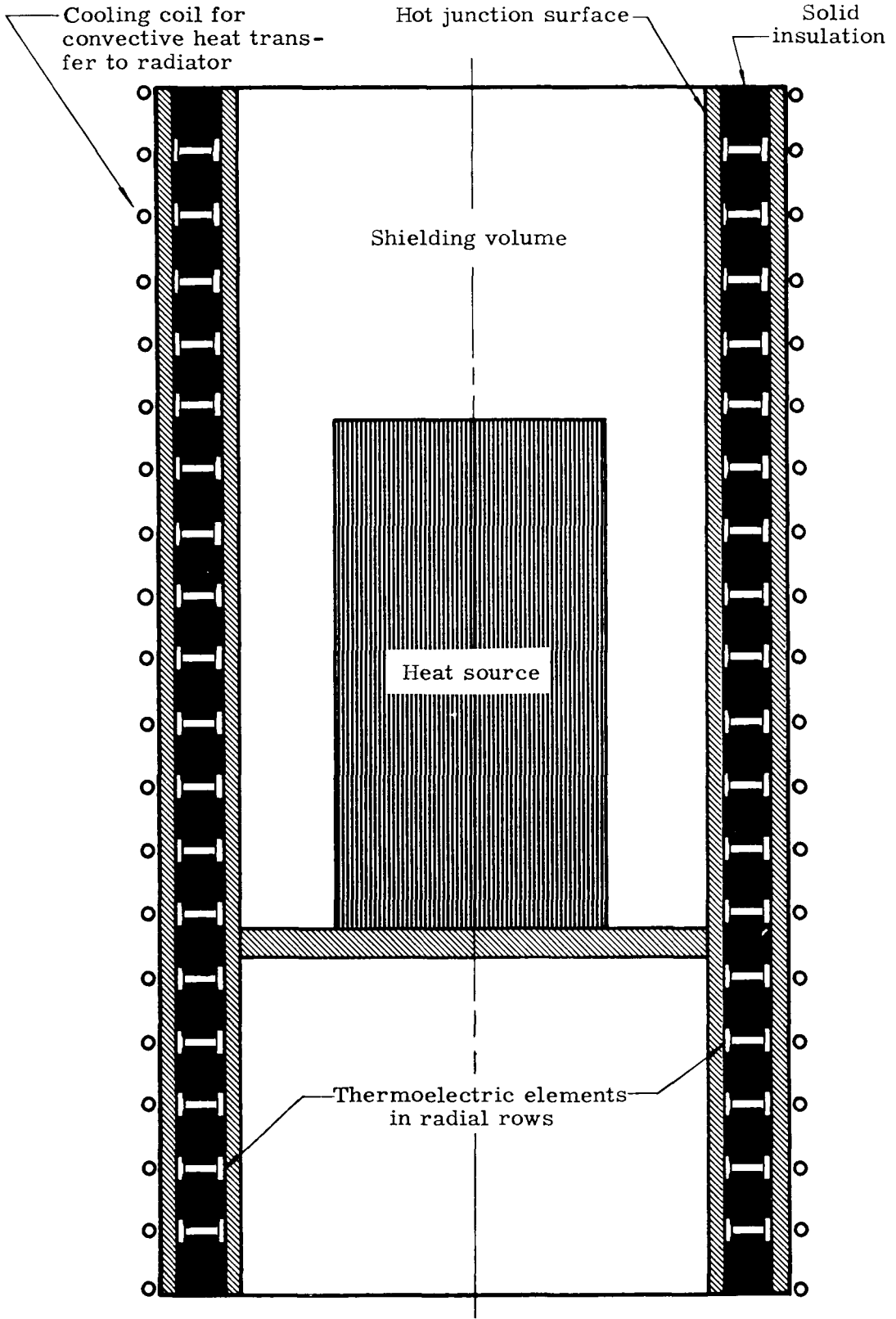


Fig. 1. Type A Generator Configuration

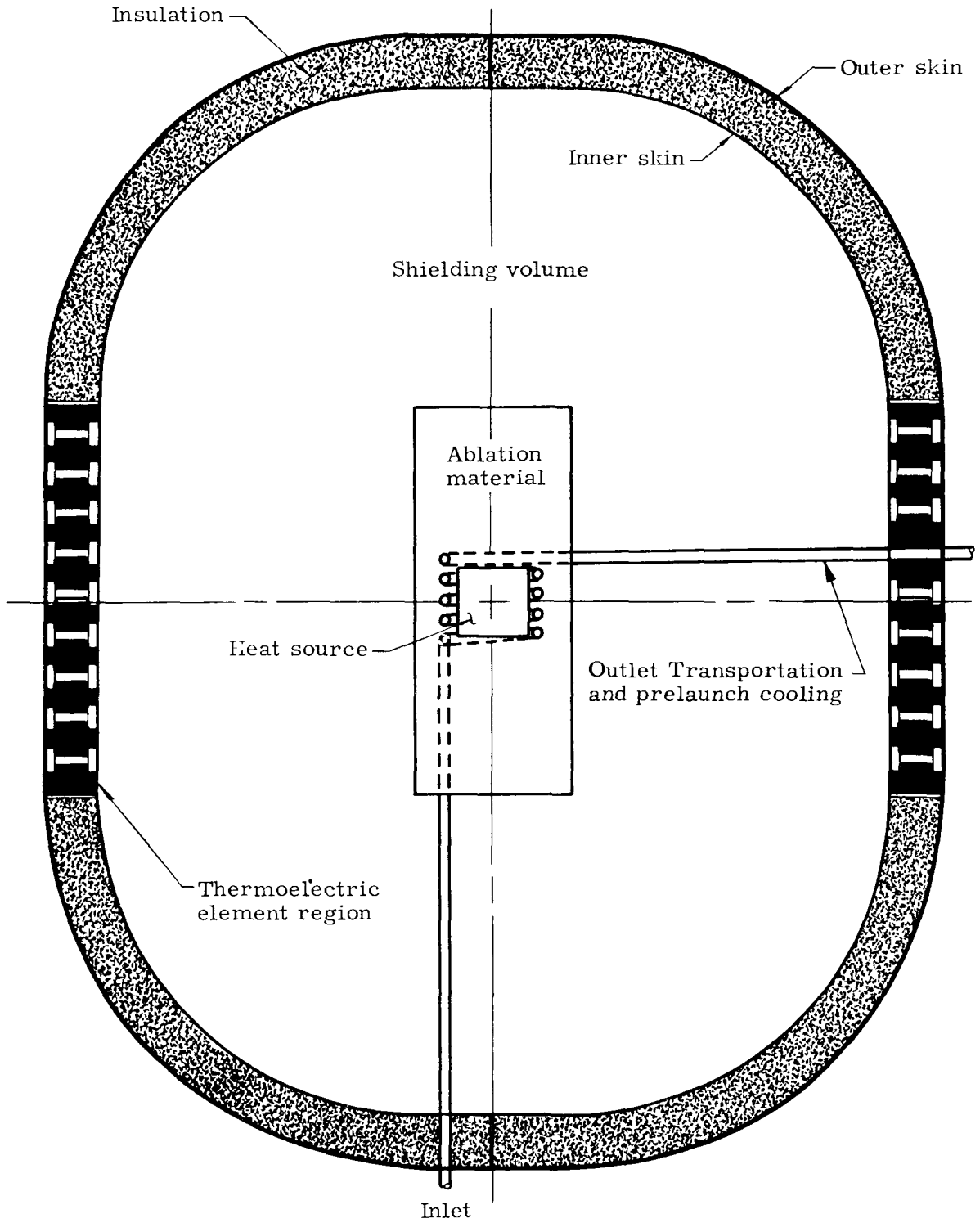


Fig. 2. Type B Generator Configuration

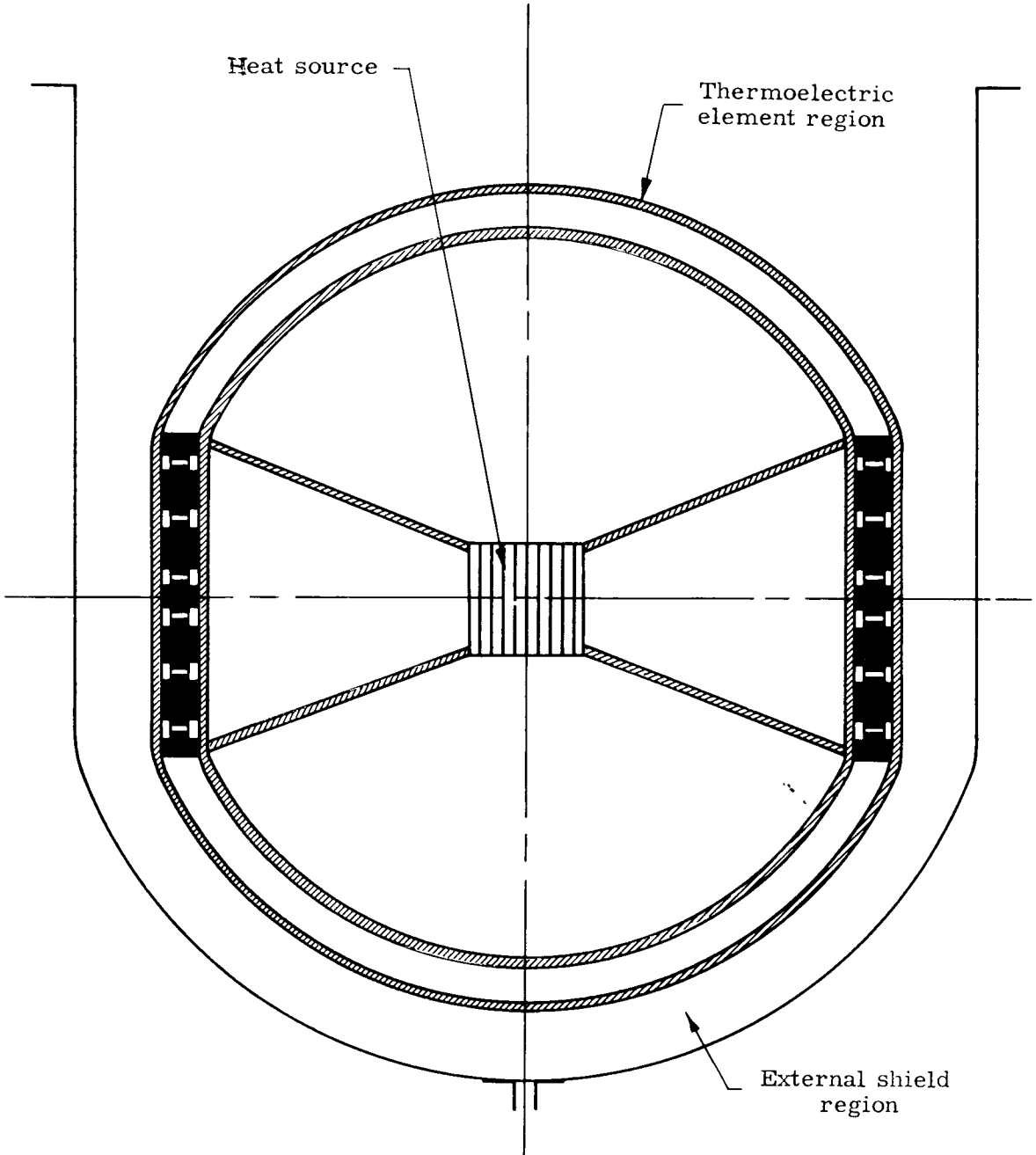


Fig. 3. Type C Generator

Each type of generator will be considered individually except for those areas of interest which are common to all three.

#### A. TYPE A--CONVECTIVE BOUNDARY GENERATOR

In this design, the radiator surface for the generator was assumed to be the skin of the satellite vehicle, considered to be a cylinder five feet in diameter. A portion consisting of 1.5 to 2.5 feet of the length of the cylinder was assumed to be available for the radiator region. Heat removed from the cold junction area of the generator was transferred by forced convection of water to the radiator surface. Laminar flow was assumed to reduce mechanical pumping requirements, and a mathematical treatment of the case indicated that laminar flow for an ideal incompressible fluid could be achieved in a gravity-free field since it was independent of gravitational forces.

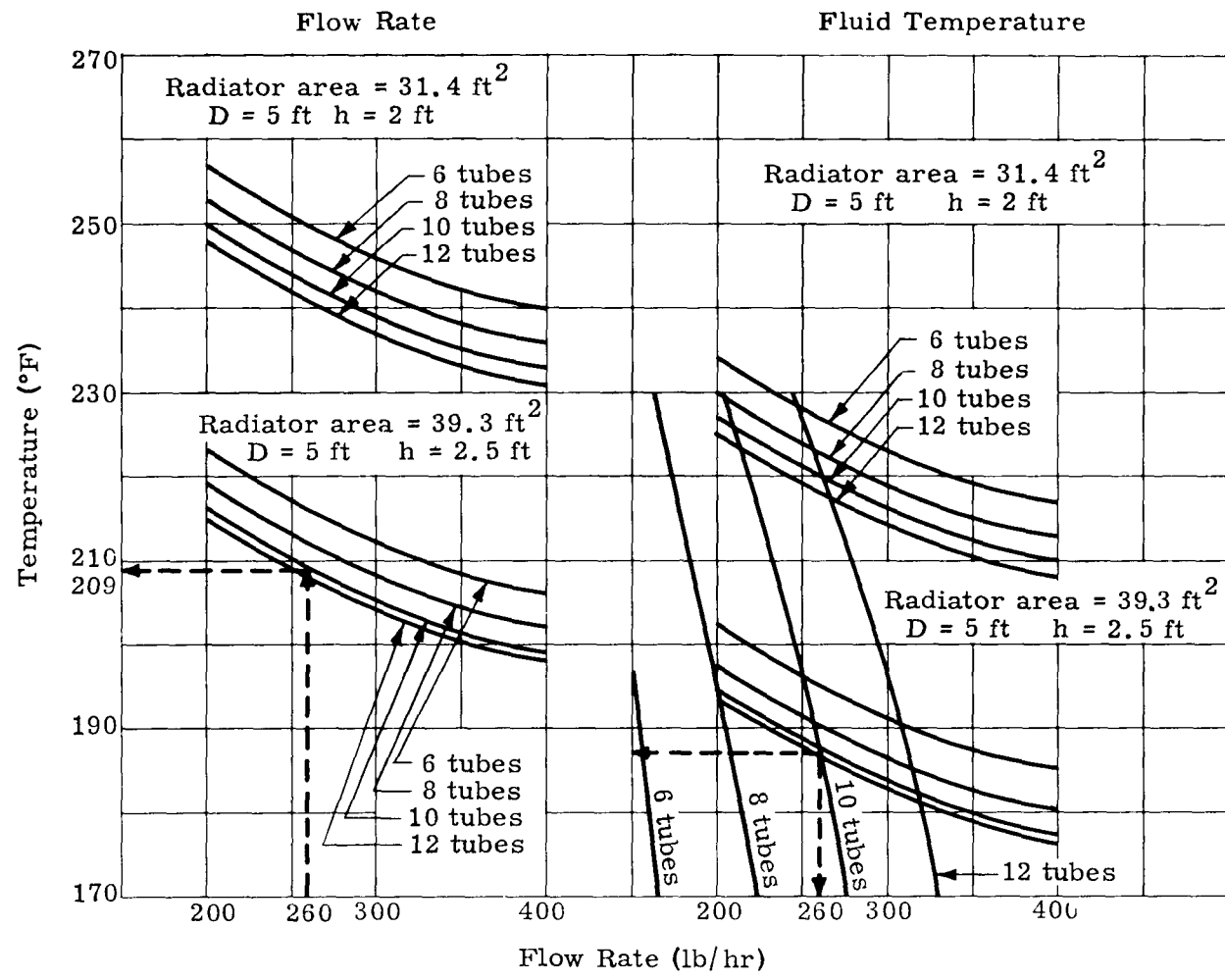
The surface temperature of the satellite skin was determined by Singer's equation.\* By utilizing this temperature as the radiator temperature, a series of curves was obtained which related radiator area, cold junction temperature, flow rate of water and number of flow tubes. These data are summarized in Fig. 4.

The thermoelectric converter was optimized by a procedure similar to that described in the next section for the radiative boundary-internal shield configuration. When minimization of the weight of this configuration was attempted, it was found that the condition of the water coolant approached the transition from laminar to turbulent flow, and other heat transfer media with low coefficients of viscosity and high specific heats were therefore sought. Allyl, amyl, tertiary amyl, butyl, ethyl, isoamyl and isobutyl alcohols as well as methyl ethyl ketone, palmitic acid and ethyl ether were considered, but none permitted a lower pumping rate or system weight than water.

Computation of the weight of the Type A generator gave a figure of approximately 110 pounds. This fact, together with the reliability problem introduced by a continuously moving part--the water pump--ultimately led to the elimination of this design, although lower cold junction temperatures, and hence higher overall efficiencies, could be obtained in comparison to the other designs under consideration.

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\* "Studies of a Minimum Orbital Unmanned Satellite of Earth (MOUSE) Part III Radiation Equilibrium and Temperature," D.T. Goldman and S.F. Singer, *Astronautical Acta*, 3(2) 110-29 (1957).



All tube diameters assumed to be 0.25 in. ID

Example:

1. Choose radiator area (39.3 ft<sup>2</sup>) and no. of tubes (10)

2. Locate fluid temperature (187° F) and flow rate (260 lb/hr) on RHS with flow rate pick off cold junction temperature on ordinate.

Fig. 4. Cold Junction Temperature and Cold Junction Fluid Temperature Versus Maximum Fluid Flow Rates

Since greater conversion efficiency results in a smaller fuel requirement, a potential user of these generators might wish to sacrifice weight savings for lowered fuel costs. Therefore, the design of the Type A generator was completed to the degree shown in Fig. 5. Details of the isotope core will be provided in the discussions of the Types B and C generators.

### B. TYPE B--RADIATIVE BOUNDARY GENERATOR, INTERNALLY SHIELDED

The basis of this design was the biological shielding requirement. The shield thickness, in turn, was dependent on the dose level that could be tolerated at the surface of the unit and at a mean working distance of 3 feet from the center of the source. If neutron attenuation in air is neglected and 8-3/4 inches of borated water are employed as a shield, the dose at 3 feet is 80 mrem/hr. The dose rate versus shielding thickness for various power levels is shown in Fig. 6. Figures 7 and 8 show, respectively, the dose at the surface of the unit and at 3 feet from the surface for various shielding thicknesses. The size of a curium-powered radiative-type thermoelectric unit that wholly contains the biological shield was approximately the same as that powered by Cerium-144 (SNAP-IA), but the shielding material was borated water rather than mercury. This substitution reduced the structural requirements of the generator surface. The shielding calculation methods and results are described further in Appendix A.

The second size-determining factor, the surface temperature of the fuel core, was dependent on the power density of the fuel. Curium-242 has a power density of 1620 watts/cc or 122 watts/gm; therefore, it was necessary to include a filler material of good thermal conductivity to reduce the thermal gradient encountered in the fuel element. This problem is discussed further in the next chapter. It was also necessary to provide a surface area large enough to maintain the fuel container surface temperature within reasonable limits. This limit was between 1500 to 1600° F due to the increased amount of structural material required. The surface area versus surface temperature for various power levels is shown in Fig. 9.

An indication of the fuel container surface area that is required is shown by using Fig. 9 and the knowledge that approximately 5000 thermal watts are required initially for a unit that will last six months.\* If

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\* Later, more detailed analyses showed that an increase in thermal output of the heat source of 30% was required to overcome the detrimental effect of thermoelement contact resistance.

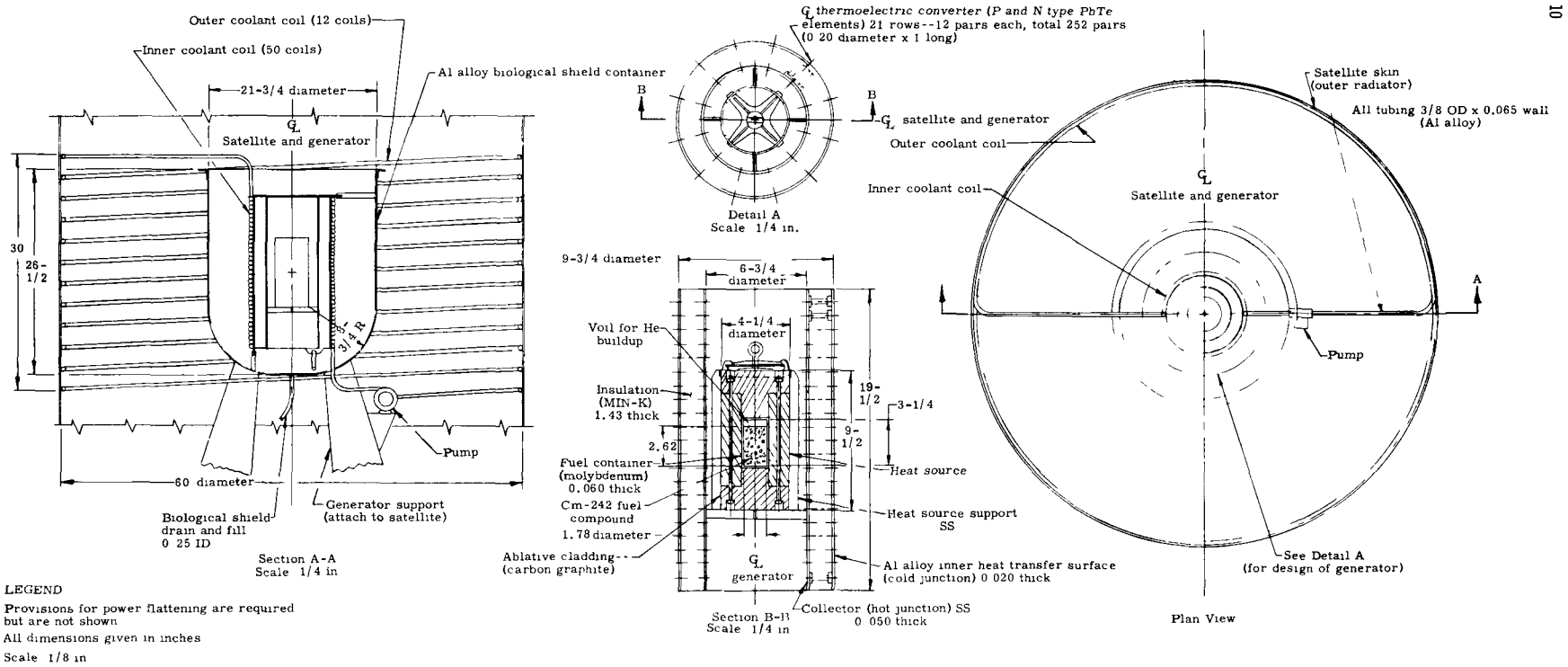


Fig 5. One Hundred-Watt Generator--Type A Preliminary Design

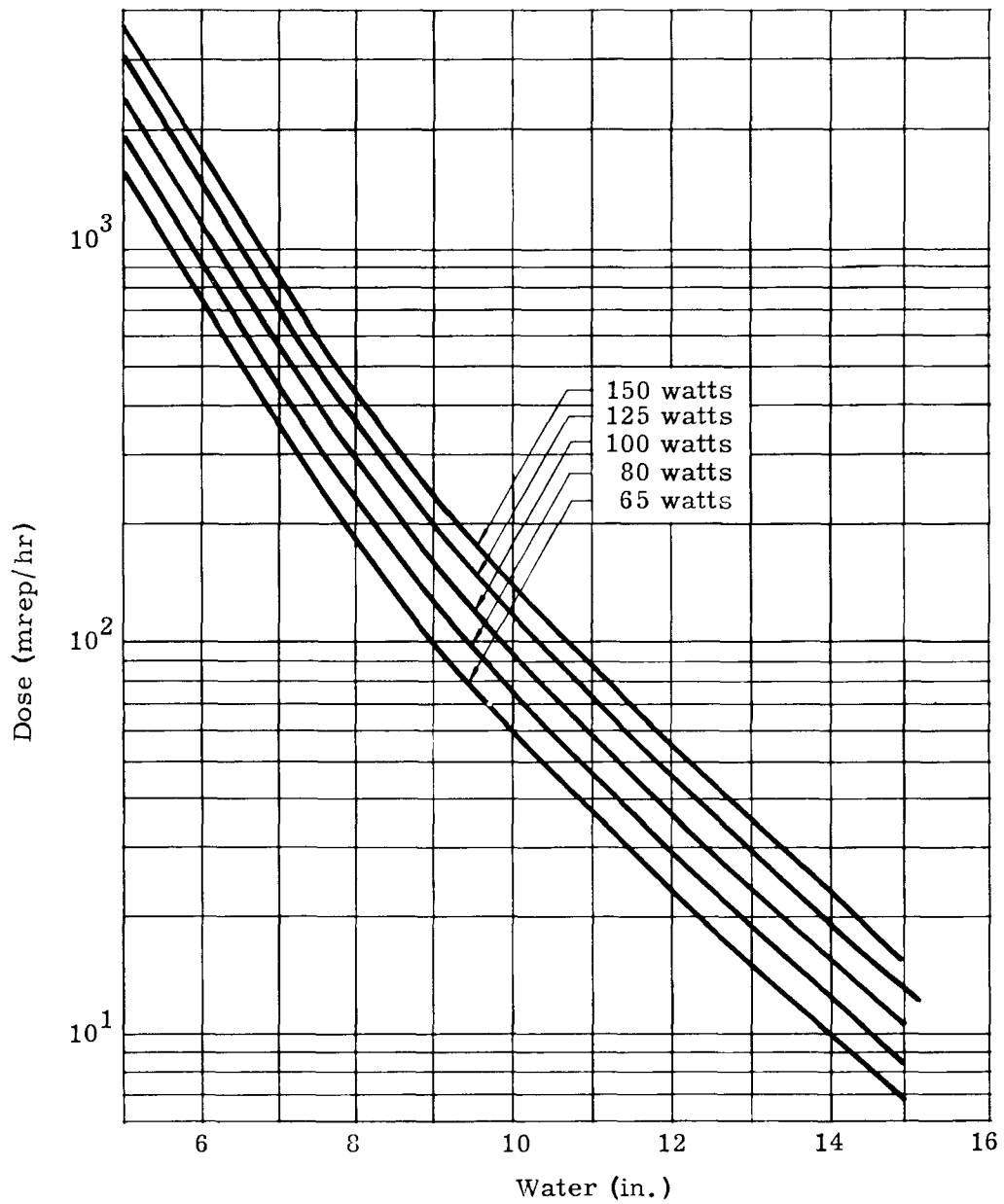


Fig. 6. Dose at the Surface of Indicated Thickness of Water

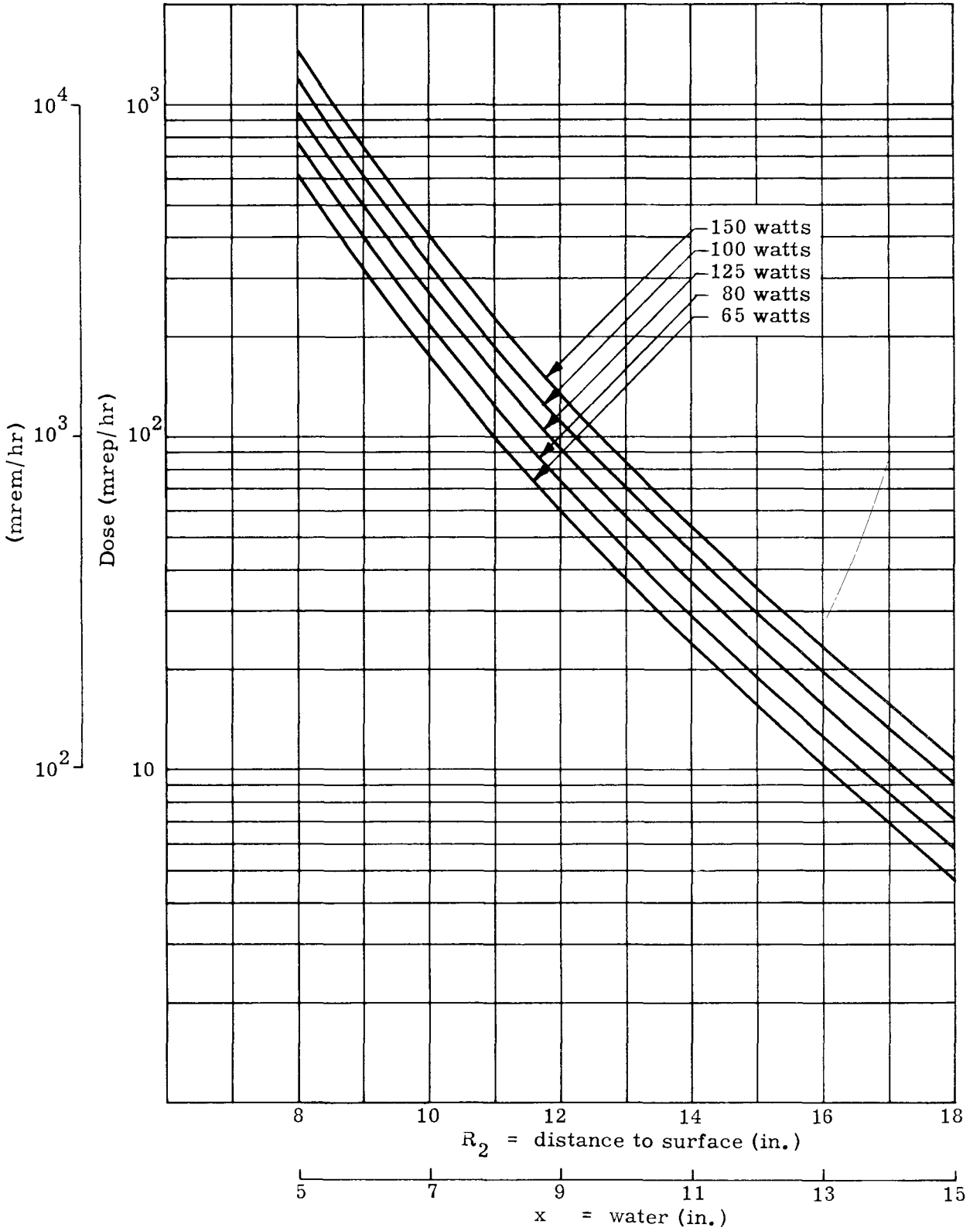


Fig. 7. Dose at Surface of Unit with Indicated Thickness of Water

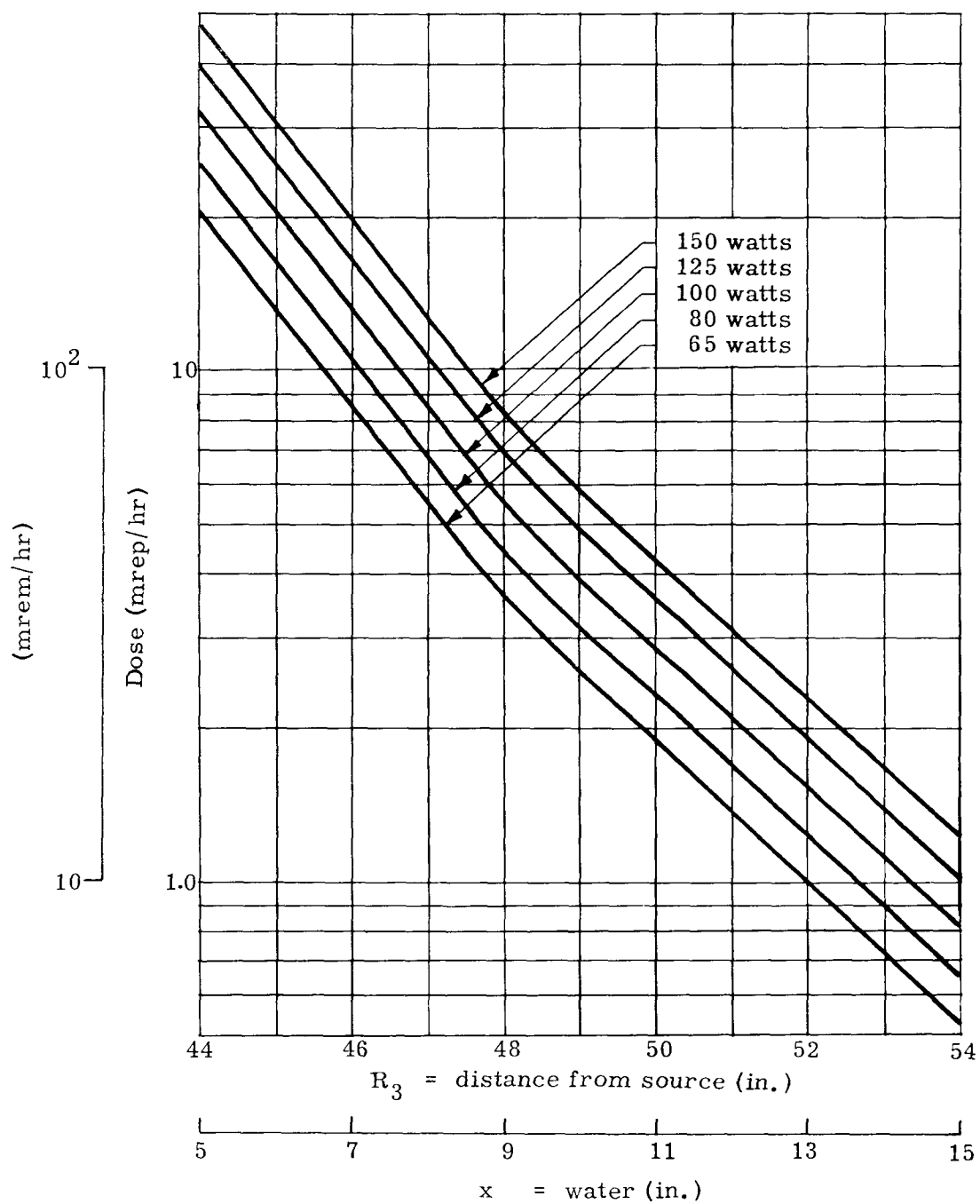


Fig. 8. Dose at Three Feet from Unit Surface with Water Thickness as Indicated

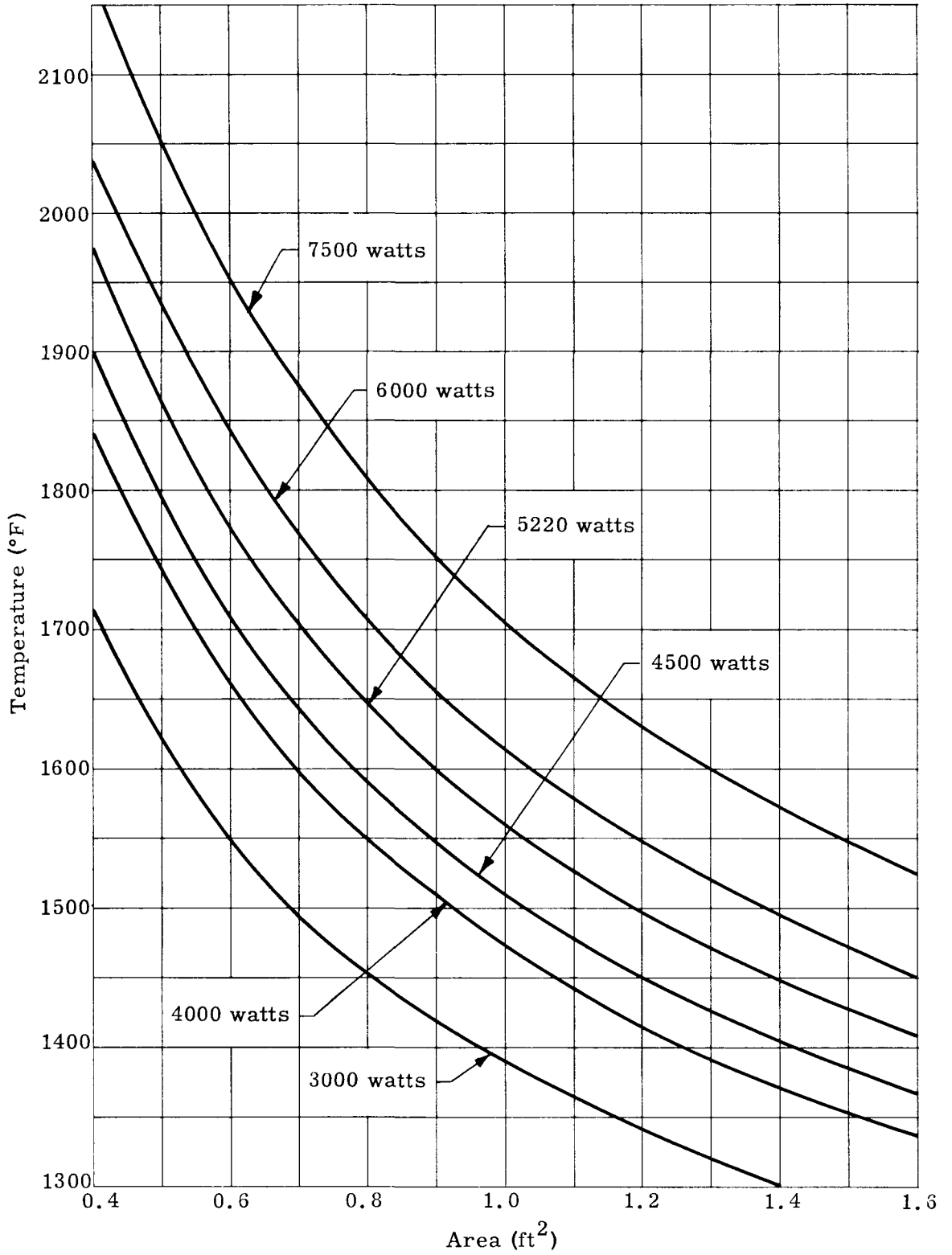


Fig. 9. Surface Temperature Versus Fuel Container Surface Area

the surface temperature is to be maintained between 1500 and 1600° F, the fuel container surface area must vary between 0.9 to 1.2 square feet. In this design, a surface temperature of 1530° F was attained for a 1.1-square foot surface area. (See Appendix C for derivation of equations used.) It is obvious that the power density of the isotope cannot be fully exploited in a radiative-type unit.

An indication of how rapidly the thermal dump area requirement increased with the life of the unit is shown in Fig. 10. A unit with a six-month operational life required a thermal dump area of 1.75 square feet while this requirement reached 5.1 square feet for a unit with a one-year operational life.

As the life and quantity of the isotope increased, the surface temperature of the fuel container increased as shown in Fig. 9. It would be necessary, therefore, to increase the surface area of the fuel container, and an increase in the size of the fuel container would necessitate an increase in the outer biological shield container.

Figure 11 shows a schematic of the unit with the principal dimensions indicated. A cooling coil was included in the graphite ablative material that surrounds the molybdenum isotope container. This cooling system may be employed during transportation and prelaunch cooling. This heat source was designed for intact re-entry.

The presently accepted operational philosophy is to have intact re-entry in the event of first and second stage aborts, burnup in case of normal re-entry; injection angle errors and final stage partial burnout can result in re-entry of partially exposed fuel elements, but only in unpopulated areas. Analyses of re-entry trajectories have been performed under Task 2 and Subtask 5.5 of AEC Contract AT(30-3)217.

To provide for burnup of the radioisotope fuel in the upper atmosphere (greater than 70,000 feet), a heat source using molybdenum as the container material, without ablative cladding, was designed. Details of the design and analysis of the heat source will be presented under the discussion of the Type C generator. Modification of the heat source substantially affected the overall design of the generator, as can be seen by examination of Fig. 12.

The shape of the heat source was changed since it was redesigned to contain five separate fuel slugs rather than one, as in Fig. 11. The cooling coil was removed, assuming that the shielding water could be circulated to cool the source. The increased isotope requirement resulted in extending the radius of the generator to provide for 9-3/4 inches of biological shield. The larger radius allowed the height of the generator to be reduced while still providing the required surface area for radiating rejected heat to space.

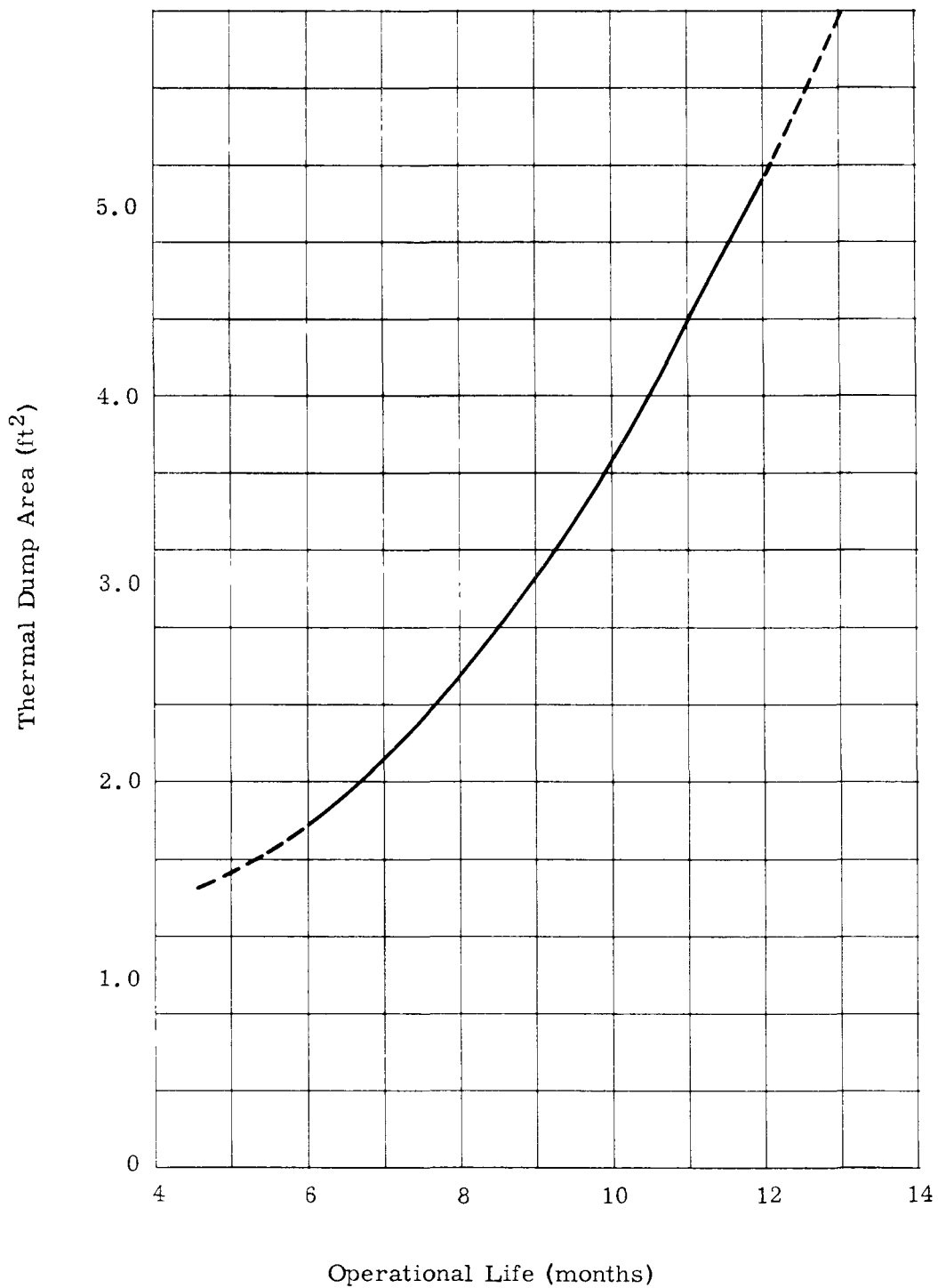
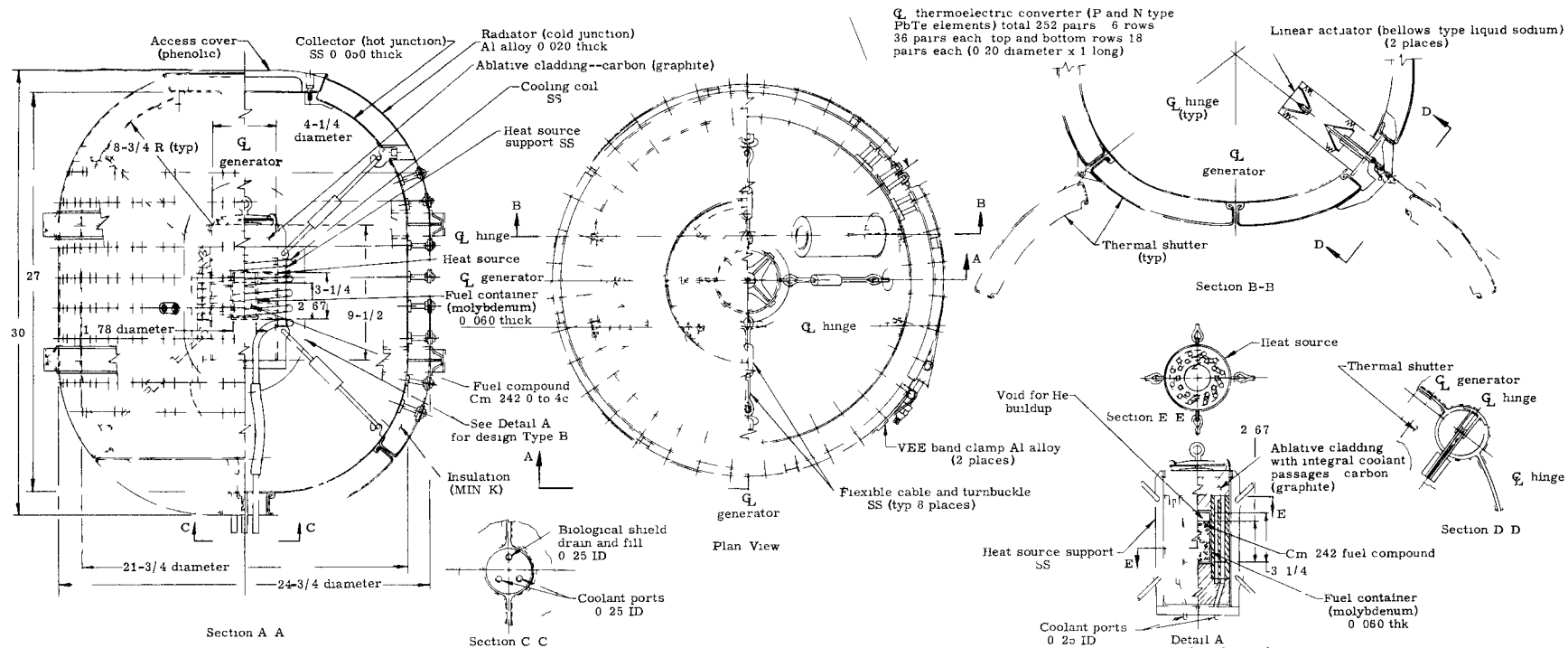


Fig. 10. Thermal Dump Area for 100-Electrical Watt Unit Versus Operational Life



All dimensions given in inches

Fig 11 Type B Preliminary Design Heat Source Surrounded by Ablative Cladding and Externally Cooled

TABLE 1

Original Design Parameters for Type B Generator (Ref. Fig. 11)

Efficiency--%	
Thermoelectric	6.59
Thermal (insulation)	78.3
Carnot	47.6
Overall	5.16
Temperatures--° F	
Hot junction	1000
Cold junction	305
Thermal shutter	1000
Fuel container surface	1530
Fuel centerline	1715
Thermal Features	
Thermal insulation thickness--in.	1.5 (Min-K-1301)
Heat loss--watts	420
Life--days	
Fabrication, transportation and launch	45
Operational life	180
Dose Rate	
Surface of unit--rem/hr	1
Three feet from surface of unit--mrem/hr	61
Biological Shield	
Borated water--in.	8-3/4
Thermal Dump Area--sq ft	1.75
Weight--lb	
Molybdenum fuel container and fuel	2.8
Graphite ablative material	10
Transportation cooling coil	2
Hot junction stainless steel shell (50 mils)	29
Cold junction aluminum shell (20 mils)	5
Thermoelectrics	19
Thermal insulation	37
Subtotal	104.8
Structure (25%)	26.2
Total	131.0
Thermoelectric Data	
EMF--volts	28
Pairs--No.	250
Area--sq ft	0.422
Length--in.	1



The thermal shutter was mounted at the bottom of the unit and was split in two parts, as shown in Figs. 11 and 12. The shutter activator is described in the next section. It should be noted that the shutter, when hinged on opposite ends, could function without reradiating heat to the cold junction area.

When the shielding requirements had been determined, the fuel container size necessary to give reasonable surface temperatures was determined. The surface temperature versus fuel container surface area is shown in Fig. 9 for various power levels. With the thickness of shield and size of the fuel container fixed, it was possible to determine the overall size of the unit if a thickness of thermal insulation was known. To reduce the heat loss and thereby increase the overall efficiency, 1-1/2 inches of Min-K-1301 thermal insulation was employed. Thus, the surface area and, subsequently, the cold junction temperature were established from the information given in Figs. 13 through 16, which are plots of heat transferred versus area for various temperatures and emissivities.

The thermoelectric design could then proceed by employing a hot junction temperature of 1000° F which is near the maximum practical temperature for PbTe elements. An important factor that must be considered in obtaining the maximum efficiency for given hot and cold junction temperatures is the element segmentation temperature. The segmentation temperature is the temperature at the point where the doping of the elements is changed to obtain a more efficient thermoelectric unit. The significance of the segmentation temperature is clearly illustrated in Fig. 17, which is a plot of the figure of merit ( $Z$ ) versus segmentation temperature. This plot shows that for a relatively small change in the point of segmentation, a sharp change in figure of merit is encountered. The maximum for the curve is dependent on both the hot and cold junction temperatures and therefore varies for each design. With a hot junction temperature of 1000° F and a cold junction of 305° F, the maximum figure of merit occurs at 400° F for the P couple and at 575° F for the N couple. The analysis of a generator employing segmented thermoelements is discussed in Appendix B.

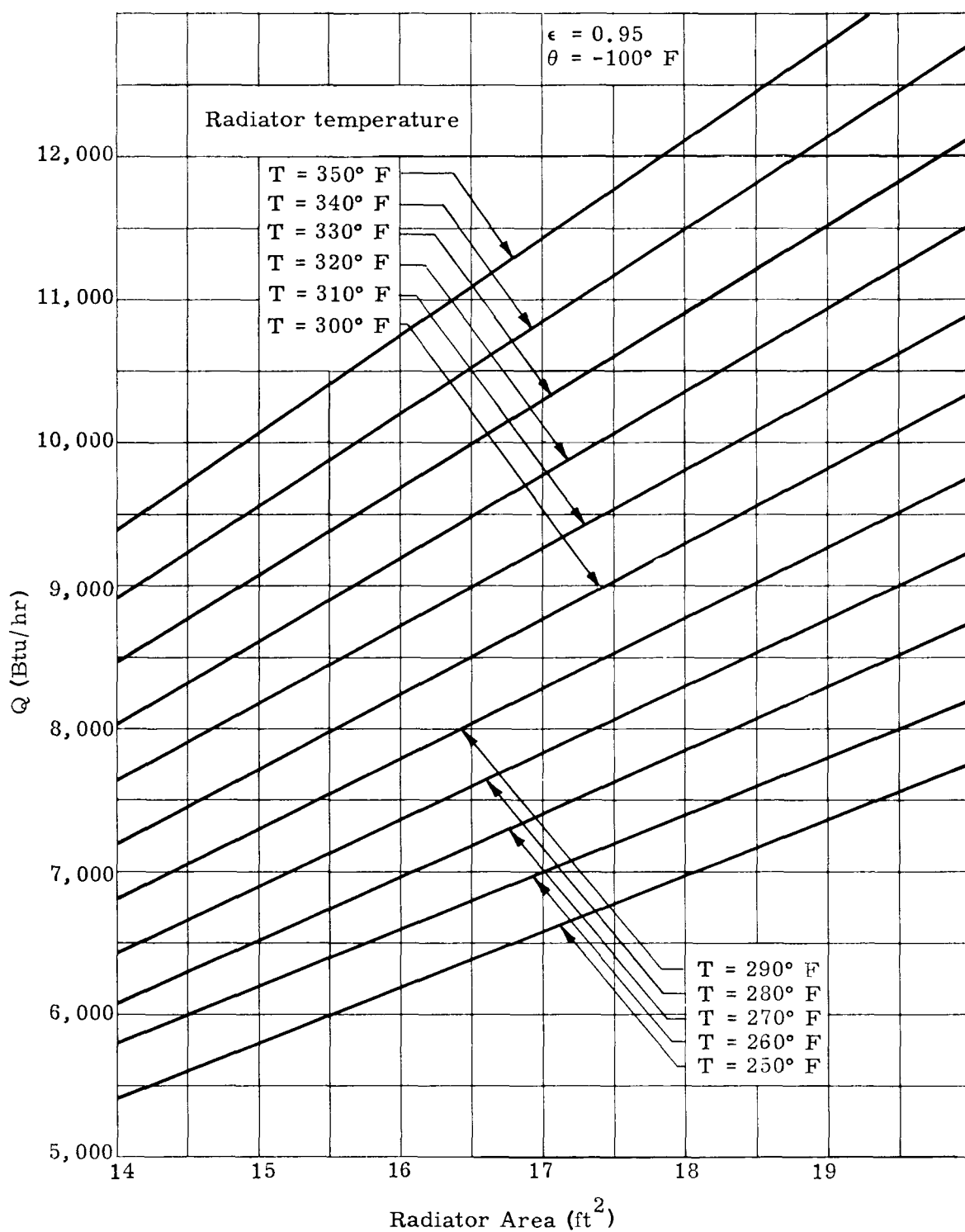


Fig. 13. One-Hundred-Watt Thermoelectric Generator Radiator Data

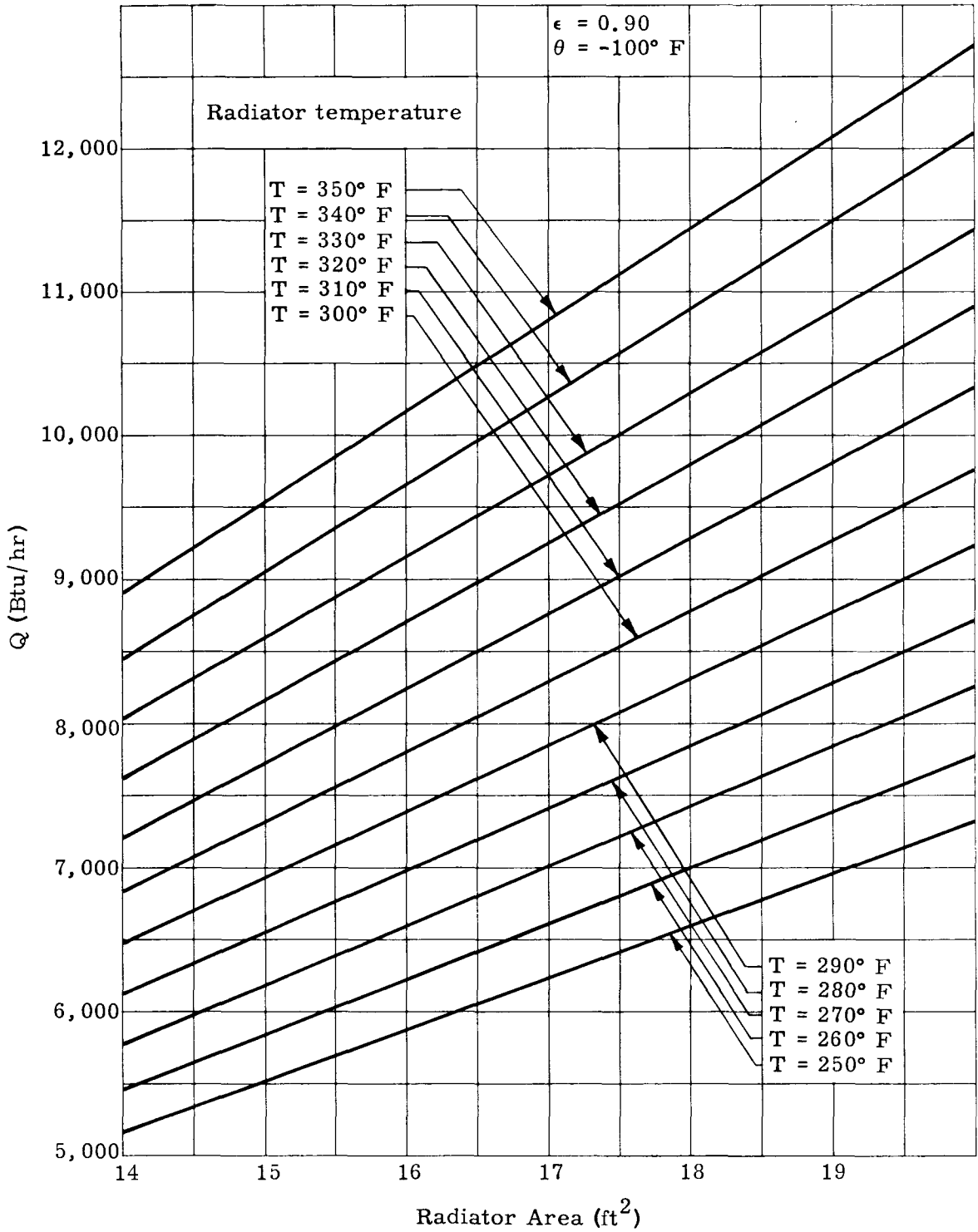


Fig. 14. One-Hundred-Watt Thermoelectric Generator Radiator Data

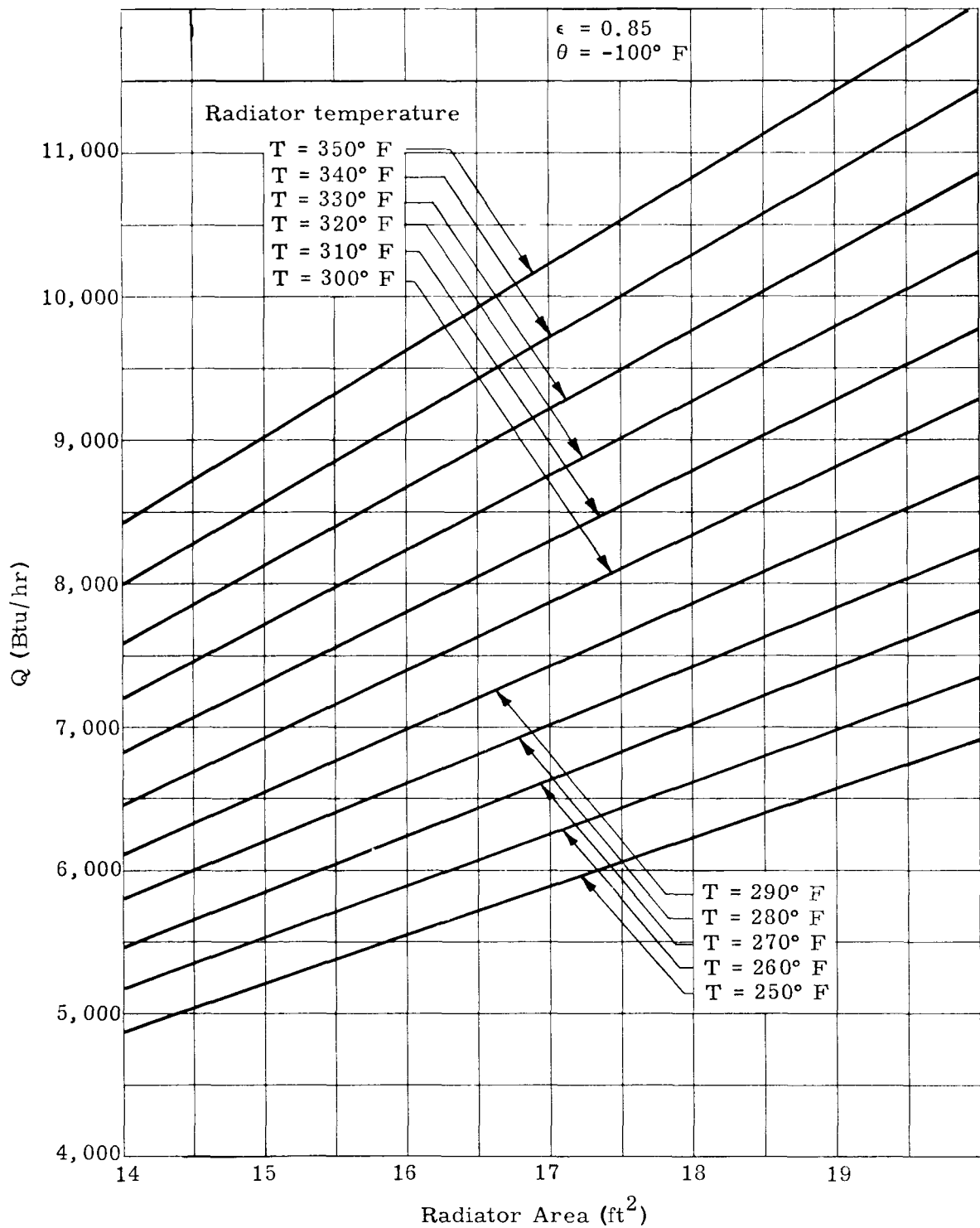


Fig. 15. One-Hundred-Watt Thermoelectric Generator Radiator Data

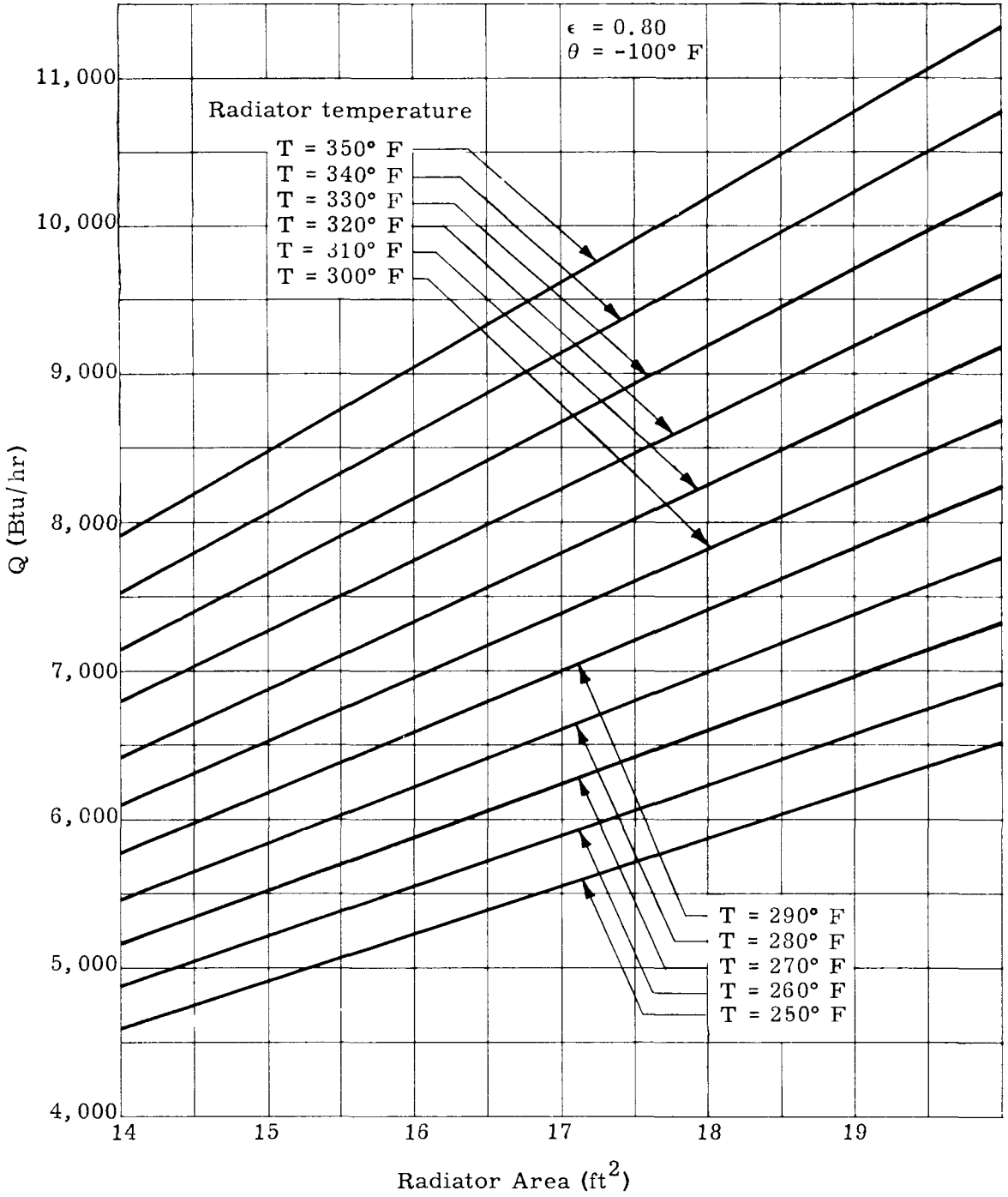


Fig. 16. One-Hundred-Watt Thermoelectric Generator Radiator Data

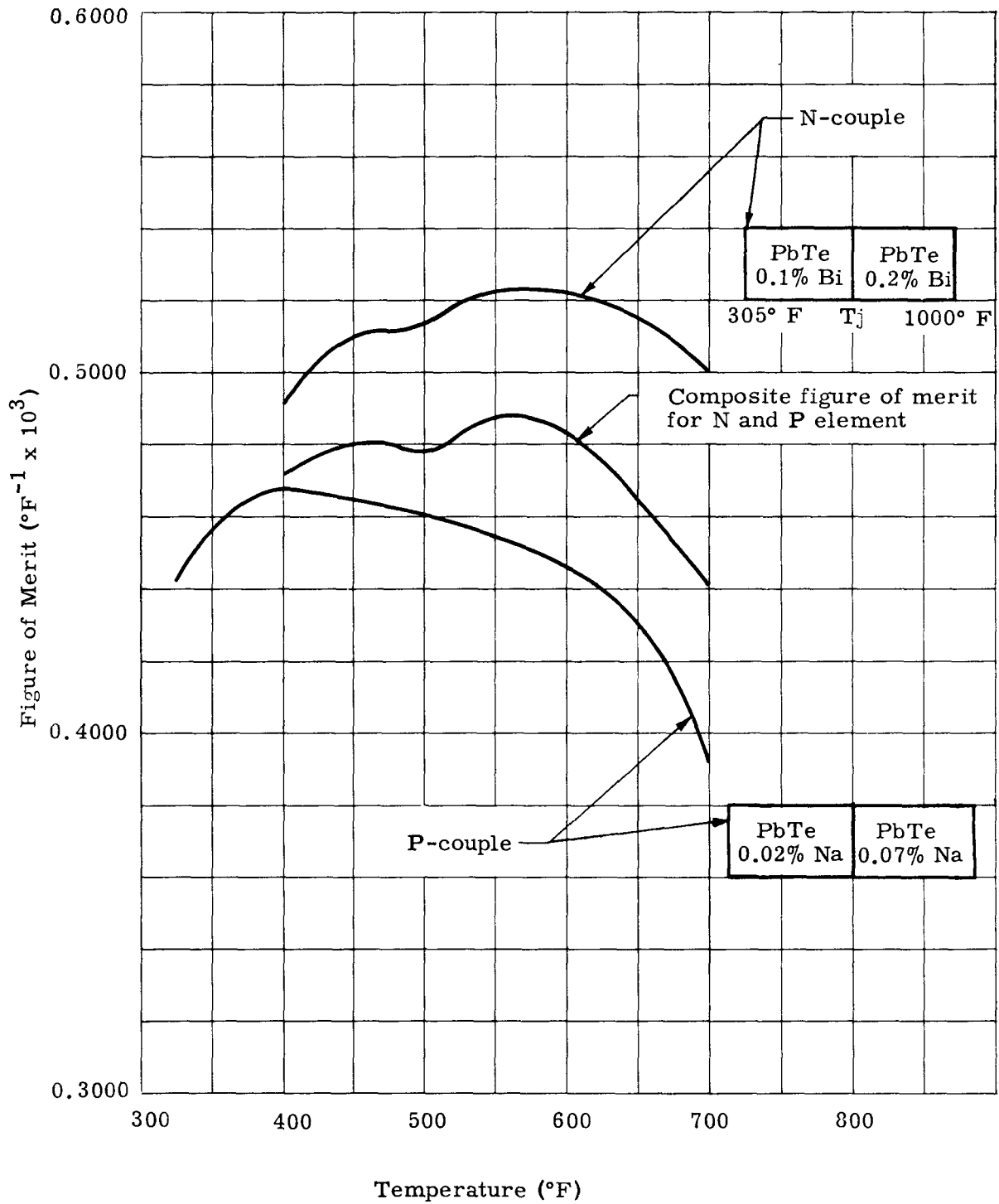


Fig. 17. Figure of Merit Versus Segmentation Temperature--100-Watt Unit

### C. TYPE C--RADIATIVE BOUNDARY GENERATOR WITH SPLIT BIOLOGICAL SHIELD

This design, which is the one recommended for ultimate use, was optimized on a basis of minimum weight. Part of the biological shielding was contained between the hot junction and heat source, and the remainder was contained in a removable external shell which could be jettisoned when the shielding fluid was dumped. An alternative open to the vehicle designer might be to incorporate this external shell into the structure of the third stage.

In the other designs the thermoelectric converter configuration was established by heat removal or shielding requirements and, thus, was not optimized. In the present design, optimization of the converter established the generator configuration.

The IBM-709 computations were used in designing this weight-optimized generator. The presence of shielding was ignored since the shield would be removed before the generator became operative. This optimization results in a weight saving of approximately 50% with only a negligible increase in fuel requirements.

The design procedure evolved from the computer program showed that weight could be minimized by raising the cold junction temperature, i.e., making the outer surface and, likewise, the whole generator, smaller. Although the thermoelectric efficiency was reduced because of the smaller temperature difference between the ends, the improvement in thermal efficiency that resulted from having a smaller insulation area through which heat is lost resulted in only a small overall efficiency drop.

Another design requirement imposed was that the fuel block be melted or sublimed and the fuel dispersed in the atmosphere upon the return of the generator from space. This precluded the use of graphite in the heat source, although it had been considered as an ablative material previously. Hastelloy C was therefore selected as the material of construction for the block, based on the experience gained in designing other generators for space applications.

A computer code was developed to aid in optimizing the design of thermoelectric generators. The code was based on an idealized concept in which the generator consisted of three concentric spheres. The innermost sphere was the heat source radiating to the hot junction (the middle sphere) from which heat was conducted through the thermoelements and insulation to the outer sphere or cold junction. No provision was made for decay of the heat source so that calculations were based on an end-of-life operation.

The variable parameters in the idealized concept were the power output, the cold junction temperature and the length of the thermoelectric elements. The utility of the code is that it reduces a large number of elaborate calculations to a few minutes of IBM-709 time. Four minutes of machine time were equivalent to roughly 80 to 120 hours of hand calculations.

The principal disadvantage of the computer program was the ideal nature of its generator model. In practice, it is generally impractical, if not impossible, to use a spherical generator. However, the computer program will save considerable design effort by pointing out immediately the outline of the best design for minimum weight, minimum isotope investment, etc. Since most of the generators in the 100- to 200-watt range are cylinders with roughly hemispherical caps, with overall length only slightly greater than the radius, the approximation is not extreme.

Another limitation was that the mathematics involved in the optimum design does not permit an allowance for the contact resistance of the thermoelectrics. This allowance is made by overdesigning the generator. Thus, if a 30% allowance is made for contact resistance, the generator will be designed to deliver 130 watts for an actual output of 100 watts. As a result, the power output parameter for this problem was set at 130 watts. The other parameters were varied over a range of 400 to 550° F for the cold junction temperature and 0.75 to 2.5 centimeters for the thermoelement length. Figure 18 shows the results of the computer calculation. The weight of the generator is plotted against the cold junction (i.e., radiator) temperature for each thermoelectric length.

The weights shown are much lower than the actual weight of the design because of the ideal nature of the computer model. Sources of additional weight are the thermal shutter for dumping excess heat, the fuel block which must be designed to accommodate much higher heat fluxes than the end-of-life flux calculated by the code, additional hardware for mounting the thermoelectrics beyond that allowed for in the code, shutter control mechanisms, etc.

A breakdown of the hand calculations involved in the computer code, the arrangement of the input data and a Fortran listing of the code are included in Appendix D. There are a number of contradictory requirements involved in the design of the fuel block. To lower the surface temperature of the block, maximum surface area is desired. Since volume (i.e., weight) must be minimized, the ideal shape from this point of view would be a long thin cylinder. A cylindrical shape was decided upon because of fabrication problems involved with shapes approaching the sphere of the idealized generator used in the computer program.

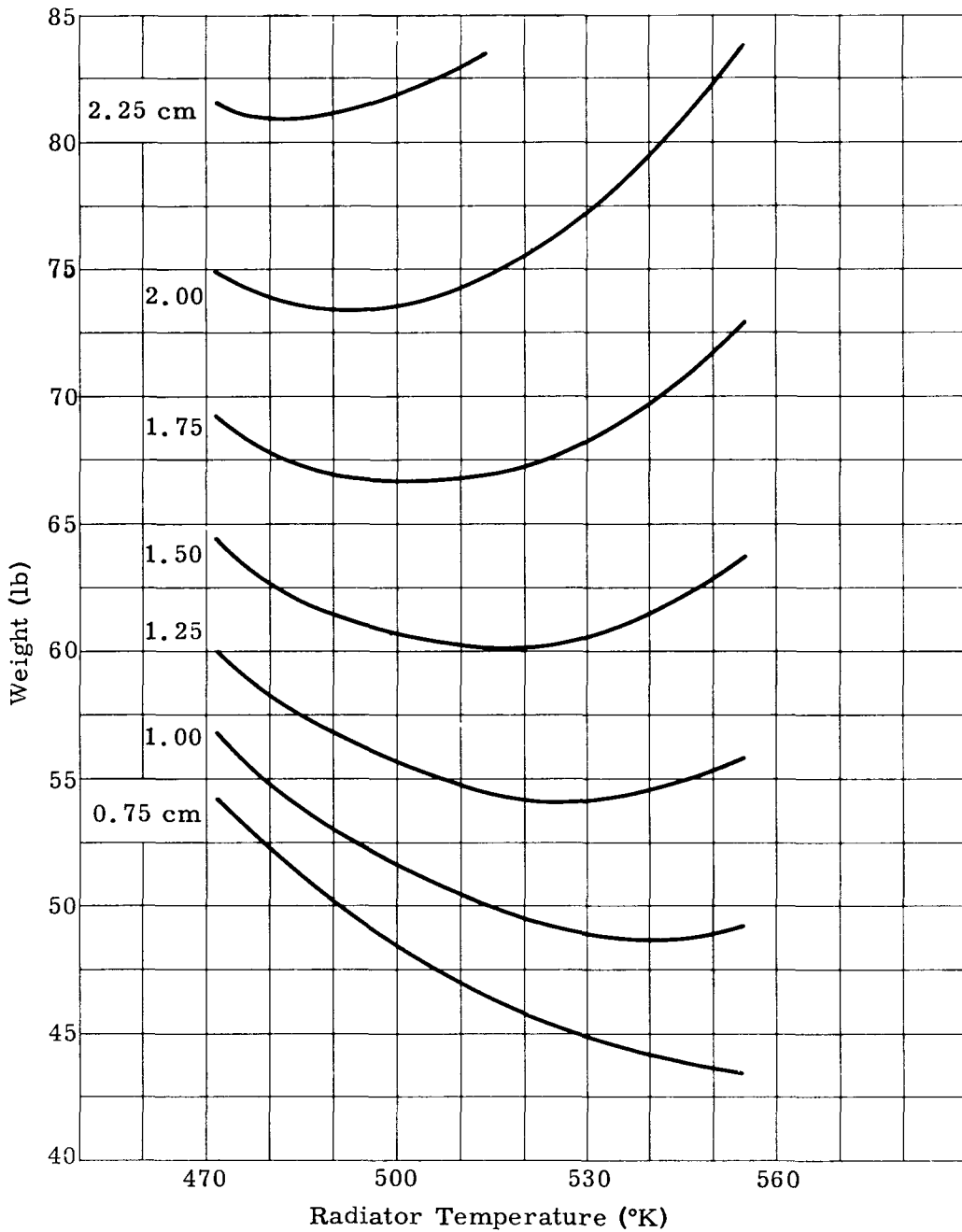


Fig. 18. Generator Weight Versus Radiator Temperature Parametric in Thermoelectric Length--Electrical Power Output = 130 Watts

In contradiction to these maximum surface and minimum volume considerations are other desirable characteristics. Since the excess heat is to be dumped at one end of the generator, the area of the fuel block facing that end should be large. Another requirement to be satisfied is that the temperature gradient from one end of the fuel block to the other should be minimal so that more heat can be dumped from the end facing the shutter thus thermal stresses will be minimized and the temperature at the end of the block facing away from the thermal shutter will not be excessively higher than the average block temperature. These requirements are best satisfied by a squat cylinder of smaller height than diameter. To attain the best compromise it was decided to make the height equal to the diameter; that is,  $L/D = 1:1$ .

Thus, the fixed quantities in the design are a surface temperature of  $1800^{\circ}\text{F}$  and equal height and diameter. Figure 19 shows how the dimensions of the block vary with emissivity. Assuming that an emissivity of 0.9 is attainable on the surface,  $L = D = 4.3$  inches. Allowing a small safety factor for nonuniformity of temperature, this dimension was chosen as 4.5 inches.

The  $1800^{\circ}\text{F}$  surface temperature mentioned is rather optimistic. The high temperature reduces the strength of the Hastelloy C block and may cause failure on impact. Should tests prove that this is the case, then the surface area of the block, as well as its weight, will have to be increased.

A reflector might also be required to assist in dumping the heat through the thermal shutter. This would increase the temperature on the surface of the block to more than  $1800^{\circ}\text{F}$ . The attachment of molybdenum fins to increase the radiating surface of the block without a large increase in weight might serve to alleviate this temperature burden should it appear. This same technique might eliminate the heat control problem in a borderline situation.

Consideration of the fabrication problems involved because of the excessive centerline temperatures that would be experienced, and the experience gained from design of other relatively high-powered generators (i.e., SNAP-IA) indicate that a single isotope capsule within the fuel block would not be practical. Hence, the decision was made to distribute the fuel in five capsules spaced in a uniform fashion within the block.

To conserve weight, the lateral surface of the cylinder was "scalloped" to give the same effective radiating surface with less weight. It might also be possible to hollow out the flat surfaces of the cylinder slightly to decrease weight.

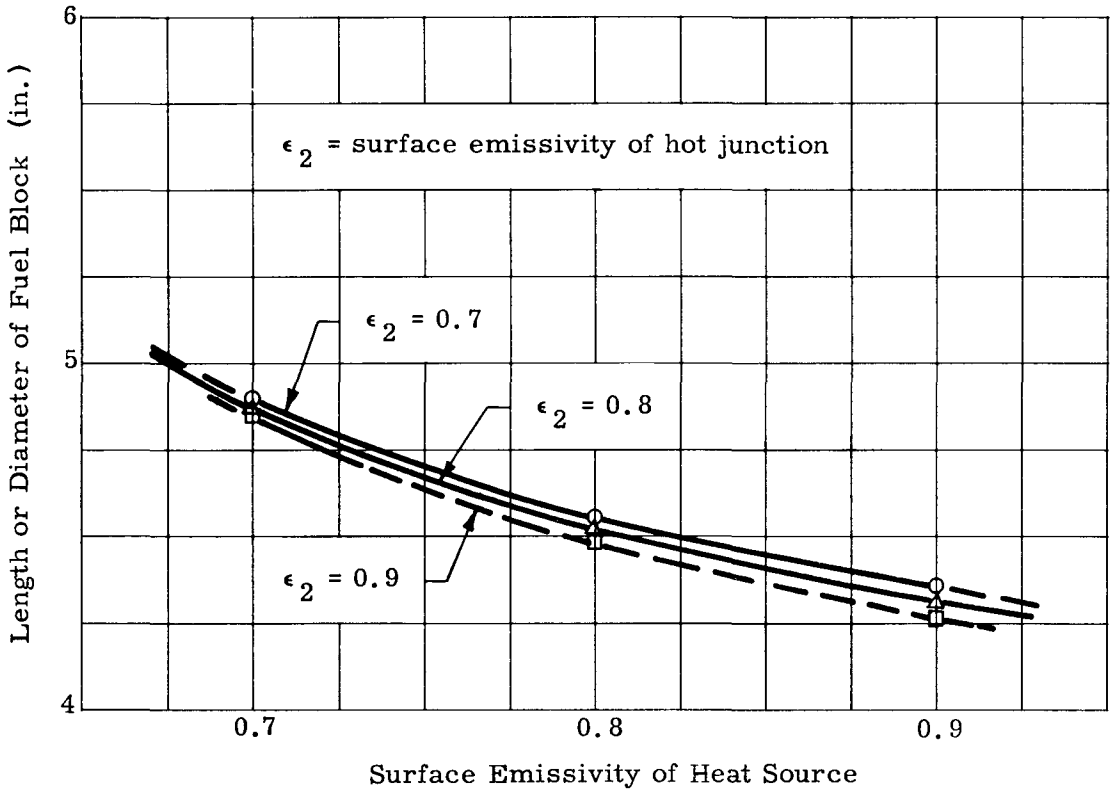


Fig. 19. Variation of Heat Source Dimensions with Surface Emissivities at a Surface Temperature of 1800° F--Power Level of 5800 Watts at Launch

The five holes in the fuel block are 0.956 inch in diameter and are equally spaced with their centers on a 2.75-inch diameter. The holes are drilled 3.75 inches deep into the block, filled with 2.4 inches of the fuel mixture and capped with a 3/4-inch threaded and welded plug. Six-tenths of an inch void space is allowed in each hole for helium accumulation from the alpha emissions.

Three calculations were made to determine the temperature difference between the hottest part of the fuel block and its surface. These calculations gave values of 562, 579 and 650° F.

From these values, it can be seen that the hottest part of the block will be about 2400° F. This is below the melting temperature of nickel but slightly above the melting point of Hastelloy C. However, since this temperature is at the center of the fuel block, the surface of the fuel pellet should be well below the melting point, although the strength of Hastelloy C will be very low at that temperature.

Investigation of other materials with better thermal conductivity and higher melting points led to molybdenum and Inconel. These materials have very poor resistance to sea water corrosion, and recent plasma jet experiments indicate that molybdenum may not burn up completely on re-entry. Thus, unless some method can be developed to improve the corrosion resistance of the other materials, Hastelloy C, although not an ideal solution, appears to be the only practical one.

The calculations used in determining these dimensions and temperatures are shown in Appendix E.

Lead telluride thermoelectric elements were selected for this study because of their availability, relatively low cost, and detailed knowledge of their physical, chemical and thermoelectric properties. Their length was set arbitrarily at one centimeter for purposes of computation since no rigid voltage specification for the generator was imposed.

As shown in the explanation of the computer program in Appendix D, the only fixed thermoelectric requirement remaining was determination of a discrete cross-sectional area. To minimize weight, the minimum number of short thermoelements was used. The absence of a rigid voltage specification made this possible. Since the largest thermoelectric normally fabricated is 1/2 inch in diameter, this size was picked for the positive element. The negative element was calculated to be 0.455 inch in diameter.

Recent tests of PbTe thermoelements show that the actual power output was significantly less than the theoretically calculated output. This deficiency was attributed to contact resistance at the hot junction of the thermoelectrics. The average of the results showed about a 25% drop from calculated power output to actual output. Allowance is made for this loss as explained earlier.

The thermoelectric calculations employed are shown in Appendix F.

Prior to actual launch, the thermal output of the Curium-242 is to be removed by circulating the water comprising the internal portion of the generator shield. This circulation would be accomplished by external pumps connected by hoses that would be removed prior to launch. The heat source and generator would most probably be shipped separately to the launch site and assembled there. Cooling of the generator would continue from assembly until a few minutes before launch. The hoses would be part of the umbilical connection to the payload so that if a hold occurs after the shield water is dumped, the water can be replaced to allow repairs to the missile and prevent the generator from overheating.

Calculation shows that the minimum time required for the parts of the generator to heat up to working temperature is about 20 minutes. Thus, the generator cooling could be stopped about 15 minutes prior to launch and a final operational check accomplished as the generator is heated. This would allow the generator to be operating at full power by the time it was in orbit. If a hold is called more than 12 minutes after the shield water is dumped, gas cooling may be necessary before the shielding fluid is pumped back in. This problem could be eliminated by scheduling the shield dump at launch -10 minutes instead of launch -15 minutes.

If the circulation system should fail while the water remains in the shield, three to four hours may elapse before the temperature rise within the generator becomes great enough to damage the thermoelectric elements. Calculations used in estimating these times can be found in Appendix G.

One of the most important departures from the ideal generator model of the computer program is the thermal shutter. Its purpose is to permit surplus heat to be radiated to space at the beginning of the operational life of the generator. After this has occurred, it will close slowly during the remainder of the operational period at a rate such that the decreasing thermal output of the heat source is directed more and more to the thermoelectric elements, thus maintaining constant electrical output. The shutter is therefore designed to sense the hot junction temperature, rather than the heat source or cold junction temperature.

Several problems, a number of which are impractical, if not impossible, to solve analytically, arise in the computation. The dumping of large quantities of heat through one end of the shutter causes an uneven temperature distribution over both the heat source and the hot junction surfaces. Since the heat flows toward the lowest temperature, this means that temperatures near the shutter will be lower, causing the amount of heat dumped to fall off. An attempt has been made to counteract this effect by moving the heat source closer to the thermal shutter and designing the heat source as explained earlier.

The area required for the thermal shutter is calculated in Appendix H. If the arrangement of the heat source and the size of the shutter prove insufficient to dump the heat required, other modifications can be made, such as varying the emissivity of the hot junction surface and placing a reflector around the heat source to direct more of the heat through the shutter opening.

The shutter will be controlled by a temperature-operated actuator which will tend to partially close it as the hot junction temperature attempts to fall below 1000° F. The actual placement of the controls will depend on the temperature distribution determined by testing with an electrically heated mockup of the generator.

The secondary requirement of minimum isotope investment for this design does not have as definite a minimum value as the weight of the generator. The end-of-life requirements for sufficient Cm-242 to fuel the generator were varied from 18.7 to 23.8 grams. Assuming 45 days from irradiation of Am-241 to encapsulation, this would require an initial amount of from 61.4 to 78.1 grams.

Based on the optimized weight concept, the end-of-life requirement is 21.5 grams, giving an initial fuel quantity of 70.5 grams. For the thermoelectric length of 1.00 centimeter, the minimum isotope requirement of 61.4 grams occurs at the maximum weight computed by the code of 58 pounds. The weight at the cold junction temperature picked was 48 pounds. Thus, a 20% weight saving is made by increasing the isotope requirement by 12.7%. Assuming that this 10-pound difference held for the actual weight instead of just the ideal weight, the weight saving would be approximately 13.7%, which is still slightly better than the percentage of the isotope saved by using the heavier, more efficient generator. Figure 20 shows a plot of initial isotope requirement versus cold junction temperatures for a thermoelectric length of one centimeter.

A tabulation of the characteristics of the Type C generator, based on this discussion, appears in Table 2.

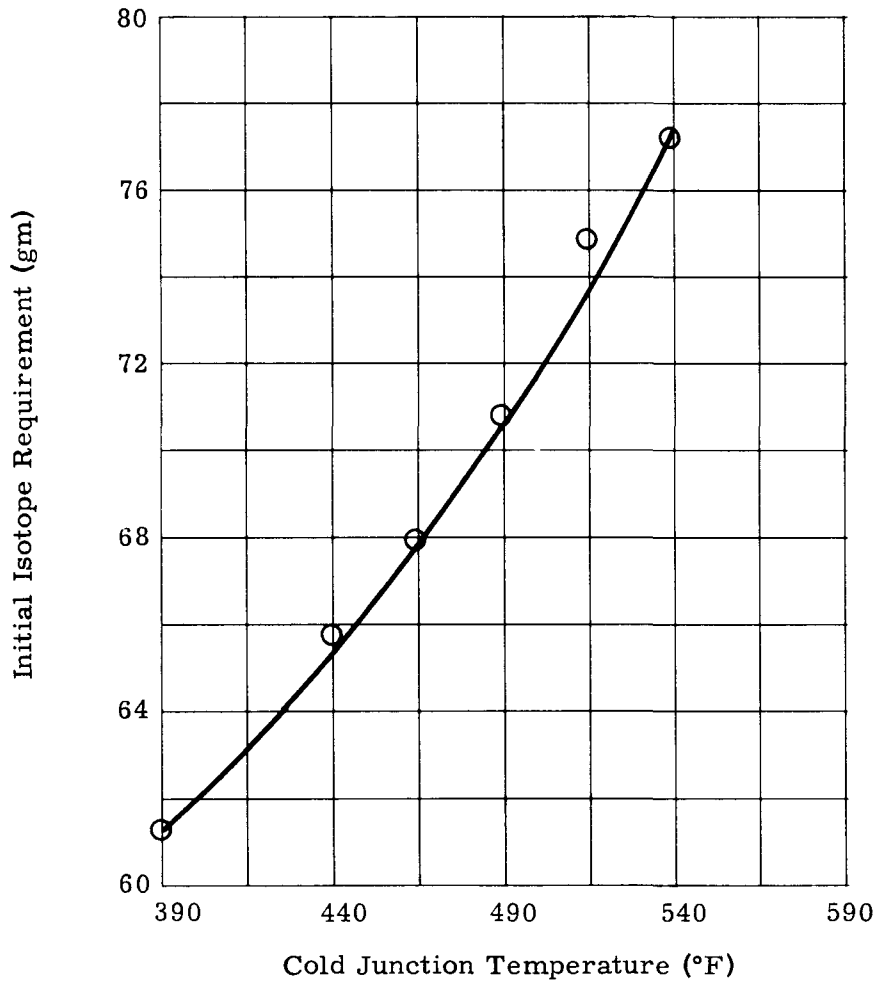


Fig. 20. Variation of Initial Requirement of Cm-242 with Cold Junction Temperature

TABLE 2  
Characteristics of the Type C Generator

Outer Shell (cold junction)--Aluminum	
Thickness--in.	0.040
Height--in.	21.5
Width--diameter--in.	19.5
Inner Shell (hot junction)--Stainless Steel	
Thickness--in.	0.050
Height--in.	19.5
Diameter--in.	17.5
Thermoelectrics--pairs of PbTe elements	169
Length--in.	0.3937
Diameter--P couple--in.	0.500
N couple--in.	0.455
Doping--P couple--% Na	1.0
N couple--% Pb I <sub>2</sub>	0.03
Heat Source--(Fig. 21)	
Height--in.	4.5
Effective diameter--in.	4.5
Fuel tubes--No.	5
Diameter of fuel tubes--in.	0.956
Height of fuel tubes--in.	3
Height of fuel pellet--in.	2.4 (20% void space)
Thermal power at encapsulation--watts	7500
Fuel mixture--by weight	20:1 Ni-Cm mixture
Encapsulating material	Hastelloy C
Thermal Shutter	
Area--sq ft	1.72
Insulation--Min-K-1301	
Thermal conductivity--Btu in./hr ft <sup>2</sup> °F (vacuum)	0.1
Thickness--in.	0.9
Density--lb/ft <sup>3</sup>	20
Temperature--°F	
Hot junction	1000
Cold junction	490
Heat source at launch	1800
Heat source at end of life	1470

TABLE 2 (continued)

Weight--lb	
Outer shell	5
Inner shell	12.5
Thermoelectrics	8
Thermoelectric connections and mounting hardware	10
Heat source	20*
Insulation	7.5
Shutter controls	2.5
Structure for mounting heat source	6
External shield container	5.5
Total	77
Efficiency--%	
Design:	
Thermoelectric	5.20
Thermal	95
Overall	4.95
Expected:	
Thermoelectric	4**
Thermal	92
Overall	3.70

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\* Might be reduced by improvement in fuel block design.

\*\* Drop is result of adverse effect of contact resistance.

The manner in which the results of the analytical studies have been incorporated in the final mechanical design of the Type C generator is illustrated in Fig. 21.

Several design features not immediately apparent in the drawing are included.

#### 1. Thermoelectric Elements

The design objective was to minimize thermal and electrical contact resistance between the elements and the collector and radiator. The hot junction ends of the elements are ground or machined to a spherical sur-

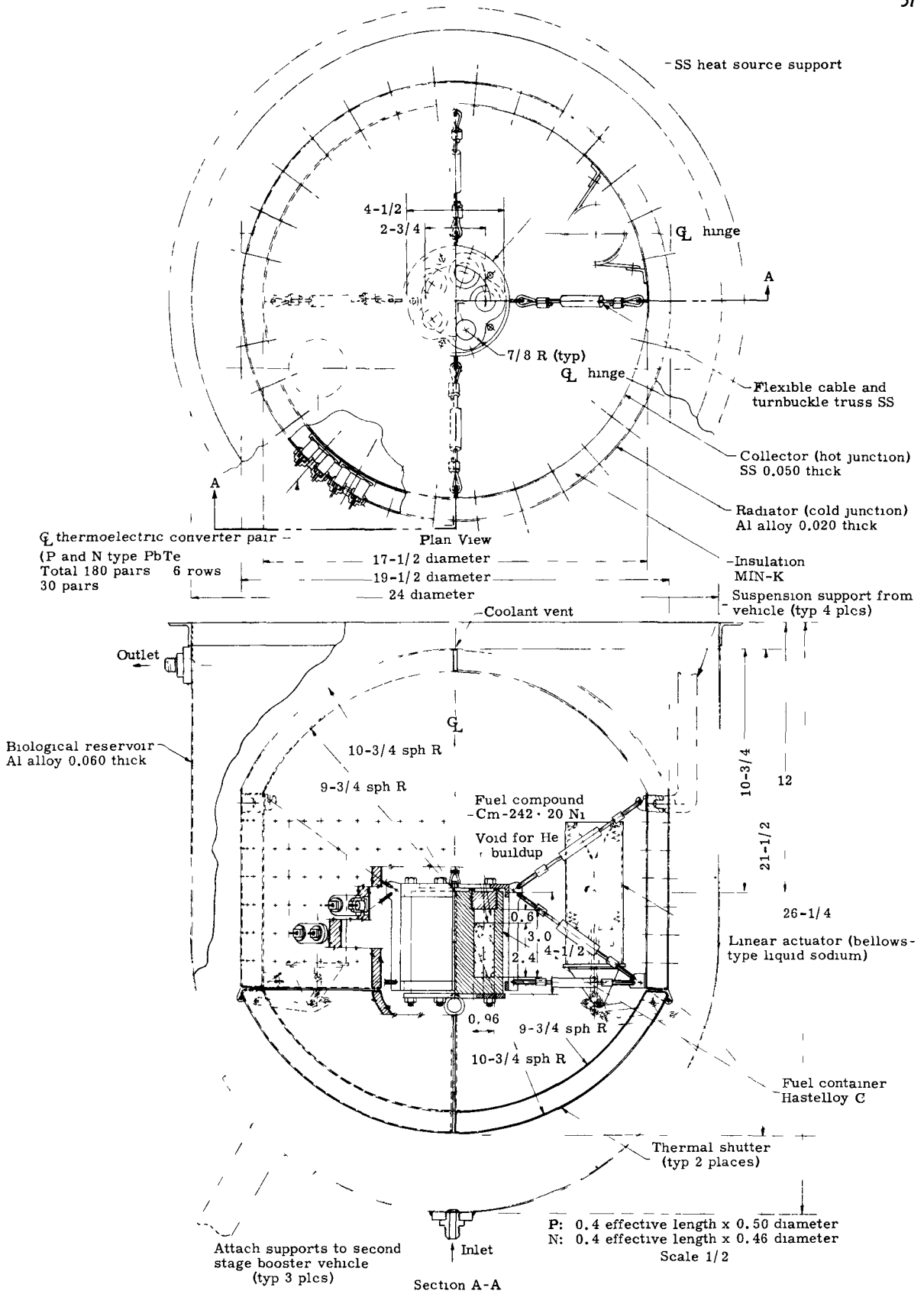


Fig. 21. One-Hundred-Watt Generator--Final Design--Type C

face to assure good contact and alignment with the electrical connectors or shoes. The latter are fabricated from nickel and insulated electrically from the collector by means of boron nitride shoes, which exhibit good thermal conduction properties. The cold junction ends of the elements are loaded axially by springs in an adjustable self-aligning collet to provide for thermal expansion of the elements. Electrical insulation of the elements from the radiator is accomplished by application of a thin adhesive coating of alumina (Martin Hard Coat) in the contact areas of the collets. Furthermore, the elements are protected from sublimation over about 2/3 of their length--from the hot ends--by spray coating with alumina or zirconia.

## 2. Thermal Insulation

Min-K-1301, a Johns-Manville insulation, has been selected as the solid insulation between the collector and radiator because of its low density, low thermal conductivity and the support it offers to the thermoelectric elements. It may be procured from the manufacturer already molded to the cylindrical and spheroidal shapes required for this generator. Difficulties have been encountered in machining holes in the insulation as it crumbles and breaks. To avoid this, it should be coated with an epoxy resin prior to machining to provide additional mechanical strength. After the holes and counterbores for the thermoelectric elements have been machined, the residual resin may be removed by baking the insulation at temperatures above the decomposition point of the resin.

## 3. Power Flattening Controls

As stated before, power flattening is required to compensate for the excessive heat generation at the beginning of operation as compared to the end of useful life of the generator. Shutters which permit heat to be radiated to space, and which close as the end of life is approached, are actuated by a mechanism which makes use of the linear thermal expansion characteristics of liquid sodium over the temperature range of 300 to 1500° F. The activator, which is novel in many respects, was designed for The Martin Company by the AiResearch Manufacturing Company. This design was prepared at no cost to Martin or to the Government.

A liquid-filled bellows principle was selected for reasons of simplicity, reliability and low weight. No power-assist mechanism, external power or rotating parts are required. The bellows assembly features end plugs which displace some of the sodium to effect a desirable ratio of extended length to relaxed length. The plugs are cone shaped for rigidity and to permit the lateral support lent by the push rod guide to be applied nearer to the center of mass of the actuator.

The estimated characteristics of the actuator are shown in Table 3.

TABLE 3  
Characteristics of Linear Actuator for Shutter

Output force--lb	50 to 75
Stroke--in.	0.75
Weight--lb	1.9
Envelope--in.	2-3/4 x 2-3/4 x 6-1/2
Linear response temperature range--°F	300 to 1500
Cycle time	Several days
Environmental characteristics	
Acceleration, any direction--grams	25
Vibration, 20 to 2000 cps,	
White noise--g rms	5
Nonoperating shock, any axis, 20 msec,	
operation after shock--g	20
Susceptibility to nuclear radiation	None over operating life

#### 4. Selection of Isotope Form and Matrix Material

After Curium-242 had been selected as the isotope to power the generator, detailed attention was paid to the chemical form in which it would be utilized. The relatively stable oxide and carbide were eliminated because of the increased shielding required for protection against neutrons from ( $\alpha, n$ ) reactions on the light elements. Elemental curium remained as the form to be used, although the specific power of curium metal is so high that it could not be utilized by itself in a reasonable geometric shape. Dilution of the curium with a suitable inert material of matrix then became necessary.

An investigation was made to determine the radiant boundary surface temperature of fuel slugs fabricated with matrix materials having optimum properties of density, melting points and thermal conductivity. Table 4 and Fig. 22 present the properties and surface temperatures of gold, copper, nickel, platinum, molybdenum, iron and graphite.

TABLE 4  
Fuel Matrix Materials for Cm-242 Compounds

<u>Material</u>	<u>Melting Point</u>		<u>Thermal Conductivity</u> (Btu/hr-ft-°F)	<u>Density</u> (gm/cc)
	(°F)	(°C)		
Molybdenum	4760	2620	84.6	10.20
Rhodium	3571	1985	50.0	12.50
Zirconium	3355	1900	15.5 (1200° C)* 9.6	6.4
Platinum	3224	1773	42.0	21.37
Titanium	3275	1800	8.1	4.50
Vanadium	3100	1710	17.9 (100° C) 21.3 (500° C)	5.96
Palladium	2829	1553	41.0	12.16
Iron (pure)	2795	1535	46.3 (1200° C)	7.85
Mo, NiCr Steel	2735	1500	21.7	
Nickel	2620	1455	35 (100° C) 14 (1200° C)	8.90
Copper	1960	1083	210	8.94
Gold	1945	1063	170	19.32
Graphite		3550	59-78.8	2.25

\*1.8% Hf alloy

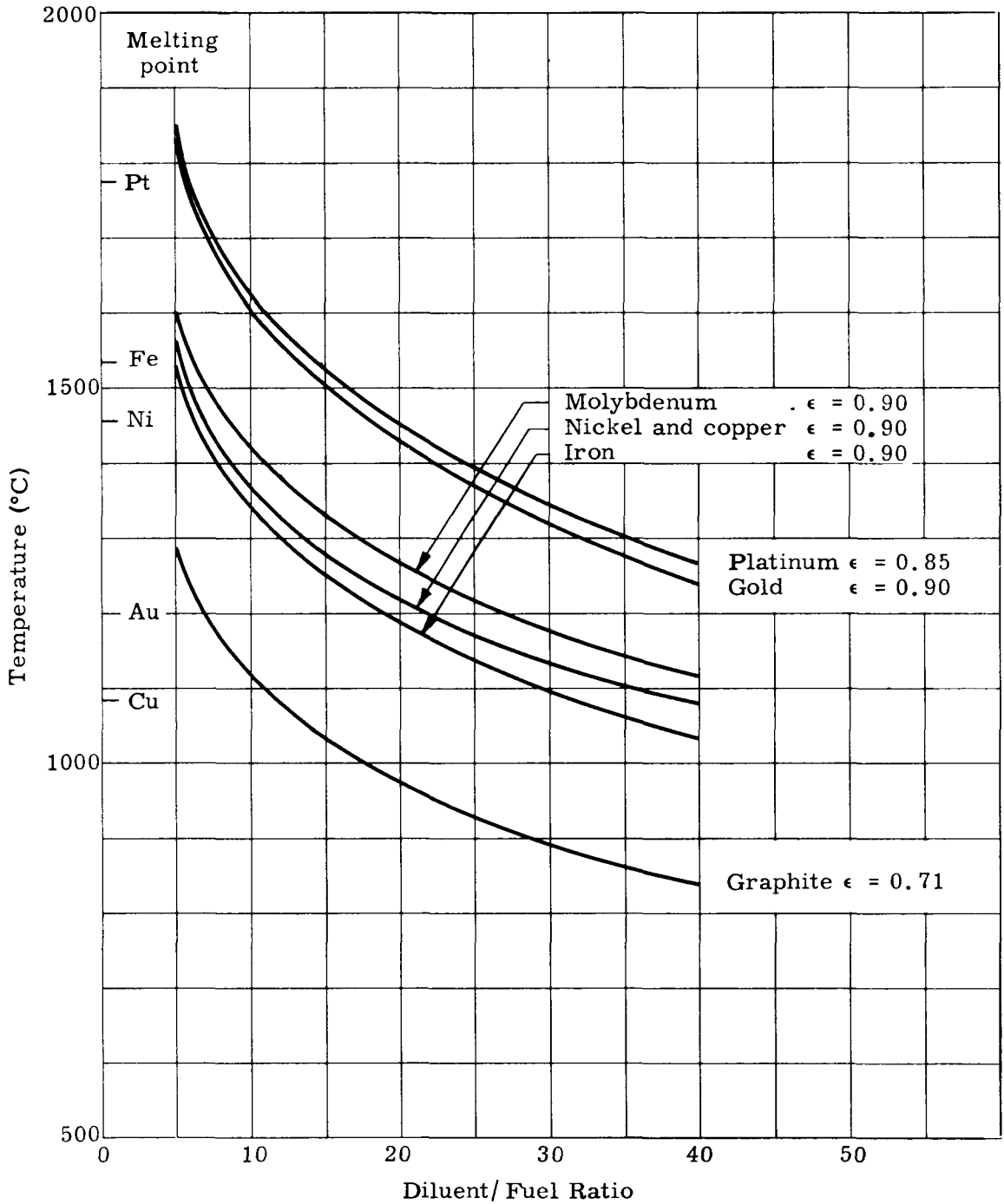


Fig. 22. Fuel Slug Surface Temperature for Radiant Heat Transfer Boundary--L/D = 1/1

Table 5 presents only limited information on several of the curium fuel compounds potentially available. Some of the properties, i.e., weight and power densities, have never been accurately determined for various compounds or else have been measured under ideal laboratory conditions where the purity of the sample and methods of preparation are far superior to those achieved on a commercial basis. Thus, the reported data are often optimistic.

The thermal conductivity data for the isotopic compounds are very limited. However, enough data are presented to allow an educated guess as to the conductivity of most of the compounds. Comparatively speaking, the oxides will have lower conductivities than the pure metal. The carbides will usually exhibit "good" conductivity. The data presented in Table 5 show that all the compounds have poor thermal conductivity and a very large temperature gradient can be expected in a fuel pellet of reasonable size if pure material is used.

Table 5 presents some of the important properties for proposed matrix materials for Cm-242. The most desirable combination of properties is low density, a melting point of 2500 to 3000° F, high thermal conductivity and preferably the ability to alloy with curium. In addition to these important properties, nuclear properties and re-entry burnup ability must be considered. From consideration of all of these properties, it is evident that any given material chosen for a matrix will be a compromise. Graphite has poor nuclear properties for use with curium because of ( $\alpha, n$ ) reactions, and is also one of the better known ablative materials\* so that its use is doubtful despite its attractive conductivity and density.

Gold and its alloys melt at a low temperature and are extremely heavy but have good thermal conductivity. Copper is less dense but also melts at a low temperature. Iron melts in the right range, is not prohibitively heavy and has fair thermal conductivity. Nickel has properties similar to iron with the exception of a lower conductivity and will alloy with curium. Molybdenum is of average density and has high conductivity, but burnup difficulties are anticipated. In addition, the oxidation of molybdenum at temperatures above 1200° F is essentially an explosive reaction. The heat released by rapid oxidation further increases the temperature, bringing about a consequent increase in oxidation rate. This could cause a serious contamination problem in the event of a launch pad abort. Of the remaining materials, vanadium appears to be a possibility with low density and somewhat better thermal conductivity than nickel. Palladium is also worthy of consideration.

Figure 22 also shows the surface temperature of a fuel slug for several ratios of the matrix materials mixed with curium. These curves present the case of a radiant boundary with no convective or

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\* "Iron Age," November 12, 1959, p. 155

TABLE 5  
Properties of Chemical Forms of Curium-242

<u>Isotope or Compound</u>	<u>Molecular Weight</u>	<u>Density (gm/cc)</u>	<u>Melting Point (°C)</u>	<u>Boiling Point (°C)</u>	<u>Power Density (watts/cc)</u>	<u>Thermal Conductivity (Btu/hr ft °F)</u>	<u>Solubility in Water</u>	<u>Half Life Days</u>
Cm-242		13.5	950±25		1620 (122 watts/gm)	7.5		162.5
CmO <sub>2</sub>	274	11.75*	1500		1245			
Cm <sub>2</sub> O <sub>3</sub>	290	10.70*	1500		1169		Soluble	
CmF <sub>3</sub>	299	9.70*	600		943		Soluble	
CmCl <sub>3</sub>	384.5	5.80*	500	Sublimes at 700- 800	488		Soluble	
CmBr <sub>3</sub>	482	7.00	400	Volatile at 700- 800	422			
CmC	254	10.0	2000		1143		Reacts with A <sub>2</sub> O to form Cm (OH) <sub>3</sub>	
Cm <sub>2</sub> (CO <sub>4</sub> ) <sub>3</sub>	664						Insoluble	
Cm <sub>2</sub> (C <sub>2</sub> O <sub>4</sub> ) <sub>3</sub>							Very in- soluble	
Cm(NO <sub>3</sub> ) <sub>3</sub>	428						Soluble	
Cm(OH) <sub>3</sub>	293						Soluble	
Cm-30 Ni by wt		9.02			34.9			
Cm-20 Ni by wt		9.05			51.7	~ 10		

\*Extrapolated values.

conductive heat transfer. The fuel slug has a power of 1000 thermal watts and the length-to-diameter ratio for all mixtures is 1:1. The relative emissivities of platinum and graphite are the natural values whereas those of the remaining materials are obtained by considering a surface coating.

As an overall compromise of the many contradictory properties desired of the fuel form, it is recommended that an alloy of nickel and curium (20 Ni, 1 Cm by weight) be employed in the Type C generator. The generator has been designed on this basis.

### III. COMPARISON OF DESIGNS CONSIDERED

A reiteration of the advantages and disadvantages of each of the three designs studied substantiates the conclusion that the Type C generator is best suited for intermediate length (six months to a year) space missions.

The Type B generator was designed to operate at a cold junction temperature of 305° F. Approximately 250 pairs of thermoelectrics were required to produce 100 watts at 28 volts, making allowances for contact resistance in the thermoelements. The weight of this generator is estimated at approximately 150 pounds. This weight-to-power ratio of more than one pound per watt is very poor for a weight minimized generator. Although the cold junction temperature gave a theoretical thermoelectric efficiency of 6.6% compared to 5.20% for the split shield generator, the increased surface area lowered the thermal efficiency to 78%, compared to 95% for the recommended configuration. Thus, the internally shielded generator weighed about twice as much as the split shield generator for the same power output. If the voltage of the chosen configurations were raised to 28 volts, there would be approximately a 100% increase in the number of thermoelectrics, accompanied by increases in overall size and weight. However, since a converter is to be used to supply various voltages, the lower voltage does not seriously penalize the Type C generator performance.

The Type A generator was about intermediate in weight when compared with the other two generators. The heaviest configuration was estimated at just over 110 pounds. The thermoelectric efficiency was highest in the Type A design because of a cold junction temperature of about 180° F. However, there were other reasons for discarding this design. The need for dumping the heat from the satellite surface would require that the design of the satellite be based, to a large extent, on the demands of the power supply. Other reasons included the use of a pump, a moving part which decreases the overall reliability of the generator, the lack of experimental knowledge about fluid flow in null gravity and the shielding problems. Still another consideration is the heating of the skin of the vehicle which might affect the operation of the instruments within the generator.

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#### IV. RECOMMENDATIONS FOR FUTURE STUDY

There are two definite areas in which improvement can be made in the weight-to-power ratio. The first of these is in the mounting of the thermoelectrics, where much work is now being done toward the improvement of bonding methods. Reduction of weight could be taken as a secondary aim.

The largest saving, however, should be possible in the design of the fuel block. It is open to conjecture that a few grams of fuel should require 25% or more of the weight of the complete generator. Since the primary reason for the heavy fuel block is impact resistance, the block should be redesigned so it will break apart on impact. However, it should break into definite fragments which would contain the radioactive material. The breaking of the connections between fragments would take up part of the kinetic energy of the block and since the surface areas of the pieces are small, shear stress--the primary cause of failure on impact--will be minimized.

A possible design would be a number of small containers connected by supporting struts which would break on impact. These containers would be surrounded by a molybdenum shell to present a uniform temperature surface to the hot junction. It is recommended, therefore, that a design and test program be initiated to improve the heat source design.

Testing will also be required to determine the optimum position of the heat source with regard to dumping heat through the thermal shutter. It may be necessary to incorporate a reflector to direct more heat toward the shutter area.

The building of a prototype and a demonstration of its continued operation over a period of time at least equivalent to any proposed mission life are required to demonstrate the integrity and reliability of the generator.

## APPENDIX A

## SHIELDING DESIGN METHODS

Since the basis of the radiative boundary design was the shielding required for the fast neutrons produced by the spontaneous fission and ( $\alpha$ , n) reactions, three methods were employed in determining the dose. The first method employed was the Albert-Welton point kernel method<sup>(1)</sup>. Average penetration characteristics of neutrons in a shield composed of water and other elements are obtained by this calculation. This method employs the removal cross section, i. e., all absorption processes are lumped as a single absorption process, to describe the rate of neutron removal through a given material. Since the thickness of the hydrogenous material is somewhat less than that required to validate the use of removal cross sections, this method will result in a slight underestimate of the exterior dose rate. When the resultant hardened spectrum is determined, the number of neutrons at each energy level is multiplied by the corresponding relative biological effectiveness at that energy. Thus, a plot of dose versus energy is obtained and subsequently integrated over the entire energy spectrum. In the calculations to determine the total dose, the energy spectrum of fission neutrons as presented by Rockwell<sup>(2)</sup> was employed as the initial source spectrum for both the spontaneous fission and ( $\alpha$ , n) neutrons.

The bulk of the shielding calculations, however, was performed using the moments method and the data given by Aronson, R.<sup>(3)</sup>. The sources considered were point isotropic sources with neutrons

- (1) Albert, R. D., and Welton, T. A., Report WAPD-15, 30 November 1950.
- (2) Rockwell, T. III, "Reactor Shielding Design Manual," TID-7004, 1956.
- (3) Aronson, R., Certaine, J., Goldstein, H., and Preiser, S., "Penetration of Neutrons from a Point Isotropic Fission Source in Water," NYO-6267, 22 September 1954.

emerging in a fission spectrum. These results are compared for order of magnitude to those obtained for hydrogen of density 0.111 gm/cm (density of hydrogen in water)<sup>(4)</sup>. Dose rates are shown for various power levels at three different distances from the source in Figs. 7 and 8.

In the Albert-Welton point kernel method, the neutron flux = constant  $\times e^{-\epsilon x}$ ; for a point source; neutron flux =  $\frac{\text{constant}}{4 \pi r^2} e^{-\epsilon x}$

where

$x$  = shield thickness

$\epsilon$  = a constant = removal cross section

$r$  = distance from point source,  $x$

The theoretical hydrogen total cross section is given by:

$$\sigma_H = \frac{3\pi}{4} \left[ K^2 + \left( \frac{-1}{a_t} + \frac{1}{2} n_t K^2 \right)^2 \right]^{-1} + \frac{\pi}{4} \left[ K^2 + \left( \frac{-1}{a_s} + \frac{1}{2} n_s K^2 \right)^2 \right]^{-1} \text{ cm}^2$$

where

$K$  = wave number of neutron in center-of-mass system =  $1/\lambda$

$$a_t = 0.528 \times 10^{-12} \text{ cm} \quad r_s = 1 \times 10^{-13} \text{ cm} \quad \lambda = 2.86 \times 10^{-9} \sqrt{E} \text{ ev}$$

$$a_s = 2.375 \times 10^{-12} \text{ cm} \quad r_t = 1.56 \times 10^{-13} \text{ cm}$$

A good approximation between 2 and 12 mev is

$$\sigma_H = \frac{5.13}{E^{0.725}} \text{ barns} \quad E \text{ in mev}$$

(4) Aronson, R., "Neutron Penetration in Hydrogen," NDA-15C-39, 1 November 1954.

If the neutron fission spectrum as empirically determined by Los Alamos is multiplied by the Albert-Welton neutron attenuation function, the hardened fission spectrum at point x is determined. Thus,

$$N(x) = 0.484 e^{-E} \sinh \sqrt{2E} e^{-\epsilon x}$$

where

$$\Sigma = \Sigma_H + \Sigma_O$$

$$\Sigma_H = \frac{\rho N_a \sigma_H}{A} = \text{macroscopic hydrogen removal cross section}$$

$$N_a = \text{Avogadro's number } 6.02 \times 10^{23} \text{ atoms/gram-atom}$$

$$A = \text{atomic weight}$$

$$\rho_H = \text{density, gm/cm}^3$$

$$\Sigma_O = \text{oxygen removal cross section empirically determined at 0.91 barn.}$$

Thus, the total neutron dose over neutron energies from 0.7 to 10 mev can be determined by graphical integration of a curve obtained by multiplying the hardened neutron spectrum which penetrates 10 inches of water, by the neutron flux-dose conversion relation.

In the moments method, the Boltzmann equation was solved for penetration of neutrons from a point isotropic fission source in water. This method consists of replacing the Boltzmann equation for the flux from a plane isotropic fission source by a set of simultaneous integral equations. These equations are in terms of the energy variable lethargy ( $u = \ln E/E_0$ ) for the spatial moments of the Legendre coefficients of the flux, where  $E_0$  = arbitrary fixed energy that was chosen as 0.33 mev for convenience.

Hydrogen collisions with neutrons were taken as elastic scattering that is, isotropic in the center-of-mass system. All oxygen collisions other than elastic scattering were considered absorptions. Neutrons

from inelastic scattering and (n, 2n) reactions were assumed to have energies too low to contribute significantly to the neutron dose. The dose versus shield thickness for both water and hydrogen ( $\rho_H = 0.111$  gm/cc) is shown in Fig. A-1.

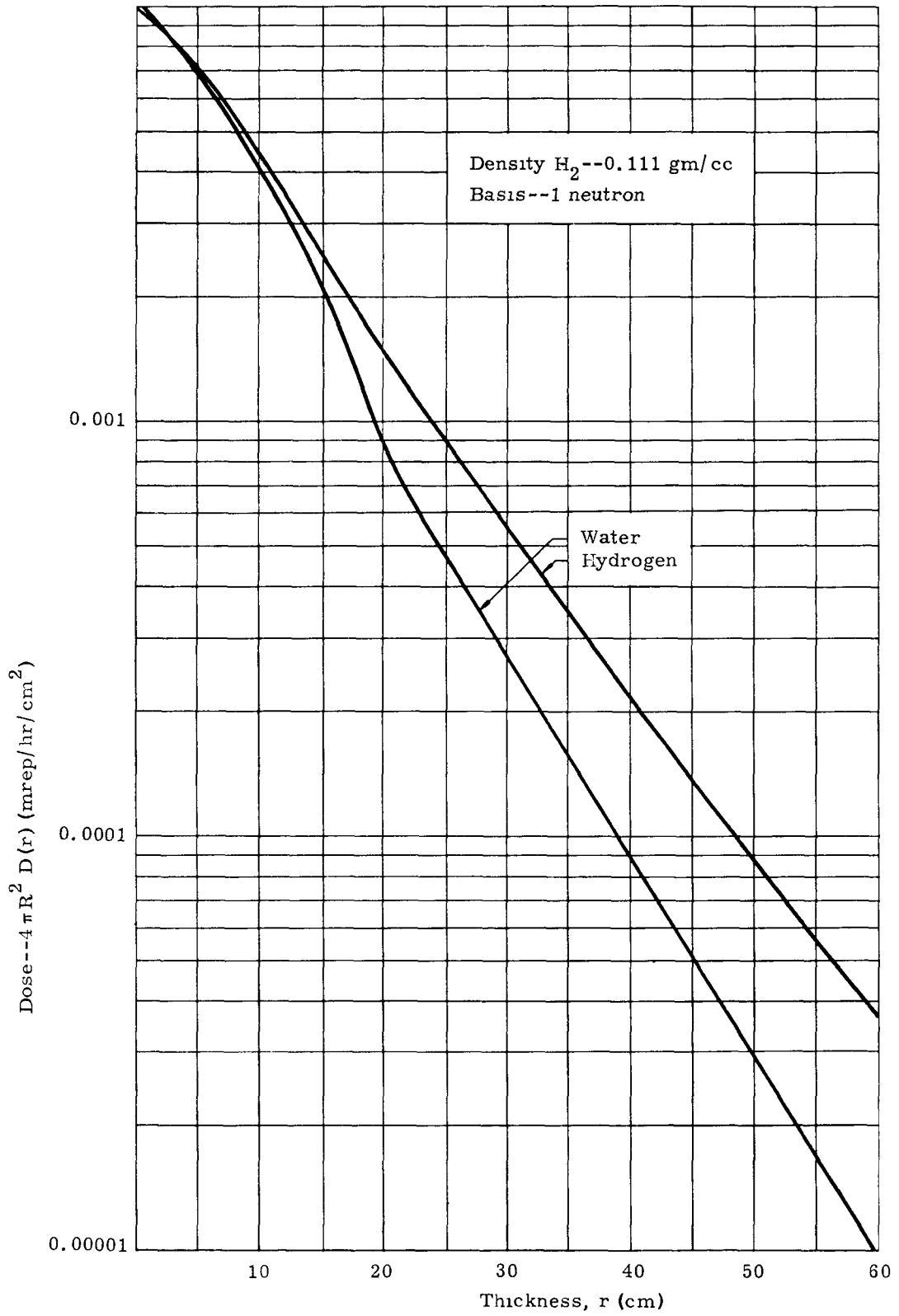


Fig. A-1. Dose Versus Shield Thickness

APPENDIX B

THERMOELECTRIC ANALYSIS PROCEDURE MANUAL

1. Optimum Segmentation Temperature

The optimum segmentation temperatures for both the n and p thermoelectric elements are determined by plotting the resultant figure of merit versus segmentation temperature. The maximum on the curve is then the point of optimum segmentation. Figure 17 shows this curve for both sodium- and bismuth-doped Pb Te for a hot junction temperature of 1000° F and a cold junction temperature of 305° F.

2. General Design

The general design equations employed in determining the thermoelectric efficiency are listed.

$T_C$	$T_S$	$T_H$	$T_C$	$T_S$	$T_H$
Pb Te 0.1% Bi	Pb Te 0.2% Bi		Pb Te 0.02%	Pb Te 0.07% Na	
305° F	575° F	1000° F	305° F	400° F	1000° F

$$e_{1000} - e_{575} = e_1$$

$$e_{575} - e_{305} = e_2$$

$$e' = \frac{e_1 + e_2}{\Delta T} \quad \text{similar calculation for the Na doped element}$$

$$|e'| + |e''| = e = \text{thermoelectric power of couple, volts/°C}$$

$\rho$  = the specific electric resistance (ohm - cm), found by integrating for each element over the temperature range from 1000 to 305° F.

$$K\rho = \left[ (K' \rho')^{1/2} + (K'' \rho'')^{1/2} \right]^2$$

where

$K$  = thermal conductivity, watt/cm °C = 0.02 watt/cm °C

Optimizing with respect to external and internal resistance yields:

$$x_m = \sqrt{1 + \frac{T_h e^2}{K\rho}}$$

The maximum efficiency is defined by:

$$\eta = \frac{1}{\frac{1 + x_m}{x_m} \frac{T_h}{\Delta T} + \frac{(1 + x_m)^2}{x} \frac{K\rho}{e^2 \Delta T}}$$

$T_h$  = hot junction temperature, degrees absolute

$$\Delta T = T_h - T_c.$$

## APPENDIX C

## FUEL CONTAINER THERMAL ANALYSIS

The temperature distribution in the heat source has a steady-state radial distribution in cylindrical coordinates  $(r, \theta, Z)$  given by

$$\frac{\partial^2 t}{\partial r^2} + \frac{1}{r} \frac{\partial t}{\partial r} + \frac{W}{K} = 0, \text{ where } t = \text{temperature.}$$

$$\frac{\partial^2 t}{\partial r^2} = -\frac{W}{K} - \frac{1}{r} \frac{\partial t}{\partial r}; \text{ integrating twice,}$$

$$t = -\frac{W}{4K} r^2 + C_1 \ln r + C_2.$$

$$\frac{dt}{dr} = 0 \text{ at } r = 0, \quad t = t_2 \text{ at } r = r_2$$

$$C_1 = 0, \quad C_2 = t_2 + \frac{W}{4K} r_2^2$$

$$t = -\frac{W}{4K} r^2 + t_2 + \frac{W}{4K} r_2^2$$

$$t - t_2 = \frac{W}{4K} (r_2^2 - r^2)$$

$$\Delta t = \text{Max at } (r = 0) = \frac{W}{4K} r_2^2$$

The temperature distribution in the ablative material with no internal heat source and steady-state conditions is:

$$\frac{\partial^2 t}{\partial r^2} + \frac{1}{r} \frac{\partial t}{\partial r} = 0$$

$$q = K \frac{dt}{dr} A = -K \frac{(t_2 - t_1) 2\pi L}{\ln(r_2/r_1)}.$$

$$\frac{\partial t}{\partial r} = \frac{t_2 - t_1}{\ln(r_2/r_1)} \frac{1}{r}$$

1. Surface Temperature

The radiation between a sphere or cylinders and an enclosing sphere or cylinder when each body has a different emissivity is given by:

$$q = \frac{\sigma A_1 (T^4 - \theta^4)}{\frac{1}{\epsilon_1} + \left(\frac{A_1}{A_2}\right) \left(\frac{1}{\epsilon_2} - 1\right)} .$$

The variation of temperature of the fuel container with surface area is shown in Fig. 9.

## APPENDIX D

IBM-709 COMPUTER CODE PROGRAM  
GENERALIZED ISOTOPE-POWERED THERMOELECTRIC GENERATOR

## A. GENERATOR CALCULATION CODE

The purpose of this computer program is to outline the general range of parameters for any given design requirement. Since it is based on a spherical generator shape, the applicability of the calculated values to the actual design values will depend on how closely the design approaches a sphere.

The code is basically a repetitive 33-step operation, based on 21 equations, including one trial and error determination. Calculating by hand, each series of 33 steps takes about two hours. Using the program, approximately four minutes of machine time are required for a series of 56 calculations. The time per calculation decreases with the increasing number of calculations.

The generator configuration used by the program consists of three concentric spheres. The smallest is the heat source which radiates its heat to the second sphere or the hot junction. Between the outer sphere (cold junction) and hot junction are uniformly distributed thermoelectric elements surrounded by insulation. Temperature distributions are also assumed to be uniform.

The series of 33 steps proceeds as follows. The first nine steps are devoted to selecting the operating temperatures and the materials with their particular characteristics.

Select:

- (1) Fuel material--this specifies the power density and specific gravity.
- (2) Clad material--characteristics needed here are density, emissivity and temperature. The thermal characteristics of the clad material determine the maximum temperature of the inner sphere.
- (3) Support material--the cross sectional area and the density of the support material are required to find the total weight. It is assumed that the heat conducted through these supports is negligible.
- (4) Hot junction material--density, emissivity and shell thickness are necessary.
- (5) Thermoelectric material--density and hot junction temperature are determined by this selection.
- (6) Cold junction material--density, infrared emissivity, thickness and absorptivity for solar radiation are determined.

- (7) Insulation material--density and thermal conductivity are the properties of interest.
- (8) Power output.
- (9) Cold junction temperature.

The actual computation begins with Step 10. The equations used are tabulated following the calculation procedure.

The following are computed using the equations indicated.

- (10)  $Z_c$  - composite figure of merit - eq. (1)
- (11)  $X_m$  - resistance ratio - eq. (2)
- (12)  $\eta_{el}$  - thermoelectric efficiency - eq. (3)
- (13)  $q_{res}$  - reversible energy rate (i. e., heat transmitted through the thermoelectrics due to the Pelter effect) - eq. (4)
- (14)  $A_{ther}$  - thermoelectric area - eq. (5)
- (15)  $q_{ther}$  - heat conducted through thermoelectrics - eq. (6)
- (16) Select  $\eta_{th}$  - thermal efficiency - ( $\sim 0.9$ )
- (17)  $A_3$  - cold junction area - eq. (7)
- (18)  $A_2$  - hot junction area - eq. (8)
- (19)  $q_{ins}$  - heat conducted through insulation - eq. (9)
- (20)  $\eta_{th}$  - thermal efficiency - eq. (10)
- (21)  $q_s$  - thermal power requirement - eqs. (11) and (12)

As a computational check, the results of the calculations by each should be approximately equal (< 3% difference).

- (22)  $A_1$  - surface area of source cladding - eq. (13)
- (23)  $W_s$  - source weight - eq. (14)
- (24)  $W_c$  - clad weight - eq.(15)
- (25)  $W_{sup}$  - support weight - eq.(16)
- (26)  $W_{is}$  - weight of inner shell (hot junction) - eq.(17)
- (27)  $W_{ther}$  - weight of the thermoelectrics - eq. (18)
- (28)  $W_{ther} \times 0.25$  - weight of electrical connectors
- (29)  $W_{ins}$  - weight of insulation - eq. (19)
- (30)  $W_{os}$  - weight of outer shell (cold junction - eq. (20)
- (31)  $\sum_i W_i$  - total weight - eq. (21)
- (32) Return to Step 9.
- (33) Repeat series until sufficient data are obtained for a plot of cold junction temperatures versus weight for any thermoelectric length.

### 1. Table of Equations Used in Program

$$Z = \frac{[e_N + e_P]^2}{\left[ \sqrt{k_P \rho_P} + \sqrt{k_N \rho_N} \right]^2} \quad (1)$$

where  $e$  = Seebeck coefficient (volts/°C)

$k$  = thermal conductivity of the thermoelectric  $\left( \frac{\text{watts}}{\text{cm } ^\circ\text{C}} \right)$

$\rho$  = electrical resistivity of the thermoelectrics (ohm-cm)

Subscripts P and N refer to P- and N-type thermoelectrics, respectively.

$$X_m = \sqrt{1 + Z \left( \frac{T_2 + T_3}{2} \right)} \quad (2)$$

where  $T_2$  = hot junction temperature

$T_3$  = cold junction temperature.

$$\eta_{el} = \frac{X_m [T_2 - T_3]}{(1 + X_m)T_2 + \frac{(1 + X_m)^2}{Z} - \frac{T_2 - T_3}{2}} \quad (3)$$

$$q_{res} = \left( \frac{1 + X_m}{X_m} \right) W_e \left( \frac{T_2}{T_2 - T_3} \right) \quad (4)$$

where  $W_e$  = the output power of the generator.

$$A_{ther} = \frac{\left[ 1 + \sqrt{\frac{k_N \rho_P}{k_P \rho_N}} \right] X_m}{e(T_2 - T_3) \frac{1 + X_m}{1 + X_m}} \sqrt{\frac{\rho_P^l}{\frac{k_N \rho_P}{k_P \rho_N} + \rho_N^l}} \frac{e(T_2 - T_3)}{W_e (1 + X_m)} \quad (5)$$

where  $e = |e_P| + |e_N|$

$l$  = length of the thermoelectrics.

$$q_{ther} = \frac{W_e (1 + X_m) \left[ \sqrt{\frac{\rho_P^l}{\frac{k_N \rho_P}{k_P \rho_N} + \rho_N^l}} \right] \left( k_P \sqrt{\frac{k_N \rho_P}{k_P \rho_N}} + k_N \right)}{e^2 (T_2 - T_3) \frac{X_m}{1 + X_m} l} \quad (6)$$

$$A_3 = \frac{4 W_e}{\eta_{el} \eta_{th}} \frac{1}{4 \sum_{ir} \sigma T_3^4 - (1 - \alpha_v) 1400 \left( \mu + \frac{\alpha_E}{\pi} \cos \xi \right) - 188.5 \sum_{ir}} \quad (7)$$

where  $\Sigma_{ir}$  = the infrared emissivity of the cold junction surface

$\sigma$  = the Stefan-Boltzman constant (watts/m<sup>2</sup> - °K<sup>4</sup>)

$(1 - \alpha_v)$  = absorptivity of the surface for solar radiation

$\mu$  = orbit orientation factor (equals 1 for polar orbit)

$\alpha_E$  = absorptivity for radiation from the earth

$\cos \xi$  = cosine of the geocentric angle of the satellite's orbit. All units are watts, meters and °K.

$$A_2 = \pi \left( \sqrt{\frac{A_3}{\pi}} - 2 \left[ l + 1.27 \right] \right)^2 \quad (8)$$

$l$  is in centimeters; 1.27 refers to the distance required for mounting the thermoelectrics.

$$q_{ins} = \frac{k_{ins} (T_2 - T_3) 4(\pi A_{ther})}{\left[ \ln \left( \frac{2r_3 \sqrt{\pi} - \sqrt{A_{ther}}}{2r_3 \sqrt{\pi} + \sqrt{A_{ther}}} \right) - \ln \left( \frac{2r_2 \sqrt{\pi} - \sqrt{A_{ther}}}{2r_2 \sqrt{\pi} + \sqrt{A_{ther}}} \right) \right]} \quad (9)$$

where  $k_{ins}$  = thermal conductivity of the insulation

$r_3$  and  $r_2$  = radii of cold and hot junction spheres, respectively.

$$\eta_{th} = \frac{1}{1 + \frac{q_{ins} \eta_{el}}{W_e}} \quad (10)$$

$$q_s = q_{ins} + q_{ther} + q_{res} \quad (11)$$

$$q_s = \frac{W_e}{\eta_{el} \eta_{th}} \quad (12)$$

$$A_1 = \frac{A_2 q_s}{\Sigma_j \left[ \sigma A_2 (T_1^4 - T_2^4) - \left( \frac{1}{\Sigma_2} - 1 \right) q_s \right]} \quad (13)$$

where  $\Sigma$  = surface emissivity

Subscripts 1 and 2 = source cladding surface and hot junction, respectively.

$$W_s = \frac{W_e}{\eta_{th} \eta_{el}} \quad \frac{\rho_s}{P} \quad (14)$$

where  $\rho_s$  = source density (gm/cm<sup>3</sup>)

$P$  = power density (watts/cm<sup>3</sup>).

$$W_c \left[ \frac{\pi D_1^3}{6} - \left( \frac{W_e}{\eta_{el} \eta_{th} P} + \frac{q_s(12)}{100} \right) \right] \rho_{clad} \quad (15)$$

where  $D_1$  = diameter of the source sphere

$q_s(12)$  = thermal power calculated in eq. (12)

$\frac{q_s(12)}{100}$  = void space to allow for helium accumulation.

$$W_{sup} = (D_2 - D_1) A_{sup} \rho_{sup} \quad (16)$$

where  $A_{sup}$  = cross-sectional area of the source supports

$\rho_{sup}$  = density of the supports.

$$W_{is} = \pi D_2^2 t_{is} \rho_{is} \quad (17)$$

where  $t_{is}$  = thickness of the inner shell (hot junction)

$\rho_{is}$  = density of the shell.

$$W_{ther} = A_{ther} l \rho_{ther} \quad (18)$$

where  $\rho_{ther}$  = thermoelectric density.

$$W_{ins} = (\pi D_2^2 - A_{ther}) l \rho_{ins} \quad (19)$$

where  $\rho_{ins}$  = insulation density.

$$W_{os} = (\pi D_2)^2 t_{os} \rho_{os}$$

where  $t_{os}$  = outer shell thickness

$\rho_{os}$  = outer shell density.

$$\text{Total weight} = W_s + W_c + W_{sup} + W_{is} + 1.25 W_{ther} + W_{ins} + W_{os}. \quad (21)$$

## B. INPUT DATA FOR THE GENERATOR CODE

The data loaded into the machine consists of 10 cards containing fixed parameters plus an additional number of cards determined by the number of variations of each of the two variables. In this application of the code, seven different cold junction temperatures and eight different thermoelectric lengths were used. This required 144 additional input cards. The information contained on the cards is summarized here. The key to the symbols is found in the following code listing:

<u>Card No.</u>	<u>Format</u>	<u>Information</u>
1	1P2E 12.5	PDENS, DENSO
2	1P3E 12.5	DENCL, EMISCL, T1
3	1P2E 12.5	DENSU, ASUP
4	1P3E 12.5	DENIS, THKIS, EMISTS
5	1P2E 12.5	DENTH, T2
6	1P2E 12.5	DENOS, ABSOS, THKOS
7	1P2E 12.5	DENINS, CONINS
8	1P2E 12.5, 2I12	ETATH, EPS, NOUT, NEXT (NOUT and NEXT = 0)
9	1P3E 12.5	ALPHAE, U, C
10	I12	IMAX*

\* Although IMAX is defined as the index for output power, it is used as the index for thermoelectric length since the power level is generally fixed for any given generator design.

The other 144 cards consist of eight identical sets of 18 as follows:

<u>Card No.</u>	<u>Format</u>	<u>Information</u>
1	1PE 12.5, I12	THL (I), NO
2	1PE 12.5	WE (I)
3, 3'	1P6E 12.5	T3 (L, I)
4, 4'	1P6E 12.5	TPP (L, I)
5, 5'	1P6E 12.5	TPN (L, I)
6, 6'	1P6E 12.5	DENP (L, I)
7, 7'	1P6E 12.5	DENN (L, I)
8, 8'	1P6E 12.5	CCNP (L, I)
9, 9'	1P6E 12.5	CCNN (L, I)
10, 10'	1P6E 12.5	EIR (L, I)

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C          SPACE POWER SOURCE PROGRAM
C
C SOURCE DENSITY # DENSO
C POWER DENSITY # PDENS
C CLAD DENSITY # DENCL
C CLAD EMISSIVITY # EMISCL
C CLAD TEMP # T1
C SUPPORT DENSITY # DENSU
C AREA OF SUPPORT # ASUP
C INNER SHELL DENSITY # DENIS
C INNER SHELL THICKNESS # THIKIS
C INNER SHELL EMISSIVITY # EMISIS
C THERMOELECTRIC DENSITY # DENTH
C LENGTH OF THERMOELECTRIC # THL%I□
C TEMPERATURE OF INNER SHELL # T2
C INSULATION DENSITY # DENINS
C INSULATION CONDUCTIVITY # CONINS
C DENSITY OF OUTER SHELL # DENOS
C ABSORPTIVITY OF OUTER SHELL # ABSOS
C THICKNESS OF OUTER SHELL # THIKOS
C INDEX FOR OUTPUT POWER # I,MAXIMUM # IMAX
C INDEX FOR T3 FOR EACH POWER # L,MAXIMUM # NO
C TEMPERATURE OF OUTER SHELL # T3%L,I□
C ELECTRICAL RESISTIVITY OF P # DENP%L,I□
C ELECTRICAL RESISTIVITY OF N # DENN%L,I□
C THERMOELECTRIC POWER OF P # TPP%L,I□
C THERMOELECTRIC POWER OF N # TPN%L,I□
C CONDUCTIVITY OF P # CONP%L,I□
C CONDUCTIVITY OF N # CONN%L,I□
C EMISSIVITY OF OUTER SHELL # EIR%L,I□
C OUTPUT POWER # WE%I□
C COSINE OF GEOCENTRIC ANGLE # C
C REFLECTIVITY OF EARTH # ALPHAE
C COMPOSITE FIGURE OF MERIT # ZC
C RESISTANCE RATIO # XM
C THERMOELECTRIC EFFICIENCY # ETATH
C REVERSIBLE ENERGY RATE # QRES
C THERMOELECTRIC AREA # ATHER
C THERMOELECTRIC HEAT RATE # QOTHER
C THERMAL EFFICIENCY # ETATH
C OUTER SHELL AREA # A3
C INNER SHELL AREA # A2
C INSULATION HEAT RATE # QINS
C OUTSIDE AREA OF CLAD # A1
C CLAD WT # WTC
C INNER SHELL WT # WTIS
C SOURCE HEAT RATE #QS6 AND QS7
C THERMOELECTRIC WT # WTTHER
C WT OF ELECTRICAL CONNECTORS # WTT25
C INSULATION WT # WTINS
C OUTER SHELL WT # WTOS
C TOTAL WT # SUMWT
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C ECLIPSE FACTOR # U
C CONVERGENCE CRITERION FOR THERMAL EFFICIENCY # EPS1
C
  DIMENSION WE%20, T3%20, 20, TPP%20, 20, TPN%20, 20, DENP%20, 20,
1DENN%20, 20, CONP%20, 20, CONN%20, 20, LMAX%20, EIR%20, 20, THL%20
  READ 200, PDENS, DENSO
  READ 201, DENCL, EMISCL, T1
  READ 200, DENSU, ASUP
  READ 201, DENIS, THIKIS, EMISIS
  READ 200, DENTH, T2
  READ 200, DENINS, CONINS
  READ 201, DENOS, ABSOS, THIKOS
  READ 207, ETATH, EPS, NOUT, NEXT
  READ 201, ALPHAE, U, C
  READ 203, IMAX
  DO 205 I#1, IMAX
  READ 206, THL%I, NO
  READ 208, WE%I
  READ 204, %T3%L, I, L#1, NO
  READ 204, %TPP%L, I, L#1, NO
  READ 204, %TPN%L, I, L#1, NO
  READ 204, %DENP%L, I, L#1, NO
  READ 204, %DENN%L, I, L#1, NO
  READ 204, %CONP%L, I, L#1, NO
  READ 204, %CONN%L, I, L#1, NO
  READ 204, %EIR%L, I, L#1, NO
  LMAX%I#NO
205 CONTINUE
200 FORMAT%1P2E12.5
201 FORMAT%1P3E12.5
202 FORMAT%1P4E12.5
203 FORMAT%I12
204 FORMAT%1P6E12.5
206 FORMAT%1PE12.5, I12
207 FORMAT%1P2E12.5, 2I12
208 FORMAT%1PE12.5
  ABO#ABSOS
  WRITE OUTPUT TAPE 10, 300
300 FORMAT%43H1 DESIGN PARAMETERS FOR SPACE POWER SOURCES///12H INPUT
  1DATA
  WRITE OUTPUT TAPE 10, 301, PDENS, DENSO
301 FORMAT%8H0 SOURCE//19H POWER DENSITY #1PE12.5//13H DENSITY #
  11PE12.5
  WRITE OUTPUT TAPE 10, 302, DENCL, EMISCL, T1
302 FORMAT%6H0 CLAD//13H DENSITY #1PE12.5//16H EMISSIVITY #1PE12
  1.5//8H T1 #1PE12.5
  WRITE OUTPUT TAPE 10, 303, DENSU, ASUP
303 FORMAT%9H0 SUPPORT//13H DENSITY #1PE12.5//10H AREA #1PE12.5
  WRITE OUTPUT TAPE 10, 304, DENIS, THIKIS, EMISIS
304 FORMAT%13H0 INNER SHELL//13H DENSITY #1PE12.5//15H THICKNESS
  1 #1PE12.5//16H EMISSIVITY #1PE12.5
  WRITE OUTPUT TAPE 10, 305, DENTH, T2
305 FORMAT%16H0 THERMOELECTRIC//13H DENSITY #1PE12.5//8H T2 #1PE12.

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15□
WRITE OUTPUT TAPE 10,306,DENINS,CONINS
306 FORMAT%12H0 INSULATION//13H DENSITY #1PE12.5//18H CONDUCTIVI
ITY #1PE12.5□
WRITE OUTPUT TAPE 10,307,DENOS,ABSOS,THIKOS
307 FORMAT%13H0 OUTER SHELL//13H DENSITY #1PE12.5//18H ABSORPTIV
DO 309 I#1,IMAX
NO#LMAX%I□
ITY #1PE12.5//15H THICKNESS #1PE12.5□
WRITE OUTPUT TAPE 10,308,WE%I□,THL%I□,%T3%L,I□,TPP%L,I□,TPN%L,I□,D
1ENP%L,I□,DENN%L,I□,CONP%L,I□,CONN%L,I□,EIR%L,I□,L#1,NO□
308 FORMAT%16H0 OUTPUT POWER #1PE12.5//17H0 THERMO LENGTH #1PE12.5//72
1H T3 TP-P TP-N DEN-P DEN-N CON-P CON-N
2EMIS //1P8E9.2□□
309 CONTINUE
WRITE OUTPUT TAPE 10,3091,ALPHAE,U,C
3091 FORMAT%16H0 REFLECTIVITY #1PE12.5//18H ECLIPSE FACTOR #1PE12.5//1
10H COSINE #1PE12.5□
I#1
8 WRITE OUTPUT TAPE 10,9,WE%I□
9 FORMAT%16H1 OUTPUT POWER #1PE12.5□
IF%SENSE SWITCH 3□41,40
41 PRINT 9,WE%I□
40 L#1
STORE#ETATH
10 ESQ#%TPP%L,I□&TPN%L,I□&%TPP%L,I□&TPN%L,I□□
ZC#ESQ/%SQRTF%CONP%L,I□*DENP%L,I□□&SQRTF%CONN%L,I□*DENN%L,I□□□**
12.□
EPS1#1.E15
DELT#T2-T3%L,I□
XM#SQRTF%1.&%T2&T3□/2.□*ZC□
XM1#1.&XM
ETAEL#%XM*DELT□/%XM1*T2&XM1*XM1/ZC-DELT/2.□
QRES#%XM1*WE%I□*T2□/%XM*DELT□
SR#SQRTF%CONN%L,I□*DENP%L,I□□/%CONP%L,I□*DENN%L,I□□□
FACTOR#%DENP%L,I□*THL%I□□/SR&DENN%L,I□*THL%I□□/%ESQ*DELT*DELT*XM
1□/%WE%I□*XM1*XM1□□
ATHER#FACTOR*%1.&SR□
QTHER#%FACTOR*%CONP%L,I□*SR&CONN%L,I□□*DELT□/THL%I□
SIGMA#5.67E-8
IF%SENSE SWITCH 3□15,20
15 PRINT 151
151 FORMAT%13H0 THERMAL EFF//□
NA#1
20 ETATH1#ETATH
NA#NA&1
THINS#THL&1.27
EPS2#EPS1
A3#%4.*WE%I□□/%ETAEL*ETATH□□/%4.*EIR%L,I□*SIGMA*T3%L,I□**4. -ABO*
11400.*%U& ALPHAE*C/3.141593□-188.5*EIR%L,I□□
A3#A3*1.E4
A2#3.141593*%SQRTF%A3/3.141593□-2.*THINS□**2.□

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R3#SQRTF%A3/12.56637□
R2#SQRTF%A2/12.56637□
D3#2.*R3
D2#2.*R2
SATHER#SQRTF%ATHER□
QINS# CONINS*DELT*7.089816 *SATHER/LOGF%D3*1.772454-SATHER□*%D2
1*1.772454&SATHER□/%D3*1.772454&SATHER□/%D2*1.772454-SATHER□□
ETATH#1./%1.&QINS*ETAEL/WE%I□□
EPS1#EPS*ETATH
IF%SENSE SWITCH 3□23,22
23 PRINT 230,ETATH
230 FORMAT%1PE12.5□
22 IF%ABSF%ETATH-ETATH1□-EPS1□30,30,500
500 IF%ABSF%EPS1□-ABSF%EPS2□□20,501,501
501 IF%NA-101 □502,505,505
502 IF%ETATH-ETATH1□503,503,504
503 ETATH#ETATH-.05
GO TO 20
504 ETATH#ETATH&.05
GO TO 20
505 WRITE OUTPUT TAPE 10,506,ETATH
506 FORMAT%15H NONCONVERGENT/22H THERMAL EFFICIENCY #1PE12.5□
507 IF%SENSE SWITCH 3□508,31
508 PRINT 506,ETATH
GO TO 31
30 QS6#QINS&QOTHER&QRES
QS7#WE%I□/%ETAEL*ETATH□
SIGMA#5.67E-12
A1#%A2*QS7/EMISCL□/%SIGMA*A2*%T1**4.-T2**4.□-%1./EMISIS-1.□*QS7□
R1#SQRTF%A1/12.56637□
D1#2.*R1
WTS#QS7*DENS0/PDENS
WTC#%.523598*D1**3.-WTS/DENS0-QS7/100.□*DENCL
WTSUP#%D2-D1□*ASUP*DENSU
WTIS#3.141593* D2*D2 *THIKIS*DENIS
WTHER#ATHER*THL%I□*DENTH
WTTH25#.25*WTHER
WTINS#%3.141593*D2*D2-ATHER□*THINS*DENINS
WTOS#3.141593*D3*D3*THIKOS*DENS0
SUMWT#WTS&WTC&WTSUP&WTIS&WTHER&WTTH25&WTINS&WTOS
IF%SENSE SWITCH 3□51,50
51 PRINT 100,T3%L,I□
PRINT 510,SUMWT
510 FORMAT%12H TOTAL WT #1PE12.5□
50 WRITE OUTPUT TAPE 10,100,T3%L,I□
100 FORMAT%25H0 OUTSIDE RADIATOR TEMP #1PE12.5□
WRITE OUTPUT TAPE 10,101,ZC,XM,ETAEL,QRES,ATHER,QOTHER
101 FORMAT%29H COMPOSITE FIGURE OF MERIT #1PE12.5//20H RESISTANCE RA
1T10 #1PE12.5//29H THERMOELECTRIC EFFICIENCY #0PF10.4//24H REVERS
2IBLE HEAT RATE #1PE12.5//23H THERMOELECTRIC AREA #1PE12.5//28H T
3HERMOELECTRIC HEAT RATE #1PE12.5□
WRITE OUTPUT TAPE 10,102,A3,A2,QINS,ETATH
102 FORMAT%20H0 OUTER SHELL AREA #1PE12.5//20H INNER SHELL AREA #1PE1

```

```
12.5//24H  INSULATION HEAT RATE #1PE12.5//22H  THERMAL EFFICIENCY #
20PF10.4□
  WRITE OUTPUT TAPE 10,103,QS6,QS7,A1,WTS,WTC,WTSUP,WTIS,WTHER,WTTH
125,WTINS,WTOS,SUMWT
103  FORMAT%25H0 SOURCE HEAT RATE,EQ.6 #1PE12.5//25H  SOURCE HEAT RATE,
1EQ.7 #1PE12.5//24H  OUTSIDE AREA OF CLAD #1PE12.5//13H  SOURCE WT
2#1PE12.5//11H  CLAD WT #1PE12.5//14H  SUPPORT WT #1PE12.5//18H  IN
3NER SHELL WT #1PE12.5//21H  THERMOELECTRIC WT #1PE12.5//31H  WT OF
4 ELECTRICAL CONNECTORS #1PE12.5//17H  INSULATION WT #1PE12.5//18H
5 OUTER SHELL WT #1PE12.5//12H  TOTAL WT #1PE12.5□
  ETATH#STORE
1030 IF%L-LMAX%I□60,31,98
  60 L#L&1
  GO TO 10
  98 PRINT 1098,L
1098 FORMAT%4H1 L#I12,36H,TOO BIG-STATEMENT 1030. CHECK INPUT□
  GO TO 1000
  31 IF%I-IMAX□32,33,99
  32 I#I&1
  GO TO 8
  99 PRINT 1099,I
1099 FORMAT%4H1 I#I12,34H,TOO BIG-STATEMENT 31. CHECK INPUT□
  GO TO 1000
  33 WRITE OUTPUT TAPE 10,104
104  FORMAT%9H1 THE END□
1000 CONTINUE
  Y#FMPBF%X□
  STOP
  END%0,1,0,0,1□
```

## APPENDIX E

CALCULATION OF DIMENSIONS OF HEAT SOURCE --  
TYPE C GENERATOR

$$L = D = 2R$$

$$A = 2\pi R^2 + 2\pi R(2R) = 6\pi R^2$$

$$q = \sigma FA(T_1^4 - T_2^4)$$

$$F = \frac{1}{\frac{1}{\epsilon_1} + \frac{A_1}{A_2} \left(\frac{1}{\epsilon_2} - 1\right)}$$

where

L = length of heat source

D = diameter of heat source

R = radius of heat source

A = surface area

q = heat given off by source

F = view factor

$\epsilon$  = surface emissivity

T = surface temperature

$\sigma$  = Stefan-Boltzmann constant

Subscripts 1 and 2 = heat source surface and hot junction surface, respectively.

Take  $\epsilon_1 = \epsilon_2 = 0.9$

q at launch = 5800 watts

$$\frac{A_1}{A_2} \approx 0.1$$

$$T_1 = 1800^\circ \text{ F} \quad T_2 = 1000^\circ \text{ F}$$

$$F = \frac{1}{\frac{1}{0.9} + 0.1 \left( \frac{1}{0.9} - 1 \right)} = 0.8928$$

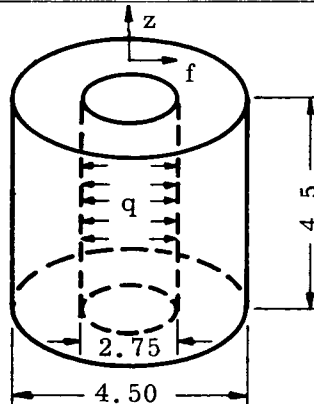
$$(5800)(3.415) = (0.1718)(0.8928)(6\pi R^2)(22.60^4 - 14.60^4)$$

$$R = \sqrt{\frac{(5800)(3.415)}{(0.1718)(215,438)(6\pi)(0.8928)}}$$

$$R = 2.139 \text{ inches}$$

$$D = L = 4.278 \text{ inches}$$

Calculation of Centerline Temperature of Fuel\*



$$\Delta T = \frac{-4q\ell}{k\pi^2} \sum_{m=0}^{\infty} \frac{F_0 \left[ (2m+1) \frac{\pi r}{\ell}; (2m+1) \frac{\pi b}{\ell} \right]}{(2m+1)^2 F_1 \left[ (2m+1) \frac{\pi a}{\ell}; (2m+1) \frac{\pi b}{\ell} \right]} \times \sin(2m+1) \frac{\pi Z}{\ell}$$

\* See Carslaw and Jaeger, "Conduction of Heat in Solids," p. 221

$\Delta T$  = temperature differential between centerline and outer surface

where

$r$  = radius

$Z$  = height

$T$  = temperature

$$F_0(x;y) = I_0(x) K_0(y) - K_0(x) I_0(y)$$

$$F_1(x;y) = I_1(x) K_0(y) + K_1(x) I_0(y)$$

$a$  = 1.375 inches

$b$  = 2.25 inches

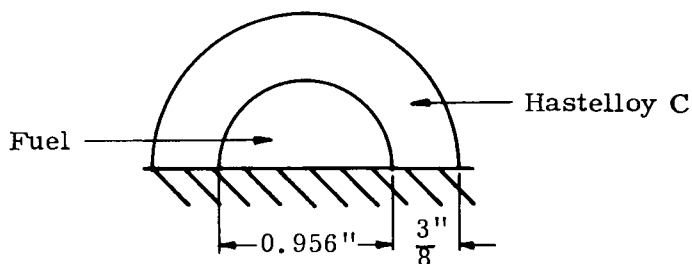
$l$  = 4.5 inches

$$q = \frac{(5800)(3.415)(144)}{(4.5)(2.75)} \text{ Btu/hr ft}^2$$

$k$  = 10 Btu/hr ft °F

Substituting into the equation and evaluating the summation gives:

$\Delta T$  = 562° F at the midpoint of the inner surface of the cylinder



For the temperature drop through one fuel pellet

$$V \Delta T = \frac{q r_2^2}{4k} \quad (\text{ends of core insulated})$$

$$q = \frac{5800}{5} \text{ watts} \times 3.415 \frac{\text{Btu}}{\text{watt hr}} \times \frac{1728 (4)}{\pi (0.956)^2 (2.4)} \text{ ft}^{-3}$$

$$r_2^2 = \frac{(0.956)^2}{(144) 4}$$

$$k = 14 \text{ Btu/hr ft } ^\circ \text{F}$$

$$\Delta T = \frac{(290) (3.415) (12)}{(14) (\pi) (2.4)} = 110^\circ \text{F}$$

For the drop through the Hastelloy C

$$q = -k 2\pi r l \frac{dT}{dr}$$

$$k = 8 \text{ Btu/hr ft } ^\circ \text{F}$$

$$\int \frac{dr}{r} = \frac{-2k\pi l}{q} \int dT$$

$$r_1 = 0.478 \text{ inch}$$

$$r_2 = 0.853 \text{ inch}$$

$$l \ln \frac{r_2}{r_1} = \frac{2k\pi l}{q} \Delta T$$

$$q = 1160 \text{ watts}$$

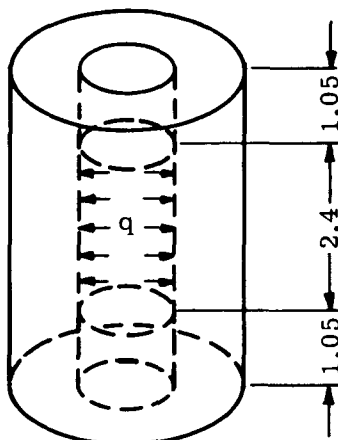
$$l = 2.4 \text{ inches}$$

$$\Delta T = \ln \left( \frac{r_2}{r_1} \right) \frac{q}{2k\pi l}$$

$$\Delta T = \frac{0.853}{0.478} \frac{(1160) (3.415) (12)}{(16) (\pi) (2.4)} = 0.5766 \frac{(1160) (3.415) (12)}{(16 \pi) (2.4)} = 215^\circ \text{F}$$

$$\Delta T_{\text{total}} = 325^\circ \text{F}$$

Since half of the surface loses no heat, the temperature drop calculated for the remaining portion should be approximately 1/2 of the actual drop. Thus, the real temperature drop should be approximately 650° F.



Same as Case 1 except that flux input is restricted to the middle 2.4 inches of the cylinder and part of the flux is transmitted through the top and bottom, reducing the heat input to the sides of the hollow cylinder.

$$\Delta T = \frac{-4q\ell}{k\pi} \sum_{m=0}^{\infty} \frac{F_0 \left[ (2m+1) \frac{\pi r}{\ell} ; (2m+1) \frac{\pi b}{\ell} \right]}{(2m+1)^2 F_1 \left[ (2m+1) \frac{\pi a}{\ell} ; (2m+1) \frac{\pi b}{\ell} \right]} \cos (2m+1) \frac{\pi L}{\ell} \sin (2m+1) \frac{\pi Z}{\ell}$$

where symbols are the same as Case 1

Values are the same except for

$$q = \frac{(5800)(3.415)}{2\pi(1.375)^2 + (2.4)\pi(2.75)}$$

$$L = 1.05 \text{ inches}$$

$$\Delta T \text{ at midpoint of inner surface} = 562^\circ \text{ F}$$

## APPENDIX F

THERMOELECTRIC CALCULATIONS FOR  
TYPE C GENERATOR

The thermoelectric cross sectional area as calculated in the code was  $391.7 \text{ cm}^2$  ( $60.71 \text{ in.}^2$ ). Starting from this figure, diameter and number of pairs, internal and optimum load resistance and voltage output are calculated.

The diameter of the positive element is taken as 1/2 inch.

$$\frac{\frac{A_p}{l_p}}{\frac{A_n}{l_n}} = \left[ \frac{k_n \rho_p}{k_p \rho_n} \right]^{1/2}$$

where

A = cross sectional area of thermoelement

l = length of thermoelement

$\rho$  = resistivity

Subscripts p and n refer to positive and negative elements respectively.

Since  $l_p = l_n$

$$\frac{A_p}{A_n} = \left[ \frac{k_n \rho_p}{\rho_n k_p} \right]^{1/2} = \left[ \frac{(1.874)(1.778)}{(1.469)(1.559)} \right]^{1/2} = 1.206$$

$$A_n = \frac{\pi(0.5)^2}{(4)(1.206)} = 0.1628 \text{ in.}^2$$

$$A_p = 0.1963 \text{ in.}^2$$

$$N = \frac{60.72}{A_n + A_p} = \frac{60.71}{0.3591} = 169 \text{ pairs}$$

This might actually be taken as 170 pairs since the symmetrical arrangement of an even number of pairs would probably be easier.

$$\begin{aligned} \text{Internal resistance} &= NI \left( \frac{\rho_p}{A_p} + \frac{\rho_n}{A_n} \right) \\ &= (169)(0.3937) \left( \frac{0.001778}{0.1963} + \frac{0.001469}{0.1628} \right) \\ &= 1.20 \text{ ohms} \end{aligned}$$

Optimum resistance ratio as calculated by the code = 1.28

$1.20 + (0.30)(1.20) =$  internal resistance + contact resistance

$(1.56)(1.28) = 2.00$  ohms load resistance

$$\begin{aligned} \text{Output voltage} &= \frac{(\text{total voltage})(\text{load resistance})}{\text{total resistance}} \\ &= \frac{(169 \text{ pairs})(0.1489 \text{ volts/pair})(2.00)}{3.56} \\ &= 14.14 \text{ volts} \end{aligned}$$

## APPENDIX G

THERMAL TRANSIENT UPON REMOVAL OF  
BIOLOGICAL SHIELD

The time it takes for the generator to heat to its maximum or operating temperature is dependent on the thermal diffusivity and geometry of its components. Since the thermoelectric elements are liable to damage if heated much over 1000° F, this is the limiting characteristic involved in calculating the time. As a conservative safety factor, the specific heat of components outside the volume enclosed by the hot junction is ignored.

It will be assumed that the cooling water was circulated at a rate which would maintain the fuel block surface temperature at 212° F and the hot junction temperature at 150° F. Since a 600° F differential is maintained between surface and centerline, this gives an average temperature of about 350° F for the block (volume increases as the square of the radius).

The specific heat of the Hastelloy C-nickel block is taken to be the same as the stainless steel (0.145 Btu/lb ° F).

Weight of stainless steel hot junction = 12.5 pounds

Weight of fuel block = 20 pounds

Weight of support structure at  
average temperature of 180° F = 6 pounds

Heat absorbed by components in being raised to operating temperature =

$$(12.5)(0.145)(1000 - 150) + 20(0.145)(1800 - 350)$$

$$+ 6(0.145)(1400 - 180) = 6805 \text{ Btu}$$

Thermal output at launch = (5800)(3.415) = 19,800 Btu/hr

$$\frac{6805}{19,800} = 0.343 \text{ hour} = 20.6 \text{ minutes}$$

Were the cooling system to fail prior to the time the shield was dumped, the heat capacity of the solid components of the generator would be greatly augmented by the heat capacity and enthalpy of vaporization of the water.

The internal volume of the generator is approximately equal to

$$\frac{4}{3} \pi (8.75)^2 (9.75) \text{ in.}^3$$

The volume of the heat source is approximately  $\frac{\pi(4.5)^3}{4} \text{ in.}^3$

$$\text{Water volume} = \frac{\pi}{1728} (4/3 (8.75)^2 (9.75) - (\frac{4.5}{4})^3) \text{ ft}^3$$

$$\text{Water volume} = 1.766 \text{ ft}^3$$

$$(1.766)(62.4 \text{ lb/ft}^3) = 110 \text{ pounds of water}$$

Assuming average temperature of water is 150° F and that at least 50% must boil off before any direct heating of the components may begin, the additional heat capacity is

$$(110)(212 - 150) + (55)(970) = 60,170 \text{ Btu}$$

$$\frac{60,170}{19,800} = 3.04 \text{ hours}$$

Thus at least three hours must elapse before any danger of overheating the generator occurs from cooling system failure just prior to launch. Should the failure occur prior to the launch date the time will, of course, be less than three hours. Since the joints around the thermal shutter are not pressure resistant, the steam generated will not present a hazard.

## APPENDIX H

## CALCULATION OF THERMAL SHUTTER AREA--TYPE C GENERATOR

For the purpose of this calculation, it will be assumed that the thermal shutter bares a hot junction surface at 1000° F to space with an equivalent temperature of -100° F.

$$q = \sigma \epsilon A (T_1^4 - T_s^4)$$

This is the same equation used to determine fuel block dimensions in Appendix B except that the ratio  $\frac{A_1}{A_2} = 0$

$$q = 5800 - 2680 = 3120 \text{ watts} = 10,655 \text{ Btu/hr}$$

Solving for A, using  $\epsilon$  as 0.8

$$A = \frac{10,655}{(0.1718)(0.8)(14.60^4 - 3.60^4)}$$

$$A = \frac{10,655}{(0.1718)(0.8)(45,437 - 170)} = 1.72 \text{ ft}^2$$

As a check on this, assume that the shutter opens the interior of the generator directly to space. Thus, the end of the fuel block (at about 1700° F) and the hot junction (at 1000° F) would see space through a hole 17.5 inches in diameter.

The heat dumped by the end of the fuel block

$$q = (0.1718)(0.9) \frac{(\pi)(4.5)^2 (21.60^4)}{(4)(144)}$$

$$q = 3713 \text{ Btu/hr}$$

Thus, the area of  $1.72 \text{ ft}^2$  is more than sufficient to dump the excess heat of the fuel block. Since the shutter opening does not completely fill the solid angle subtended by the end of the fuel block, the heat dumped from the end of the fuel block will be less than that calculated above, but this will be more than compensated by heat dumped through the opening from the other hot surfaces of the generator interior. If the shutter is dumping too much heat, it can be partially closed, but if it is not dumping a sufficient amount of heat, then the generator must be redesigned.